SONDERFORSCHUNGSBEREICH 504

Rationalitätskonzepte,
Entscheidungsverhalten und
ökonomische Modellierung

No. 03-29

Security And Potential Level Preferences With Thresholds

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October 2003

The authors want to thank Martin Hellwig, Peter Wakker, Ithzak Gilboa, Craig Fox, Martin Peterson, and Lennart Sjöberg for their suggestions and comments. Financial support of the second author by Deutsche Forschungsgemeinschaft via the Graduiertenkolleg îAllokation auf Finanz- und G¨utermärkteni, University of Mannheim, and by the Marie-Curie-program of the European Union is gratefully acknowledged.

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December 2003

Abstract

The security level models of Gilboa (1988) and of Jaffray (1988) as well as the security and potential level model of Cohen (1992) accommodate succesfully classical Allais paradoxa while they offer an interesting explanation for their occurrence. However, experimental data suggest a systematic violation of these models when lotteries with low probabilities of bad or good outcomes are involved. The present paper develops an axiomatic model that allows for thresholds in the perception of security and potential levels. The derived representation of preferences accomodates the observed violations of the original security and potential level models and provides a natural explanation for their occurence. Additionally, a more fundamental problem of the original models is resolved.

Keywords: Allais paradoxa, Security Level, Potential Level, Thresholds
JEL Classification Number: D81

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*The authors want to thank Martin Hellwig, Peter Wakker, Ithzak Gilboa, Craig Fox, Martin Peterson, and Lennart Sjöberg for their suggestions and comments. Financial support of the second author by Deutsche Forschungsgemeinschaft via the Graduiertenkolleg "Allokation auf Finanz- und Gütermärkten", University of Mannheim, and by the Marie-Curie-program of the European Union is gratefully acknowledged.

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1 Introduction

In a well-known study on the psychology of decision making under risk, Lopes (1987) concluded that a decision maker takes into account three different factors while evaluating lotteries: What is the expected utility of this lottery? What is the worst outcome I can end up with by choosing this lottery (i.e. what is the security level of this lottery)? What is the best outcome I can end up with (i.e. what is the potential level)? This conclusion motivated Cohen (1992) to develop a three-criteria decision model which generalizes expected utility by allowing for security level and potential level considerations. An extension of this model has been provided by Essid (1997). Earlier models of Gilboa (1988) and Jaffray (1988) are very similar to Cohen's model but restrict attention to the security level alone. All three approaches explain Allais paradoxa by discontinuities of preferences resulting from the different security and potential levels of the lotteries involved. More recently, Cahteauneuf et al. (2003), building upon earlier work of Dow and Werlang (1994) and Eichberger and Kelsey (1999), have integrated Cohen's ideas in a model of decision making under uncertainty.

The accommodation of Allais paradoxa by the security level and potential level (SL-PL) models is in our view intuitively very appealing. However, SL-PL models exhibit two major problems. First, they perform descriptively rather poorly when they are confronted with experimental data that go beyond the classical Allais paradoxa. A second and somewhat more fundamental problem can be characterized as follows: in real life there is always an (arbitrarily) small chance of immediate death and also a tiny chance of finding a suitcase on the street containing a huge cash amount of say ten billion dollars. Thus, it may be argued that in all decision problems death is always the security level while the amount of ten billion dollars is the potential level. If the security and potential levels are, however, identical in all lotteries, SL-PL models simply reduce to expected utility.

This second problem indicates that the shortcoming of SL-PL models is not so much owed to their assumption of security and potential considerations in general but rather to their assumption that security and potential considerations refer exclusively to the worst, respectively best, outcome in the support of a lottery, regardless of how small their probability actually is. This motivated us to develop an axiomatic model which extends existing SL-PL models by so-called *thresholds* such that security or potential considerations become only relevant if the probabilities of bad, respectively good, outcomes are not below some perceptual threshold level. For example, a lottery may be still perceived as very secure as long as bad outcomes realize with very small probability. Accordingly, a lottery may be associated with a low potential when the probability of a high outcome is only small for this lottery. It turns out that the introduction of threshold also resolves the first problem: as shown below, the poor descriptive performance of the original SL-PL models can be significantly improved by the introduction of thresholds.

Empirical observations that people often neglect very small probabilities (cf. Sjöberg (1999), (2000) and Stone, Yates, and Parker (1994)) can be regarded as further evidence in favor of thresholds: if the worst (respectively best) outcome has a very small probability, it seems unreasonable that people attach psychological importance to this outcome by regarding it as security (respectively potential) level and, at the same time, neglect its probability.

An analogous concept to our notion of thresholds can be seen in the Value-at-Risk (VaR) which is defined as the worst loss for a given confidence level (mostly 99%). More precisely, for a confidence level of 99% the VaR of a lottery equals x if the cumulative probability of outcomes smaller than x is given by 1%. The VaR has recently become very popular as a risk measure and it seems reasonable to consider the VaR as security level which is perfectly consistent with our model but not compatible with the original SL-PL models.

A further characteristic of our model is that it assumes a weaker version of independence than in the original SL-PL models: the risk-attitudes of a decision maker may depend in our model also on security and potential considerations. For example, our model allows for the possibility that decision makers are less risk averse for choice between insecure lotteries than for choice between secure lotteries. This is not the case for the original SL-PL models: because the utility functions for different security and potential levels differ in these models only by affine transformations, the risk attitudes are the same accross different security and potial levels.

The introduction of thresholds appears to us as a natural extension of SL-PL models, and, together with our weakened version of the independence axiom, it can successfully explain the most persistent choice patterns that are inconsistent with the original SL-PL models. Thus, as the main contribution of this paper, we demonstrate that the security and potential considerations of SL-PL models can go along with descriptive power under the intuitively appealing assumptions that the perception of security and of potential may depend on thresholds and that the risk attitudes of decision makers may depend on the security and potential levels involved.

The paper proceeds as follows. The next section introduces the original SL-PL models and presents the typical experimental designs in which violations of these models have been observed. Section 3 introduces our proposal for a partition of a set of lotteries into subsets of different security and potential levels with respect to thresholds. In section 4 we introduce our axioms and state two representation theorems: the first representation allows for violations of monotonicity with respect to first-order stochastic dominance whereas the second representation excludes such violations. In section 5 we demonstrate how the evidence against the original SL-PL models can be accommodated within our framework. All formal proofs are relegated to the appendix.

2 The original SL-PL models

In contrast to other alternatives to expected utility like models with the betweenness-property or rank dependent utility models (see, e.g., Karni and Schmeidler (1991), Starmer (2000), and Schmidt (2003) for surveys), SL-PL models presume that discontinuities in the preferences describe best what is psychologically happening when decision makers commit Allais paradoxa: as an extension to expected utility security and potential factors may lead to jumps in the preferences such that a *secure* (respectively *high potential*) lottery dominates now all *insecure* (respectively *low potential*) lotteries that are sufficiently close in the sense of some mathematically defined neighborhood.

Let x and y denote the worst and best outcomes of the lottery σ. Then the utility of a lottery σ is in Cohen's model given by

$$V(\sigma) = a(x, y) * EU(\sigma) + b(x, y),$$

where $EU(\sigma)$ denotes the standard expected utility of σ and $a(x, y)$ and $b(x, y)$ are constants depending on the given security and potential level of σ. The models of Gilboa (1988) and Jaffray (1988) are similar but restrict attention to the security level x.

In the following we present experimental data of Sopher and Gigliotti (1993) and Chew and Waller (1986), which demonstrate that a majority of decision makers violates the SL-PL models in a very systematic way despite the fact that these models deal successfully with classical Allais paradoxa.

Problem 1. Consider the following three pairs of lotteries where, e.g., $(\$1M \cdot 1)$ denotes a lottery that gives \$1 Mill. with probability one:

$S1 = (\$1M \cdot 1)$ $\quad$ $R1 = (\$0 \cdot 0.01 \oplus \$1M \cdot 0.89 \oplus \$5M \cdot 0.10)$

$S2 = (\$0 \cdot 0.89 \oplus \$1M \cdot 0.11 \oplus \$5M \cdot 0)$ $\quad$ $R2 = (\$0 \cdot 0.9 \oplus \$1M \cdot 0 \oplus \$5M \cdot 0.10)$

$S3 = (\$0 \cdot 0 \oplus \$1M \cdot 0.11 \oplus \$5M \cdot 0.89)$ $\quad$ $R3 = (\$0 \cdot 0.01 \oplus \$1M \cdot 0 \oplus \$5M \cdot 0.99)$

A decision maker with the choice pattern $(S1, R2)$, i.e., preferring $S1$ to $R1$ and preferring $R2$ to $S2$, commits the classical Allais paradox. The existing SL-PL models can accommodate this Allais paradox via the security effect: At first a decision maker prefers the secure lottery $S1$ to the insecure lottery $R1$ because by the security effect her evaluation of lotteries experiences an upward-jump when the probability of the bad outcome \$0 drops to zero. However, after substituting the bad outcome \$0 for the outcome $\$1M$ with probability weigt 0.89 in the lotteries $S1$ and $R1$ there is no longer any security effect when the resulting lotteries $S2$ and $R2$ are compared and as a consequence $R2$ may now become preferred to $S2$ as observed in the Allais paradox.

