スカラー化関数による集合値関数のミニマックス定理の一般化とその応用

Set-Valued Fan-Takahashi Inequalities Via Scalarization

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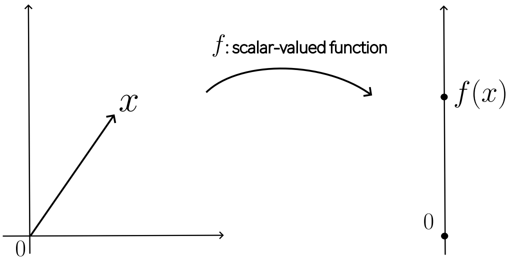
Introduction

What is set optimization problem?

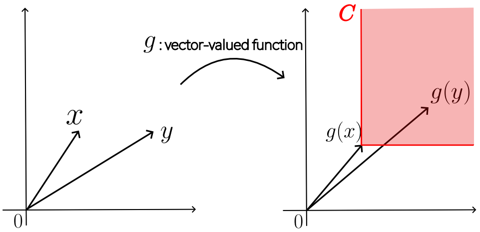
- To find a footballer from a set of football players who has the least (or most) number of goals is the scalar optimization problem where the objective function provides the number of goals of a player.



Reference: `https://agates.mimuw.edu.pl/images/nonworkshop_talks/Sharma_slides.pdf`

What is set optimization problem?

- To find the football player from a set of footballers in such a way that he/she is having several qualities, namely, ability, speed, power, and so on, is a vector optimization problem. The value of the objective function can be considered as vector whose coordinates consist of one's ability, speed, power, and so on.



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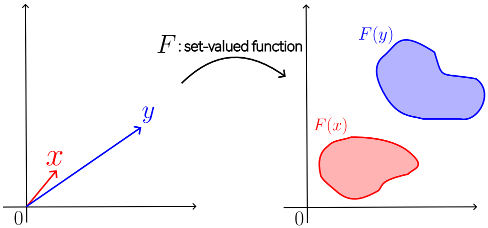
What is set optimization problem?

- Consider the objective function whose values are teams and assume that a team is a set of football players and each player is regarded as a vector whose coordinates consist of one's ability, speed, power, stamina, skill, popularity and so on. Then one can formulate the problem of choosing a good team for a football league in the form of set optimization problem with the set-valued objective function.



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Background

Background

- Georgiev and Tanaka [2] extended the minimax inequality to the form of set-valued maps.

- Kuwano, Tanaka, and Yamada [4] constructed the result of four types set-valued minimax inequalities with set relations.

- **Our goal is to generalize the result of four types set-valued minimax inequalities which is independent on the specific set-relations and scalarization functions.**

Theorem (Takahashi [5] in 1976)
Let X be a nonempty compact convex subset of a Hausdorff topological vector space and $f: X \times X \to \mathbb{R}$. If f satisfies the following conditions:

1. for each fixed $y \in X$, $f(\cdot, y)$ is lower semicontinuous,
2. for each fixed $x \in X$, $f(x, \cdot)$ is quasi concave,
3. $f(x, x) \leq 0$ for all $x \in X$,

then there exists $\bar{x} \in X$ such that $f(\bar{x}, y) \leq 0$ for all $y \in X$.

Theorem [4]
Let X be a nonempty compact convex subset of a Hausdorff topological vector space, Y a real topological vector space, C a proper closed convex cone in Y with $\mathrm{int}\, C \neq \emptyset$ and $F\colon X \times X \to \mathcal{P}(Y)\backslash\{\emptyset\}$. If F satisfies the following conditions:

1. F is C-proper and C-closed on $X \times X$,
2. for each fixed $y \in X$, $F(\cdot, y)$ is C-upper continuous,
3. for each fixed $x \in X$, $f(x, \cdot)$ is type (3L) properly C-quasi concave,
4. for all $x \in X$, $F(x, x) \preccurlyeq_C^{(3L)} \{\theta_Y\}$,

then there exists $\bar{x} \in X$ such that $F(\bar{x}, y) \preccurlyeq_C^{(3L)} \{\theta_Y\}$ for all $y \in X$.