INSERT FIGURE 1 ABOUT HERE

However, the occurrence of this security effect implies for the original SL-PL models that the decision maker must prefer $S3$ to $R3$ (see figure 1). Sopher and Gigliotti (1993) have elicited preferences for these three choice pairs and according to their results 45 individuals have chosen $(S1, R2, S3)$ whereas 58 individuals have chosen $(S1, R2, R3)$. That is, the majority of decision makers who commit this classical Allais paradox have displayed preferences that are not compatible with existing SL-PL models.

Problem 2. Consider now the following three pairs of lotteries

$Q1 = (\$40 \cdot 1)$	$T1 = (\$0 \cdot 0.5 \oplus \$100 \cdot 0.5)$
$Q2 = (\$40 \cdot 1)$	$T2 = (\$0 \cdot 0.05 \oplus \$40 \cdot 0.90 \oplus \$100 \cdot 0.05)$
$Q3 = (\$0 \cdot 0.9 \oplus \$40 \cdot 0.10)$	$T3 = (\$0 \cdot 0.95 \oplus \$100 \cdot 0.05)$

A decision maker with the choice pattern $(Q1, T2)$ commits another classical Allais paradox that is typically observed for moderate payoffs or losses. This choice behavior can not be accommodated by the security level models of Gilboa (1988) and Jaffray (1988), however, it is possible to accommodate this choice behavior within Cohen's model by a potential effect.

INSERT FIGURE 2 ABOUT HERE

The assumption of this potential effect implies in Cohen's model that the decision maker prefers also $Q3$ to $T3$ (see figure 2). But Chew and Waller's (1986) experimental data display this choice pattern $(Q1, T2, Q3)$ only for 12 individuals whereas the choice pattern $(Q1, T2, T3)$ appears for 28 individuals. Again the vast majority of decision makers who commit a classical Allais paradox violate preferences that are admissible for the existing SL-PL models.

A closer examination of problem 1 and of problem 2 reveals that SL-PL models are violated when lotteries become involved such that bad outcomes or good outcomes realize with rather small probability. We think therefore that the key for solving these systematic violations of SL-PL models is a departure from the assumption that a lottery is not secure, or is a high potential lottery, just because bad, respectively good, outcomes realize with positive probability. In contrast, our SL-PL model with thresholds, will allow to perceive lotteries as secure (of low potential) when the bad (good) outcomes realize only with sufficiently small probabilities.

3 Security and Potential Levels with Thresholds

The objective for our particular formalism of thresholds has been twofold. First, we wanted to keep the model as simple as possible. As a consequence we introduce only two new parameters to the original SL-PL models, a threshold for security levels and a threshold for potential levels, whereby the security level and the potential level of a lottery is then easily determined by its cumulative distribution function. More sophisticated SL-PL models with thresholds could be constructed, however, we are willingly trading off richness of the model for a simple formalism that captures well the basic idea. Secondly, we introduce a formalism of thresholds such that the resulting preferences will not necessarily violate monotonicity with respect to first-order stochastic dominance (FOSD). The original SL-PL models do not violate this fundamental requirement for rational decision makers, however, one can easily construct proposals for thresholds for which the discontinuous preferences of SL-PL models lead to violations of monotonicity with respect to FOSD.

Let $X = \{x_1, ..., x_n\}$ denote a finite set of totally ordered deterministic outcomes with $x_1 < ... < x_n$, and let $\triangle(X)$ denote the set of all probability distributions, i.e., lotteries, over X. A lottery $\sigma \in \triangle(X)$ is also written as $(\sigma_1 \cdot x_1 \oplus ... \oplus \sigma_n \cdot x_n)$ where σ_k denotes the probability by which outcome x_k realizes. Let $F[\sigma](x_k)$ denote the cumulative distribution function of lottery σ evaluated at outcome x_k. For so-called *thresholds* $\varepsilon, \eta \in [0, 1)$ denote by $\Pi(\varepsilon, \eta)$ a collection of sets

$$\Pi(\varepsilon, \eta) = \{\triangle(x_j, x_k)\}_{j=1,...,n;k\geq j}$$

such that

$$\sigma \in \triangle(x_j, x_k) \text{ iff } F[\sigma](x_{j-1}) \leq \varepsilon,\ F[\sigma](x_j) > \varepsilon \text{ AND } 1-F[\sigma](x_k) \leq \eta,\ 1-F[\sigma](x_{k-1}) > \eta$$

Observation: $\Pi(\varepsilon,\eta)$ *is a partition of* $\triangle(X)$ *with convex cells* $\triangle(x,y)\in\Pi(\varepsilon,\eta)$. *Moreover, for* $\varepsilon+\eta<1$ *these cells are non-empty.*

We say a lottery $\sigma\in\triangle(x,y)$, with $\triangle(x,y)\in\Pi(\varepsilon,\eta)$, has security level x and potential level y. The threshold-value ε for security levels guarantees that worse outcomes than x can realize for a lottery of security level x at most with probability ε. Accordingly, better outcomes than y can realize for a lottery of potential level y at most with probability η. For $\varepsilon,\eta=0$ the partition $\Pi(\varepsilon,\eta)$ reduces to the original SL-PL partition of Cohen (1992) where the security level of a lottery is the worst outcome in its support and the potential level is the best outcome in the support, i.e., $\sigma\in\triangle(x,y)$ if and only if $x=\min Support(\sigma)$ and $y=\max Support(\sigma)$.

4 Axiomatic Analysis

Existing axiomatizations of SL-PL models presume basically that the axioms of expected utility theory remain valid within security and potential level subsets whereas the independence axiom and continuity may be violated while passing from one subset to another. However, some weakened version of the independence axiom and of the Archimedean axiom have to be satisfied between different subsets in order to obtain a simple real-valued utility representation. Apart from introducing threshold our axiomatization differs from Cohen's (1992) model by imposing only a weakened variant of her independence axiom. As a consequence of this weakening we can accommodate indifference curves with different slopes on different SL-PL subsets such that there may be different risk attitudes within different SL-PL subsets. We employ the following three axioms:

A1-Ordering: *Asymmetry, Transitivity and Completeness of the strict preference relation* $\succ$ *on* $\triangle(X)$.

A2-Subset Dependent Archimedean Axiom: *Suppose* $\sigma\in\triangle(x,y)$ *and* $\rho,\tau\in\triangle(x',y')$ *for* $\triangle(x,y),\triangle(x',y')\in\Pi(\varepsilon,\eta)$. *If* $\tau\succ\sigma\succ\rho$ *then*

$$\lambda\cdot\tau\oplus(1-\lambda)\cdot\rho\sim\sigma$$

for a unique $\lambda\in(0,1)$.

A3-Subset Dependent Independence Axiom: *Suppose* $\triangle(x,y), \triangle(x',y') \in \Pi(\varepsilon,\eta)$. *If there exist lotteries* $\sigma, \tau \in \triangle(x,y)$ *and lotteries* $\sigma', \tau' \in \triangle(x',y')$ *such that* $\sigma \succ (\sim) \sigma'$ *and* $\tau \succeq (\sim) \tau'$ *then*

$$\lambda \cdot \sigma \oplus (1-\lambda) \cdot \tau \succ (\sim) \lambda \cdot \sigma' \oplus (1-\lambda) \cdot \tau'$$

for all $\lambda \in (0,1)$.

We define now a subset-dependent expected utility functional $V : \triangle(X) \times \Pi(\varepsilon,\eta) \to \mathbf{R}_+$ by

$$V(\sigma, \triangle(x,y)) = \sum_{k=1}^{n} \sigma(x_k) * u(x_k, \triangle(x,y)) \tag{1}$$

with $u : X \times \Pi(\varepsilon,\eta) \to \mathbf{R}_+$.

Theorem 1:
Let preferences on $\triangle(X)$ *satisfy the axioms (A1)-(A3) for some partition* $\Pi(\varepsilon,\eta)$ *with* $\varepsilon+\eta < 1$. *Then these preferences are representable by a utility function* $U : \triangle(X) \to \mathbf{R}_+$ *such that*

$$U(\sigma) = V(\sigma, \triangle(x,y))$$

with $\sigma \in \triangle(x,y)$, *whereby the function* V *is defined in (1).*

Conversely, any such U *represents preferences that fulfil the axioms (A1)-(A3).*

The representation of Theorem 1 allows for preferences that may violate monotonicity w.r.t. FOSD. However, one main motivation for our particular definition of thresholds was the desire to introduce SL-PL partitions such that preferences may be consistent with FOSD as in the original SL-PL models. We will now derive a second representation theorem which will guarantee consistency with FOSD.

Recall the definition of first-order stochastic dominance: A lottery σ dominates a lottery τ w.r.t. FOSD, i.e., $\sigma \succeq_{FOSD} \tau$, if and only if $F[\sigma](x) \leq F[\tau](x)$ for all $x \in X$. Moreover, if additionally $F[\sigma](x) < F[\tau](x)$ for some $x \in X$ we say that σ dominates a lottery τ strictly w.r.t. FOSD and we write then $\sigma \succ_{FOSD} \tau$. Verify the following two properties of $\succ_{FOSD}$ that will be exploited later on in the proof of the second representation theorem:

Continuity: Suppose $(\sigma_k)_{k\in\mathbf{N}}$ with $\lim_{k\to\infty} \sigma_k = \sigma$. If there is a τ such that $\tau \succ_{FOSD} \sigma_k$ for all $k \in \mathbf{N}$ then $\tau \succeq_{FOSD} \sigma$.

Quasiconcavity: If $\tau \succ_{FOSD} \sigma$ then $\lambda \cdot \tau \oplus (1-\lambda) \cdot \sigma \succ_{FOSD} \sigma$ for all $\lambda \in (0,1)$.

Consistency of preferences with FOSD is guaranteed by the following condition:

A4-Monotonicity with respect to FOSD: *If* $\sigma \succeq_{FOSD} \tau$ *then* $\sigma \succeq \tau$*; and if* $\sigma \succ_{FOSD} \tau$ *then* $\sigma \succ \tau$*.*

Adding (A4) to the axiomatic system of Theorem 1 leads to the second representation theorem.

Theorem 2:
Let preferences on $\triangle(X)$ *satisfy the axioms (A1)-(A4) for some partition* $\Pi(\varepsilon, \eta)$ *with* $\varepsilon + \eta < 1$*. Then these preferences are representable by a utility function* $U : \triangle(X) \rightarrow \mathbf{R}_+$ *such that*

$$U(\sigma) = V(\sigma, \triangle(x, y)) \tag{2}$$

for $\sigma \in \triangle(x, y)$*, whereby the function* V *defined in (1) has the following properties*

(i) for all $\triangle(x, y) \in \Pi(\varepsilon, \eta)$

$$u(x_m, \triangle(x, y)) < u(x_{m+1}, \triangle(x, y)) \tag{3}$$

with $1 \leq m \leq n - 1$*,*

(ii)

$$\lim_{k \rightarrow \infty} V(\sigma_k, \triangle(x, y)) \leq V(\sigma, \triangle(\bar{x}, \bar{y})) \tag{4}$$

for any sequence $(\sigma_k)_{k \in \mathbf{N}}$ *with* $\lim_{k \rightarrow \infty} \sigma_k = \sigma$, $\sigma_k \in \triangle(x, y)$ *for all* $k \in N$*, and* $\sigma \in \triangle(\bar{x}, \bar{y})$ *with* $\bar{x} \geq x$*,* $\bar{y} \geq y$*,*

(iii)

$$V(\sigma, \triangle(x, y)) \leq \lim_{k \rightarrow \infty} V(\sigma_k, \triangle(\bar{x}, \bar{y})) \tag{5}$$

for any sequence $(\sigma_k)_{k \in \mathbf{N}}$ *with* $\lim_{k \rightarrow \infty} \sigma_k = \sigma$, $\sigma_k \in \triangle(\bar{x}, \bar{y})$ *for all* $k \in N$*, and* $\sigma \in \triangle(x, y)$ *with* $\bar{x} \geq x$*,* $\bar{y} \geq y$*.*

Conversely, any such U *represents preferences that fulfil the axioms (A1)-(A4).*

For arbitrary functions $V(\cdot, \triangle(x, y))$ and $V(\cdot, \triangle(\bar{x}, \bar{y}))$ it may not be obvious whether the conditions (4) and (5) are satisfied, or not. But observe that (4) and (5) are trivially fulfilled for vNM-utility indices $u(x_k, \cdot)$ that are monotonic on $\Pi(\varepsilon, \eta)$ for all $x_k \in X$. As a consequence we can immediately derive the following corollary:

Corollary 1:
Any utility function $U : \triangle(X) \rightarrow R_{+}$ *with*

$$U(\sigma) = V(\sigma, \triangle(x, y))$$

for $\sigma \in \triangle(x, y)$*, with* V *defined in (1), is representing preferences that fulfil the axioms (A1)-(A4) if we have for all* $x_k \in X$

$$u(x_k, \triangle(x, y)) \leq u(x_k, \triangle(\bar{x}, \bar{y}))$$

with $\bar{x} \geq x$*,* $\bar{y} \geq y$*.*

5 Accommodating the Experimental Evidence

Our formalism of thresholds presented in section 3 is clearly a very idealizing concept and, therefore, it seems unreasonable that this concept can capture all empirical choice patterns which may be associated with the existence of thresholds in a decisionmaker's evaluation of lotteries. We have focused on our simple concept of a SL-PL partition, with only two parameters more than Cohen's original SL-PL partition, because we wanted to obtain a model which is as simple as possible while it can solve the two major problems concerning the original SL-PL models mentioned in the introduction.

It remains to show that our model of SL-PL preferences with thresholds can indeed accommodate the observed choice patterns of the two problems presented in section 2 which violate the original SL-PL models. In the following analysis, the employed utility values fulfil the assumptions of the Corollary 1 such that monotonicity with respect to first-order stochastic dominance is satisfied.

Problem 1. (See figure 3) Consider the following specification of the utility function for a SL-PL partition $\Pi(\varepsilon, \eta)$, with $\varepsilon = 0.01$ and $\eta = 0$:

For security level $\$1M$

$$\begin{aligned} u(\$0, \triangle(\$1M, y)) &= 0 \text{ for } \$1M \leq y \leq \$5M \\ u(\$1M, \triangle(\$1M, y)) &= 0.99 \text{ for } \$1M \leq y \leq \$5M \\ u(\$5M, \triangle(\$1M, y)) &= 1 \text{ for } \$1M \leq y \leq \$5M \end{aligned}$$

For security level $\$0$

$$\begin{aligned} u(\$0, \triangle(\$0, y)) &= 0 \text{ for } \$0 \leq y \leq \$5M \\ u(\$1M, \triangle(\$0, y)) &= (0.99)^{100} \text{ for } \$0 \leq y \leq \$5M \\ u(\$5M, \triangle(\$0, y)) &= 1 \text{ for } \$0 \leq y \leq \$5M \end{aligned}$$

For security level $\$5M$

$$\begin{aligned} u\left(\$0, \triangle\left(\$5M, y\right)\right) &= 0 \text{ for } y = \$5M \\ u\left(\$1M, \triangle\left(\$5M, y\right)\right) &= 1.98 \text{ for } y = \$5M \\ u\left(\$5M, \triangle\left(\$5M, y\right)\right) &= 2 \text{ for } y = \$5M \end{aligned}$$

When we compute now the utility numbers for the lotteries in problem 1 we obtain the desired choice pattern $(S1, R2, R3)$

$$\begin{aligned} U\left(S1\right) &= V\left(S1, \triangle\left(\$1M, \$1M\right)\right) = 0.99 \\ &> 0.9811 = V\left(R1, \triangle\left(\$1M, \$1M\right)\right) = U\left(R1\right) \end{aligned}$$

$$\begin{aligned} U\left(S2\right) &= V\left(S2, \triangle\left(\$0, \$1M\right)\right) = 0.04 \\ &< 0.1 = V\left(R2, \triangle\left(\$0, \$1M\right)\right) = U\left(R2\right) \end{aligned}$$

$$\begin{aligned} U\left(S3\right) &= V\left(S3, \triangle\left(\$1M, \$5M\right)\right) = 0.999 \\ &< 1.98 = V\left(R3, \triangle\left(\$5M, \$5M\right)\right) = U\left(R3\right) \end{aligned}$$

INSERT FIGURE 3 ABOUT HERE

Problem 2. (See figure 4) Consider the following specification of the utility function for a SL-PL partition $\Pi\left(\varepsilon, \eta\right)$, with $\varepsilon = 0.05$ and $\eta = 0$:

For security level $0

$$\begin{aligned} u\left(\$0, \triangle\left(\$0, y\right)\right) &= 0 \text{ for } \$0 \le y \le \$100M \\ u\left(\$40, \triangle\left(\$0, y\right)\right) &= 0.4 \text{ for } \$0 \le y \le \$100M \\ u\left(\$100, \triangle\left(\$0M, y\right)\right) &= 1 \text{ for } \$0 \le y \le \$100M \end{aligned}$$

For security levels $40 and $100

$$\begin{aligned} u\left(\$0, \triangle\left(x, y\right)\right) &= 1 \text{ for } \$40 \le x \le y \le \$100 \\ u\left(\$40, \triangle\left(x, y\right)\right) &= 1.4 \text{ for } \$40 \le x \le y \le \$100 \\ u\left(\$100, \triangle\left(x, y\right)\right) &= 2 \text{ for } \$40 \le x \le y \le \$100 \end{aligned}$$