Preliminaries

Preliminaries

Let X be a topological space, Y a real topological vector space, and θ_Y be a zero vector in Y. Define that $\mathcal{P}(Y)$ is the set of all nonempty subsets of Y. The sets of neighborhoods of $x \in X$ and $y \in Y$ is denoted by $\mathcal{N}_X(x)$ and $\mathcal{N}_Y(y)$, respectively.

Definition
For $A, B \in \mathcal{P}(Y)\backslash\{\emptyset\}$, we define two binary relations on $\mathcal{P}(Y)$:

$$A \preccurlyeq_1 B \overset{\text{def}}{\Longleftrightarrow} A \cap B \neq \emptyset \quad \text{and} \quad A \preccurlyeq_2 B \overset{\text{def}}{\Longleftrightarrow} B \subset A.$$

Definition (set-relations)
For $A, B \in \mathcal{P}(Y)\backslash\{\emptyset\}$ and a convex cone C, we write

$$A \preccurlyeq_C^{(3L)} B \overset{\text{def}}{\Longleftrightarrow} B \subset A + C \quad \text{and} \quad A \preccurlyeq_C^{(3U)} B \overset{\text{def}}{\Longleftrightarrow} A \subset B - C.$$

Preliminaries (Lower Semicontinuity)

Definition

Let $f : Y \to \mathbb{R} \cup \{\pm\infty\}$ and $y_0 \in Y$. We say that f is lower semicontinuous (l.s.c. shortly) at y_0 if

$$\forall r < f(y_0), \exists V \in \mathcal{N}_Y(y_0) \text{ s.t. } r < f(y), \forall y \in V;$$

Definition [1]

Let $F\colon X \to \mathcal{P}(Y)$, $x_0 \in X$, $\preccurlyeq$ a binary relation on $\mathcal{P}(Y)$ and $C \subset Y$ a convex cone. We say that F is $(\preccurlyeq, C)$-continuous at x_0 if

$$\forall W \subset Y, W \text{ open}, W \preccurlyeq F(x_0), \exists V \in \mathcal{N}_X(x_0) \text{ s.t. } W + C \preccurlyeq F(x), \forall x \in V.$$

Remark

As special cases, $(\preccurlyeq_1, C)$-continuity and $(\preccurlyeq_2, C)$-continuity coincide with " C-lower continuity " and " C-upper continuity " for set-valued maps, respectively.

Definition [1]
Let $\varphi\colon \mathcal{P}(Y) \to \mathbb{R} \cup \{\pm\infty\}$, $A_0 \in \mathcal{P}(Y)$, $\preccurlyeq$ a binary relation on $\mathcal{P}(Y)$, and C a convex cone in Y with $C \neq Y$. Then, we say that φ is $(\preccurlyeq, C)$-lower semicontinuous at A_0 if

$$\forall r < \varphi(A_0), \exists W \in \mathcal{P}(Y), W \text{ open, s.t. } W \preccurlyeq A_0 \text{ and } r > \varphi(A), \forall A \in U(W + C, \preccurlyeq);$$

where $U(V, \preccurlyeq) := \{A \in \mathcal{P}(Y) \mid V \preccurlyeq A\}$.

Theorem [1]
Let $F\colon X \to \mathcal{P}(Y)$, $\varphi\colon \mathcal{P}(Y) \to \mathbb{R} \cup \{\pm\infty\}$, $x_0 \in X$, $\preccurlyeq$ a binary relation on $\mathcal{P}(Y)$, and C a convex cone. If F is $(\preccurlyeq, C)$-continuous at x_0 and φ is $(\preccurlyeq, C)$-lower semicontinuous at $F(x_0)$, then $(\varphi \circ F)$ is lower semicontinuous at x_0.