Computing then the utility numbers for the lotteries in problem 2 gives the desired choice pattern $(Q1, T2, T3)$

$$\begin{aligned} U(Q1) &= V(Q1, \triangle(\$40, \$40)) = 1.4 \\ &> 0.2 = V(T1, \triangle(\$0, \$100)) = U(T1) \end{aligned}$$

$$\begin{aligned} U(Q2) &= V(Q2, \triangle(\$40, \$40)) = 1.4 \\ &< 1.41 = V(T2, \triangle(\$40, \$40)) = U(R2) \end{aligned}$$

$$\begin{aligned} U(Q3) &= V(Q3, \triangle(\$0, \$40)) = 0.04 \\ &< 0.05 = V(T3, \triangle(\$0, \$40)) = U(T3) \end{aligned}$$

INSERT FIGURE 4 ABOUT HERE

Remark 1. Compared to the original SL-PL models the accommodation of the choice pattern $(Q1, T2, T3)$ in problem 2 requires only a positive threshold-value whereas the accommodation of $(S1, R2, R3)$ in problem 1 requires additionally our weakened version of the independence axiom: When the slopes of the indifference curves are the same across different SL-PL subsets (as implied by the original SL-PL models) we could not have $(S1, R2)$ because the lotteries $S1, R1$, on the one hand, and the lotteries $S2, R2$, on the other hand, have in our SL-PL partition the same security and potential levels. Thus, if we assumed the independence axiom of the original SL-PL models for our SL-PL partition then $S1$ is preferred to $R1$ if and only if $S2$ is preferred to $R2$. Observe that the subset-dependent expected utility functional $V(\cdot, \triangle(\$0, y))$ results from a convex transformation of the subset-dependent expected utility functional $V(\cdot, \triangle(\$1M, y))$ which implies steeper slopes of the indifference curves on SL-PL subsets with higher security levels. In analogy to the comparison of risk attitudes within the expected utility framework we could say that the decision maker of our representation makes riskier choices when she has to decide between low-security lotteries as when she has to decide between high-security lotteries. In our opinion such security and potential level dependent risk-attitudes can make some intuitive sense and they could be justified, e.g., by the following rationale: If I feel that there are only insecure alternatives I can choose from, then I might go as well for riskier alternatives.

Remark 2. Although the choice pattern $(Q1, T2)$ violates the original *security level* models of Gilboa (1988) and of Jaffray (1988) it can be accommodated within Cohen's SL-PL model under the assumption of a *potential effect* (which had actually been introduced by Cohen (1992) for accommodating typical violations of expected utility preferences when *losses* are considered as outcomes). However, it can be easily shown that the occurrence of a potential effect implies then also $Q3 \succ T3$ in Cohen's model (compare figure 2). In contrast, our model can explain $(Q1, T2, T3)$ by the occurrence of a *security effect* under the assumption that the lottery $T2$ is considered as comparably safe. That is, the 0.05 chance of ending up with the bad outcome of \$0 does not bother here the decision maker that much as to let her evaluation of this lottery be affected by security consideration with respect to the secure lottery $Q2$.

Remark 3. Motivated by the discussion whether Allais paradoxa are persistently committed within the interior of the Marschak-Machina triangle, or not, Harless and Camerer (1994) conclude after a broad statistical investigation of experiments: "The conjecture that EU violations disappear in the interior appears to be false." The original SL-PL models can not take account of Allais paradoxa that are committed within the interior of the Marschak-Machina triangle, however, the introduction of thresholds implies obviously violations of EU-theory within the interior of the Marschak-Machina triangles that may follow quite complex patterns according to the specification of threshold values.

6 Appendix: Proofs

Proof of the observation: Convexity of each SL-PL subset $\triangle(x, y)$ is obviously implied by the definition of the cumulative distribution function. By the same argument we see immediately that $\Pi(\varepsilon, \eta)$ is a partition of $\triangle(X)$ regardless of the values of ε and η:

i.) $\triangle(x, y) \cap \triangle(x', y') = \emptyset$ for $\triangle(x, y) \neq \triangle(x', y')$ and

ii.)

$$\bigcup_{\{(x,y)\in X\times X | x\leq y\}} \triangle(x, y) = \triangle(X)$$

It remains to show that each is SL-PL subset $\triangle(x, y)$ is non-empty if $\varepsilon + \eta < 1$. Just observe that there exists always the lottery

$$\left(\varepsilon + \frac{1-\eta-\varepsilon}{2}\right) \cdot x \oplus \left(\eta + \frac{1-\eta-\varepsilon}{2}\right) \cdot y \in \triangle(x, y)$$

for $\varepsilon + \eta < 1$.$\square$

Proof of the Representation Theorems

We proceed by proving in detail the second representation theorem whose proof is more demanding than the proof of the first representation theorem because the preferences must satisfy here additionally the assumption of monotonicity w.r.t. FOSD. We will omitt an explicit proof of the first representation theorem because such a proof coincides basically with our proof of the second representation theorem when we simply do not take account of the restrictions required by monotonicity w.r.t. FOSD.

Part A. We demonstrate that all preferences on $\triangle(x, y)$ fulfilling (A1)-(A4) must be representable by (2) such that for all $\triangle(x, y) \in \Pi(\varepsilon, \eta)$ the $V(\cdot, \triangle(x, y))$ are subset-dependent EU-functionals as defined in (1).

Recall that the assumption of (A1)-(A4) implies that preferences over lotteries within the same SL-PL subset can be represented by some EU-functional; i.e., for $\sigma, \tau \in \triangle(x, y)$ we have $\sigma \succ \tau$ iff

$$\sum_{k=1}^{n} \sigma(x_k) * u(x_k, \triangle(x, y)) > \sum_{k=1}^{n} \tau(x_k) * u(x_k, \triangle(x, y)) \tag{6}$$

for strictly monotonic $u(\cdot, \triangle(x, y))$. This is by definition equivalent to

$$V(\sigma, \triangle(x, y)) > V(\tau, \triangle(x, y))$$

Presume from now on that the preferences over the lotteries within any SL-PL subset $\triangle(x, y) \in \Pi(\varepsilon, \eta)$ are represented by some expected utility function $V(\cdot, \triangle(x, y))$. Observe that by construction of $\Pi(\varepsilon, \eta)$ and by application of (A2) and (A4)

$$\begin{aligned}
\inf_{\sigma \in \triangle(x,y)} V(\sigma, \triangle(x, y)) &= V(\varepsilon \cdot x_1 \oplus (1 - \varepsilon - \eta) \cdot x \oplus \eta \cdot y, \triangle(x, y)) \\
\sup_{\sigma \in \triangle(x,y)} V(\sigma, \triangle(x, y)) &= V(\varepsilon \cdot x \oplus (1 - \varepsilon - \eta) \cdot y \oplus \eta \cdot x_n, \triangle(x, y))
\end{aligned}$$

and let us introduce the following notational conventions for these particular lotteries

$$\begin{aligned}
\inf \triangle(x, y) &= \varepsilon \cdot x_1 \oplus (1 - \varepsilon - \eta) \cdot x \oplus \eta \cdot y \\
\sup \triangle(x, y) &= \varepsilon \cdot x \oplus (1 - \varepsilon - \eta) \cdot y \oplus \eta \cdot x_n
\end{aligned} \tag{7}$$

The EU-representation $V(\cdot, \triangle(x, y))$ of preferences within $\triangle(x, y)$ implies then that there exists for every $\sigma \in \triangle(x, y)$ a unique $\nu_\sigma \in [0, 1]$ such that

$$\begin{aligned}
V(\sigma, \triangle(x, y)) &= V(\nu_\sigma \cdot \inf \triangle(x, y) \oplus (1 - \nu_\sigma) \cdot \sup \triangle(x, y), \triangle(x, y)) \\
&= \nu_\sigma * V(\inf \triangle(x, y), \triangle(x, y)) + (1 - \nu_\sigma) * V(\sup \triangle(x, y), \triangle(x, y))
\end{aligned} \tag{8}$$

Thus, for all preferences fulfilling (A1)-(A4) we can determine by (8) the utility numbers $V(\sigma, \triangle(x,y))$ for all lotteries $\sigma \in \triangle(x,y)$ w.r.t. the utility numbers

$$V(\inf \triangle(x,y), \triangle(x,y)), V(\sup \triangle(x,y), \triangle(x,y)) \tag{9}$$

Verify now the following two properties of the lotteries (7):
(1)

$$\begin{aligned} \inf \triangle(x,y) &\in \triangle(x,x) \\ \sup \triangle(x,y) &\in \triangle(y,y) \end{aligned}$$

That is, $\inf \triangle(x,y)$ and $\sup \triangle(x,y)$ are elements of $\triangle(x,y)$ if and only if $x = y$. Conversely, all SL-PL subsets $\triangle(x,y)$ with $x < y$ do neither contain a *worst* (preference-minimizing) lottery $\inf \triangle(x,y)$ nor a *best* (preference-maximizing) lottery $\sup \triangle(x,y)$.

(2) For any $\triangle(\bar{x},\bar{y}) \in \Pi(\varepsilon,\eta)$, with $\bar{x} \geq x$ and $\bar{y} \geq y$

$$\sup \triangle(\bar{x},\bar{y}) \succ_{FOSD} \sigma$$

for all $\sigma \in \triangle(x,y)$ with $\sigma \neq \sup \triangle(x,y)$, and

$$\sigma' \succ_{FOSD} \inf \triangle(x,y)$$

for all $\sigma' \in \triangle(\bar{x},\bar{y})$ with $\sigma' \neq \inf \triangle(\bar{x},\bar{y})$. (Notice: this is in particular true for $\bar{x} = x$ and $\bar{y} = y$.)

Presume that $V(\sigma, \triangle(x,y))$ is given for all $\sigma \in \triangle(x,y)$. Furthermore, assume for now that we have also the utility-numbers (9). We are going to show in a first step that we can then choose for any arbitrary SL-PL subset $\triangle(\bar{x},\bar{y}) \in \Pi(\varepsilon,\eta)$, with $\bar{x} \geq x$ and $\bar{y} \geq y$, some utility function $V(\cdot, \triangle(\bar{x},\bar{y}))$ such that

$$\sigma \succ (\sim) \sigma' \Rightarrow V(\sigma, \triangle(x,y)) > (=) V(\sigma', \triangle(\bar{x},\bar{y})) \tag{10}$$

for all $\sigma \in \triangle(x,y)$ and $\sigma' \in \triangle(\bar{x},\bar{y})$ whenever the preferences fulfil (A1)-(A4).

In a second step we demonstrate how the utility numbers

$$\begin{aligned} &V(\inf \triangle(x,y), \triangle(x,y)), \; V(\sup \triangle(x,y), \triangle(x,y)) \\ &V(\inf \triangle(\bar{x},\bar{y}), \triangle(\bar{x},\bar{y})), \; V(\sup \triangle(\bar{x},\bar{y}), \triangle(\bar{x},\bar{y})) \end{aligned} \tag{11}$$

can be derived for all $\triangle(x,y), \triangle(\bar{x},\bar{y}) \in \Pi(\varepsilon,\eta)$ such that (10) is fulfilled for any preferences on $\triangle(X)$ satisfying (A1)-(A4).

Step 1. Consider at first the case $\sigma' \succ \sigma$ for all $\sigma \in \triangle(x,y)$ and $\sigma' \in \triangle(\bar{x},\bar{y})$. Let

$$\begin{aligned} \inf \triangle(\bar{x},\bar{y}) &= \sup \triangle(x,y) \\ \sup \triangle(\bar{x},\bar{y}) &= \inf \triangle(\bar{x},\bar{y}) + 1 \end{aligned} \tag{12}$$

whereby $V(\sigma', \triangle(\bar{x},\bar{y}))$ is then determined for all $\sigma' \in \triangle(\bar{x},\bar{y})$ by (8). Obviously, (10) is satisfied.

Consider now the case that preferences overlap, i.e., there is a $\rho' \in \triangle(\bar{x},\bar{y})$ such that $\sigma \succeq \rho'$ for some $\sigma \in \triangle(x,y)$. Observe at first that this is impossible whenever $\Pi(\varepsilon,\eta)$ is given such that

$$\sup \triangle(x,y) = \inf \triangle(x,y)$$

i.e., $\varepsilon = \eta$ and $x = y$. Then the first case would apply. But if

$$\sup \triangle(x,y) > \inf \triangle(x,y)$$

there must be some $\tau^* \in \triangle(x,y)$ and some $\sigma' \in \triangle(\bar{x},\bar{y})$ such that

$$\tau^* \succ \sigma' \succ \inf \triangle(x,y) \tag{13}$$

Why? If $\sigma \succ \rho'$ just let $\sigma' = \rho'$ and $\tau^* = \sigma$. If $\sigma \sim \rho'$ and $\rho' \neq \inf \triangle(\bar{x},\bar{y})$ there is no worst lottery in $\triangle(\bar{x},\bar{y})$ and there must be some $\sigma' \in \triangle(\bar{x},\bar{y})$ such that $\sigma \succ \sigma'$ with $\tau^* = \sigma$. Moreover, by (A4) $\sigma' \succ \inf \triangle(x,y)$. Notice: $\sigma \sim \rho'$ and $\rho' = \inf \triangle(\bar{x},\bar{y})$ then $x < y$ by (A4). Just let $\sigma' = \rho'$ and observe that there must be some $\tau^* \in \triangle(x,y)$ such that $\tau^* \succ \sigma$ because by $x < y$ there is no best lottery in $\triangle(\bar{x},\bar{y})$.

By (A2) there exists a unique $\lambda \in (0,1)$ such that

$$\sigma' \sim \lambda \cdot \tau^* \oplus (1-\lambda) \cdot \inf \triangle(x,y) = \sigma^*$$

and we let

$$V(\sigma', \triangle(\bar{x},\bar{y})) = V(\sigma^*, \triangle(x,y)) \tag{14}$$

If (13) is fulfilled there must also exist a $\tau' \in \triangle(\bar{x},\bar{y})$ such that

$$\tau^* \sim \tau' \succ \sigma' \succ \inf \triangle(x,y)$$

Why? By construction of $\Pi(\varepsilon,\eta)$ we have $\sup \triangle(\bar{x},\bar{y}) \succ_{FOSD} \tau^*$ and by continuity of $\succ_{FOSD}$ we can find for each $\tau^* \in \triangle(x,y)$ some ρ such that $\rho \succ \tau^*$ by (A4). By (A2)

$$\tau^* \sim \mu \cdot \rho \oplus (1-\mu) \cdot \sigma' = \tau'$$

for a unique $\mu \in (0,1)$. Let

$$V(\tau', \triangle(\bar{x},\bar{y})) = V(\tau^*, \triangle(x,y))$$

Observe now that for preferences satisfying (A3) we have

$$\lambda \cdot \sigma' \oplus (1-\lambda) \cdot \tau' \sim \lambda \cdot \sigma^* \oplus (1-\lambda) \cdot \tau^*$$

for $\lambda \in (0,1)$ which can obviously represented by (2) because

$$\begin{aligned} V\left(\lambda \cdot \sigma' \oplus (1-\lambda) \cdot \tau', \triangle\left(\bar{x}, \bar{y}\right)\right) &= \lambda * V\left(\sigma', \triangle\left(\bar{x}, \bar{y}\right)\right) + (1-\lambda) * V\left(\tau', \triangle\left(\bar{x}, \bar{y}\right)\right) \quad (15) \\ &= \lambda * V\left(\sigma^*, \triangle\left(x, y\right)\right) + (1-\lambda) * V\left(\tau^*, \triangle\left(x, y\right)\right) \\ &= V\left(\lambda \cdot \sigma^* \oplus (1-\lambda) \cdot \tau^*, \triangle\left(x, y\right)\right) \quad (16) \end{aligned}$$

for $\lambda \in (0,1)$. Moreover, by transitivity we can then conclude that (10) is satisfied for all lotteries in $\triangle(x,y)$ and $\triangle(\bar{x},\bar{y})$.

Step 2. In the following we are going to describe an effective procedure by which the utility numbers (11) could be derived for all $\triangle(x,y), \triangle(\bar{x},\bar{y}) \in \Pi(\varepsilon,\eta)$ whenever the preferences fulfil (A1)-(A4).

Before we start observe that we want to determine the utility numbers (9) from the EU-representation $V(\cdot, \triangle(x,y))$ despite the fact that the lotteries $\inf \triangle(x,y)$ and $\sup \triangle(x,y)$ do not belong to $\triangle(x,y)$ for $x<y$ and are therefore not necessarily represented by $V(\cdot, \triangle(x,y))$. Owed to the continuity of $V(\cdot, \triangle(x,y))$ on $\triangle(x,y)$ this will be no problem; however, as a consequence our procedure will become technically more involved.

By constructing (11) for all $\triangle(x,y), \triangle(\bar{x},\bar{y}) \in \Pi(\varepsilon,\eta)$ we will proceed according to the following sequential order of SL-PL subsets

$$\begin{aligned} &\triangle(x_1,x_1), \triangle(x_1,x_2) ..., ..., \triangle(x_1,x_n); \\ &\triangle(x_2,x_2), \triangle(x_2,x_3) ..., \triangle(x_2,x_n); \\ &....; \\ &\triangle(x_n,x_n) \end{aligned}$$

That is, we start with

$$V\left(\inf \triangle(x_1,x_1), \triangle(x_1,x_1)\right), V\left(\sup \triangle(x_1,x_1), \triangle(x_1,x_1)\right)$$

which determines by (8) the utilities $V(\sigma, \triangle(x_1,x_1))$ for all $\sigma \in \triangle(x_1,x_1)$. In a next step we presume $V(\cdot, \triangle(x_1,x_1))$ as given and we derive then

$$V\left(\inf \triangle(x_1,x_2), \triangle(x_1,x_2)\right), V\left(\sup \triangle(x_1,x_2), \triangle(x_1,x_2)\right)$$

such that (10) will be fulfilled with $\triangle(x,y) = \triangle(x_1,x_1)$ and $\triangle(\bar{x},\bar{y}) = \triangle(x_1,x_2)$. This procedure is repeated until we derive the utility numbers (11) for $\triangle(x,y) = \triangle(x_{n-1},x_1)$ and $\triangle(\bar{x},\bar{y}) = \triangle(x_n,x_n)$. Moreover, observe that we have by transitivity of $\succeq$: if (10) is fulfilled for $\triangle(x,y) = \triangle(x_k,x_k)$ and $\triangle(\bar{x},\bar{y}) = \triangle(x_{k+1},x_{k+1})$ as well as for $\triangle(x,y) = \triangle(x_{k+1},x_{k+1})$ and $\triangle(\bar{x},\bar{y}) = \triangle(x_{k+2},x_{k+2})$ then (10) is also fulfilled for $\triangle(x,y) = \triangle(x_k,x_k)$ and $\triangle(\bar{x},\bar{y}) = \triangle(x_{k+2},x_{k+2})$.

Thus, after having derived the utility numbers (11) fulfilling (10) for all $\triangle(1,y), \triangle(1,\bar{y}) \in \Pi(\varepsilon,\eta)$ we consider now additionally all $\triangle(2,y), \triangle(2,\bar{y}) \in \Pi(\varepsilon,\eta)$. At first we would let $\triangle(\bar{x},\bar{y}) = \triangle(x_2,x_2)$ and $\triangle(x,y) = \triangle(x_1,x_k)$ with k being the smallest number in $\{1,...,n\}$ such that some lottery in $\triangle(x_1,x_k)$ will be preferred to some lottery in $\triangle(x_2,x_2)$. In a next step we would let $\triangle(x,y) = \triangle(x_2,x_2)$ and $\triangle(\bar{x},\bar{y}) = \triangle(x_2,x_3)$. Finally we will derive

$$V(\inf \triangle(x_n,x_n), \triangle(x_n,x_n)), V(\sup \triangle(x_n,x_n), \triangle(x_n,x_n))$$

such that (10) is fulfilled for all $\triangle(x,y), \triangle(\bar{x},\bar{y}) \in \Pi(\varepsilon,\eta)$.

Having sketched the whole procedure we describe now in some detail how the utility numbers

$$V(\inf \triangle(x_1,x_1), \triangle(x_1,x_1)), V(\sup \triangle(x_1,x_1), \triangle(x_1,x_1))$$
$$V(\inf \triangle(x_1,x_2), \triangle(x_1,x_2)), V(\sup \triangle(x_1,x_2), \triangle(x_1,x_2))$$

can be derived. An application of the same reasoning to the remaining subsets will be straightforward and is therefore omitted.

Let

$$\begin{aligned} V(\inf \triangle(x_1,x_1), \triangle(x_1,x_1)) &= 0 \\ V(\sup \triangle(x_1,x_1), \triangle(x_1,x_1)) &= 1 \end{aligned}$$

If the preferences do not overlap we simply apply (12) to obtain

$$\begin{aligned} V(\inf \triangle(x_1,x_2), \triangle(x_1,x_2)) &= 1 \\ V(\sup \triangle(x_1,x_2), \triangle(x_1,x_2)) &= 2 \end{aligned}$$

and check whether there is no $\rho' \in \triangle(x_1,x_3)$ such that $\sigma \succeq \rho'$ for some $\sigma \in \triangle(x_1,x_2)$; and so forth.

Suppose now there was a $\rho' \in \triangle(x_1,x_2)$ such that $\sigma \succeq \rho'$ for some $\sigma \in \triangle(x_1,x_1)$. By step 1 there must exist $\sigma', \tau' \in \triangle(x_1,x_2)$ and $\tau^* \in \triangle(x_1,x_1)$ such that

$$\tau^* \sim \tau' \succ \sigma' \succ \inf \triangle(x_1,x_1)$$

and

$$\begin{aligned} V\left(\sigma', \triangle\left(x_1, x_2\right)\right) &= V\left(\sigma^*, \triangle\left(x_1, x_1\right)\right) \\ V\left(\tau', \triangle\left(x_1, x_2\right)\right) &= V\left(\tau^*, \triangle\left(x_1, x_1\right)\right) \end{aligned}$$

Having determined the utilities of $\sigma', \tau' \in \triangle\left(x_1, x_2\right)$ w.r.t. utility numbers assigned to lotteries in $\triangle\left(x_1, x_1\right)$ we proceed now by deriving

$$V\left(\inf \triangle\left(x_1, x_2\right), \triangle\left(x_1, x_2\right)\right), V\left(\sup \triangle\left(x_1, x_2\right), \triangle\left(x_1, x_2\right)\right)$$

from $V\left(\sigma', \triangle\left(x_1, x_2\right)\right)$ and $V\left(\tau', \triangle\left(x_1, x_2\right)\right)$.

Construct the sequence of lotteries $\left(\tau_k\right)_{k \in \mathbf{N}}$ such that

$$\tau_k = \frac{1}{k+1} \cdot \tau' \oplus \left(1 - \frac{1}{k+1}\right) \cdot \sup \triangle\left(x_1, x_2\right)$$

and verify: $\tau_k \in \triangle\left(x_1, x_2\right)$, $\tau_k \succ \tau'$, $\tau_{k+1} \succ \tau_k$ for all $k \in \mathbf{N}$, and

$$\lim_{k \to \infty} \tau_k = \sup \triangle\left(x_1, x_2\right)$$

Define now $\nu_k \in (0,1)$ for each τ_k, $k \in \mathbf{N}$, implicitly by

$$\tau' \sim \nu_k \cdot \tau_k \oplus \left(1 - \nu_k\right) \cdot \sigma'$$

and observe that ν_k is indeed well-defined as a unique number for every τ_k by (A3). By (A4) the induced sequence $\left(\nu_k\right)_{k \in \mathbf{N}}$ is monotonically decreasing and because it is bounded from below by *zero* there must exist a unique limit-point $\nu^* = \lim_{k \to \infty} \nu_k$.

By continuity of $V\left(\cdot, \triangle(x, y)\right)$ on $\triangle(x, y)$ we obtain

$$\begin{aligned} V\left(\tau', \triangle\left(x_1, x_2\right)\right) &= \lim_{k \to \infty} V\left(\nu_k \cdot \tau_k \oplus \left(1 - \nu_k\right) \cdot \sigma', \triangle\left(x_1, x_2\right)\right) \\ &= V\left(\nu^* \cdot \sup \triangle\left(x_1, x_2\right) \oplus \left(1 - \nu^*\right) \cdot \sigma', \triangle\left(x_1, x_2\right)\right) \\ &= \nu^* * V\left(\sup \triangle\left(x_1, x_2\right), \triangle\left(x_1, x_2\right)\right) + \left(1 - \nu^*\right) * V\left(\sigma', \triangle\left(x_1, x_2\right)\right) \end{aligned}$$

Rearranging gives

$$V\left(\sup \triangle\left(x_1, x_2\right), \triangle\left(x_1, x_2\right)\right) = \frac{1}{\nu^*} * V\left(\tau', \triangle\left(x_1, x_2\right)\right) - \frac{\left(1 - \nu^*\right)}{\nu^*} * V\left(\sigma', \triangle\left(x_1, x_2\right)\right)$$

But this is our desired result.

Consider now the sequence $\left(\sigma_k\right)_{k \in \mathbf{N}}$ such that

$$\sigma_k = \frac{1}{k+1} \cdot \sigma' \oplus \left(1 - \frac{1}{k+1}\right) \cdot \inf \triangle\left(x_1, x_2\right)$$

and verify: $\sigma_k \in \triangle(x_1, x_2)$, $\sigma' \succ \sigma_k$, $\sigma_k \succ \sigma_{k+1}$ for all $k \in \mathbf{N}$, and

$$\lim_{k\to\infty} \sigma_k = \inf \triangle(x_1, x_2)$$

Define $\mu_k \in (0,1)$ for each σ_k, $k \in \mathbf{N}$, implicitly by

$$\sigma' \sim \mu_k \cdot \sigma_k \oplus (1 - \mu_k) \cdot \tau'$$

The induced sequence $(\mu_k)_{k\in\mathbf{N}}$ is then monotonically increasing by (A4) and bounded from above by *one* such that there exists a unique limit-point $\mu^* = \lim_{k\to\infty} \mu_k$. By continuity of $V(\cdot, \triangle(x,y))$ on $\triangle(x,y)$

$$V(\sigma', \triangle(x_1,x_2)) = \mu^* * V(\inf \triangle(x_1,x_2), \triangle(x_1,x_2)) + (1-\mu^*) * V(\tau', \triangle(x_1,x_2))$$

and rearranging gives the desired result

$$V(\inf \triangle(x_1,x_2), \triangle(x_1,x_2)) = \frac{1}{\mu^*} * V(\sigma', \triangle(x_1,x_2)) - \frac{(1-\mu^*)}{\mu^*} * V(\tau', \triangle(x_1,x_2))$$

Finally, observe how we can now just compute backwards to express the utilities of σ' and τ' by (8)

$$\begin{aligned} & V(\sigma', \triangle(x_1,x_2)) \\ = \; & \frac{\mu^*}{\nu^* + \mu^* - \nu^*\mu^*} * V(\inf \triangle(x_1,x_2), \triangle(x_1,x_2)) + \frac{(1-\mu^*) * \nu^*}{\nu^* + \mu^* - \nu^*\mu^*} * V(\sup \triangle(x_1,x_2), \triangle(x_1,x_2)) \end{aligned}$$

and

$$\begin{aligned} & V(\tau', \triangle(x_1,x_2)) \\ = \; & \frac{(1-\nu^*) * \mu^*}{\nu^* + \mu^* - \nu^*\mu^*} * V(\inf \triangle(x_1,x_2), \triangle(x_1,x_2)) + \frac{\nu^*}{\nu^* + \mu^* - \nu^*\mu^*} * V(\sup \triangle(x_1,x_2), \triangle(x_1,x_2)) \end{aligned}$$

Part B. We demonstrate now that all subset-dependent EU-functionals $V(\cdot, \triangle(x,y))$, $\triangle(x,y) \in \Pi(\varepsilon, \eta)$, have to satisfy (4) whenever the preferences fulfil (A1)-(A4). The proof for (5) is analog and therefore omitted.

Suppose on the contrary that there is some sequence $(\sigma_k)_{k\in\mathbf{N}}$ with $\lim_{k\to\infty} \sigma_k = \sigma$ such that $\sigma_k \in \triangle(x,y)$ for all $k \in N$ and $\sigma \in \triangle(\bar{x}, \bar{y})$ and we have

$$\lim_{k\to\infty} V(\sigma_k, \triangle(x,y)) > V(\sigma, \triangle(\bar{x}, \bar{y})) \tag{17}$$

for $\bar{x} \geq x$, $\bar{y} \geq y$, and $\triangle(x,y) \neq \triangle(\bar{x}, \bar{y})$.

Recall that $\sup \triangle(\bar{x}, \bar{y}) \succ_{FOSD} \sigma$, for all $\sigma \in \triangle(\bar{x}, \bar{y})$ with $\sigma \neq \sup \triangle(\bar{x}, \bar{y})$. Observe now that for all $\lambda \in (0,1)$

$$\lambda \cdot \sup \triangle(\bar{x}, \bar{y}) \oplus (1-\lambda) \cdot \sigma \in \triangle(\bar{x}, \bar{y})$$

and by continuity of $V(\cdot, \triangle(\bar{x}, \bar{y}))$ there must exist under assumption (17) some $\lambda \in (0,1)$ such that

$$\lim_{k \to \infty} V(\sigma_k, \triangle(x, y)) > V(\lambda \cdot \tau \oplus (1-\lambda) \cdot \sigma, \triangle(\bar{x}, \bar{y})) \tag{18}$$

Quasiconcavity of $\succ_{FOSD}$ implies

$$\lambda \cdot \tau \oplus (1-\lambda) \cdot \sigma \succ_{FOSD} \sigma$$

By continuity of $\succ_{FOSD}$there is some $M \in \mathbf{N}$ such that

$$\lambda \cdot \tau \oplus (1-\lambda) \cdot \sigma \succ_{FOSD} \sigma_k$$

for all $k \geq M$. And by (A4)

$$V(\lambda \cdot \tau \oplus (1-\lambda) \cdot \sigma, \triangle(\bar{x}, \bar{y})) > V(\sigma_k, \triangle(x, y))$$

for all $k \geq M$. Thus

$$V(\lambda \cdot \tau \oplus (1-\lambda) \cdot \sigma, \triangle(\bar{x}, \bar{y})) \geq \lim_{k \to \infty} V(\sigma_k, \triangle(x, y))$$

A contradiction to (18).□

Part C. After having proved that all preferences fulfilling (A1)-(A4) are representable by (2) it remains to prove the converse; i.e., any utility function (2) represents some preferences that fulfil (A1)-(A4). This is easily checked for the axioms (A1)-(A3), and therefore omitted. Let us now prove that the conditions (4) and (5) are sufficient for guaranteeing (A4).

Suppose on the contrary that there are $\sigma, \tau \in \triangle(X)$ such that $\tau \succeq_{FOSD} \sigma$ but

$$U(\sigma) > U(\tau) \tag{19}$$

Observe at first that by construction of $\Pi(\varepsilon, \eta)$: $\tau \succeq_{FOSD} \sigma$ only if $\sigma \in \triangle(x, y)$ and $\tau \in \triangle(\bar{x}, \bar{y})$ with $\bar{x} \geq x$ and $\bar{y} \geq y$. Moreover, the SL-PL subset dependent EU-representation $V(\cdot, \triangle(x, y))$ implies that there can not occur a violation of monotonicity w.r.t. FOSD for any $\sigma, \tau \in \triangle(x, y)$. Thus, (A4) can only be violated if $\sigma \in \triangle(x, y)$ and $\tau \in \triangle(\bar{x}, \bar{y})$ with $\bar{x} \geq x$ and $\bar{y} \geq y$, and $\triangle(x, y) \neq \triangle(\bar{x}, \bar{y})$.

Construct now the net $(\tau_\lambda)_{\lambda\in(0,1)}$ such that

$$\tau_\lambda = (1-\lambda)\cdot\tau \oplus \lambda\cdot\sigma$$

and observe that by quasiconcavity of $\succeq_{FOSD}$:

$$\tau \succeq_{FOSD} \tau_\lambda \succeq_{FOSD} \tau_\mu$$

for all $\mu \in (0,1]$ if $\mu > \lambda$. By construction of $\Pi(\varepsilon,\eta)$ there must exist a unique λ^* such that either

(i.) $\tau_{\lambda^*} \in \triangle(\bar{x},\bar{y})$ and $\tau_\lambda \in \triangle(x,y)$ for all $\lambda > \lambda^*$, or

(ii.) $\tau_{\lambda^*} \in \triangle(x,y)$ and $\tau_\lambda \in \triangle(\bar{x},\bar{y})$ for all $\lambda < \lambda^*$.

Let us consider case (i) where sequences in $\triangle(x,y)$ may have a limit-point in $\triangle(\bar{x},\bar{y})$ but not vice versa. (Case (ii.) is analogously proved via condition (5) and therefore omitted.)

Construct the sequence $(\sigma_k)_{k\in\mathbf{N}}$ such that

$$\sigma_k = \left(1-\frac{1}{k}\right)\cdot\tau_{\lambda^*} \oplus \frac{1}{k}\cdot\sigma$$

and observe that $\sigma_{k+1} \succeq \sigma_k$ by (A2) which implies

$$V(\sigma_{k+1},\triangle(x,y)) = U(\sigma_{k+1}) \geq U(\sigma_k) = V(\sigma_k,\triangle(x,y))$$

since $\sigma_{k+1},\sigma_k \in \triangle(x,y)$ for all $k\in\mathbf{N}$. Thus,

$$\lim_{k\to\infty} V(\sigma_k,\triangle(x,y)) = V(\tau_{\lambda^*},\triangle(x,y)) \geq V(\sigma,\triangle(x,y))$$

Analogously

$$V(\tau,\triangle(\bar{x},\bar{y})) = U(\tau) \geq U(\tau_{\lambda^*}) = V(\tau_{\lambda^*},\triangle(\bar{x},\bar{y}))$$

The condition (4) claims now

$$V(\tau_{\lambda^*},\triangle(\bar{x},\bar{y})) \geq V(\tau_{\lambda^*},\triangle(x,y))$$

and we obtain

$$U(\tau) \geq U(\sigma)$$

A contradiction to (19).□□

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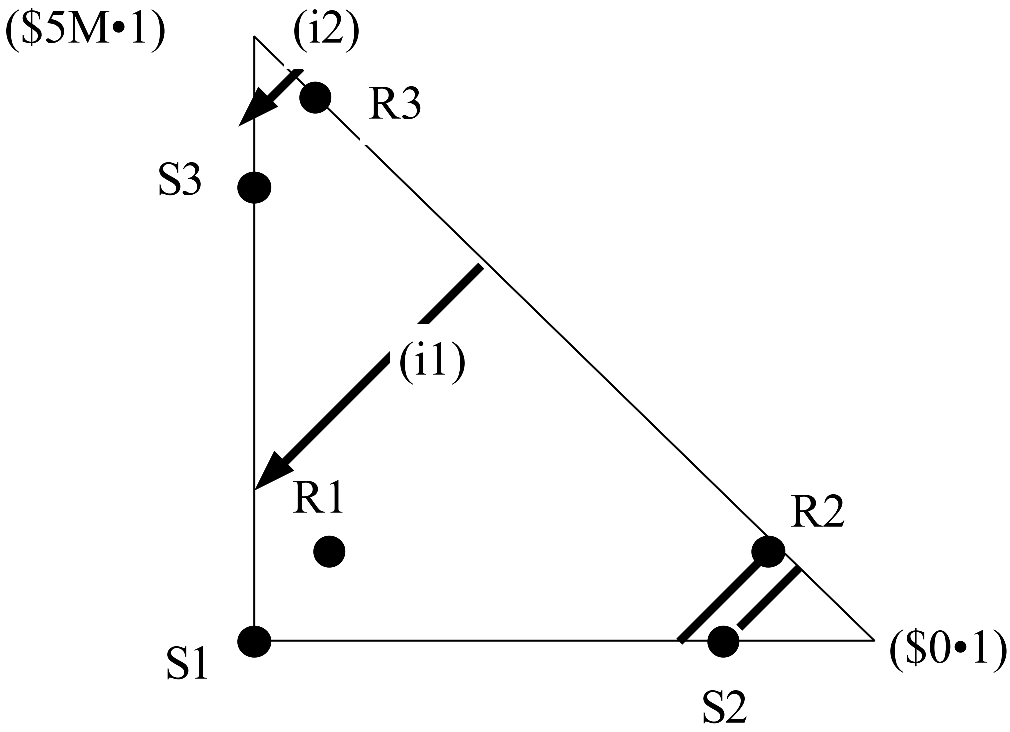

Figure 1. By a security effect S1 is indifferent to the points on the indifference curve (i1) to the effect that S1 is preferred to R1. But then the existing SL,PL-models require S3 to be indifferent to the points on (i2). Thus, S3 must be preferred to R3. A violation of the choice pattern (S1,R2,R3).

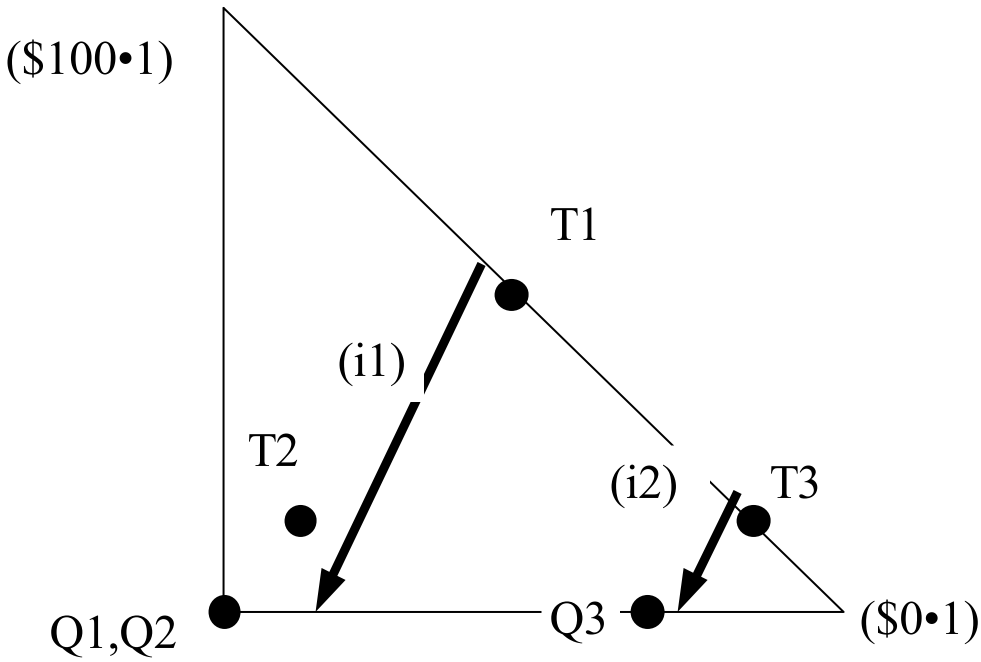

Figure 2. By a potential effect Q1 is indifferent to the points on (i1), i.e., Q1 is preferred to T1 but not to T2. Moreover, Q3, being indifferent to the points on (i2), must be preferred to T3 - a violation of the choice pattern (Q1,T2,T3).

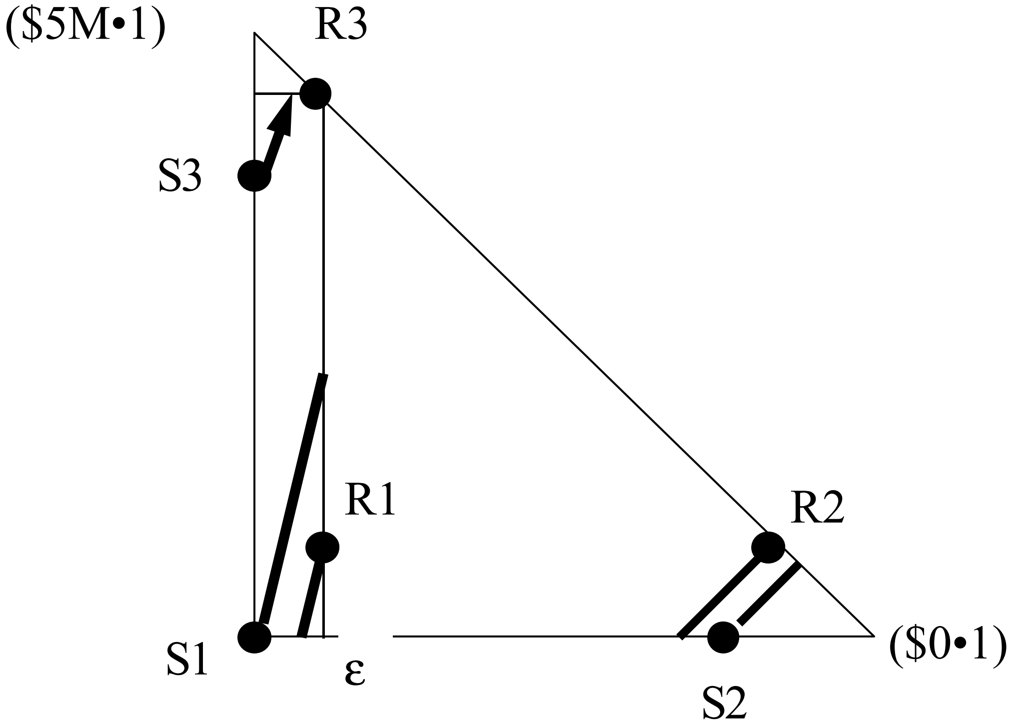

Figure 3. Introduction of a threshold for security levels and steeper slopes of the indifference curves on higher security levels can accommodate the choice pattern (S1,R2,R3).

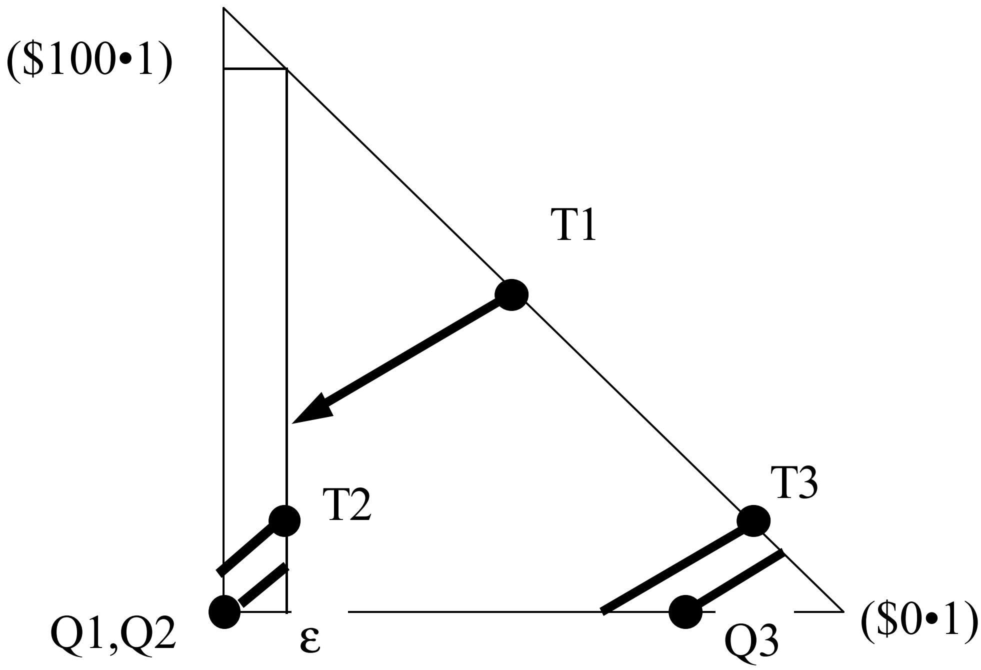

Figure 4. A threshold for security levels allows for the choice pattern (Q1,T2,T3). The slopes of the indifference curves may be the same for all security levels.

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