Preliminaries (Convexity)

Definition [3]
Let $\mathcal{A} \subset \mathcal{P}(Y) \backslash \{\emptyset\}$. $\mathcal{A}$ is said to be convex if for each $A_1, A_2 \in \mathcal{A}$ and $\lambda \in (0, 1)$,

$$\lambda A_1 + (1 - \lambda) A_2 \in \mathcal{A}.$$

Definition [3]
Let $\varphi \colon \mathcal{P}(Y) \to \mathbb{R} \cup \{\pm\infty\}$. Then,

1. φ is quasi convex if for any $\alpha \in \mathbb{R}$, $\mathrm{lev}\,(\varphi, \leq, \alpha) := \{A \in \mathcal{P}(Y) \backslash \{\emptyset\} \mid \varphi(A) \leq \alpha\}$ is convex.
2. φ is quasi concave if for any $\alpha \in \mathbb{R}$, $\mathrm{lev}\,(\varphi, \geq, \alpha) := \{A \in \mathcal{P}(Y) \backslash \{\emptyset\} \mid \varphi(A) \geq \alpha\}$ is convex.

Preliminaries (Convexity)

Definition

Let X be a nonempty set, Y a real topological vector space, C a convex cone in Y, and $F\colon X \to 2^Y \backslash \{\emptyset\}$ a set-valued map.

1. F is called $(\preccurlyeq)$-naturally quasi convex if for each $x, y \in X$ and $\lambda \in (0,1)$, there exists $\mu \in [0,1]$ such that
$$F(\lambda x + (1-\lambda)y) \preccurlyeq \mu F(x) + (1-\mu)F(y).$$
2. F is called $(\preccurlyeq)$-naturally quasi concave if for each $x, y \in X$ and $\lambda \in (0,1)$, there exists $\mu \in [0,1]$ such that
$$\mu F(x) + (1-\mu)F(y) \preccurlyeq F(\lambda x + (1-\lambda)y).$$

Definition
For a given binary relation $\preccurlyeq$, a scalarization function φ is $(\preccurlyeq)$-monotone if for any $A, B \in \mathcal{P}(Y) \backslash \{\emptyset\}$ with $A \preccurlyeq B$, $\varphi(A) \leq \varphi(B)$

Theorem
Let φ be $(\preccurlyeq)$-monotone and $(\preccurlyeq)$-quasi convex. If F is $(\preccurlyeq)$-naturally quasi convex, then $(\varphi \circ F)$ is quasi convex.

Theorem
Let φ be $(\preccurlyeq)$-monotone and $(\preccurlyeq)$-quasi concave. If F is $(\preccurlyeq)$-naturally quasi concave, then $(\varphi \circ F)$ is quasi concave.

Main results

Specific scalarization function

To extend Ky Fan inequality for set-valued maps with a binary relation, consider assumptions of scalarization fucntions. To begin with, introduce four properties;

1. φ is $(\preceq, C)$-lower semicontinuous,
2. φ is quasi concave,
3. φ is $(\preccurlyeq)$-monotone,
4. $\varphi(\{\theta_Y\}) = 0$,

and define the set of functions satisfying these properties as $\Phi(\preceq, \preccurlyeq, C)$. In addition, establish three vaital properties for Ky Fan inequality;

$$\varphi(A) \leq 0 \Rightarrow A \preccurlyeq \{\theta_Y\}. \tag{A1}$$

Theorem
Let X be a nonempty compact convex subset of a topological vector space, Y a real topological vector space, $\preccurlyeq$ a binary relation on $\mathcal{P}(Y)$, C a convex cone in Y, $\varphi\colon \mathcal{P}(Y) \to \mathbb{R} \cup \{\pm\infty\}$, and $F\colon X \times X \to \mathcal{P}(Y) \backslash \{\emptyset\}$ a set-valued map. For the scaralization function $\varphi \in \Phi(\preceq, \preccurlyeq, C)$ satisfying assumption (A1), if F satisfies the following conditions:

1. there exists $x_0, y_0 \in X$ such that $(\varphi \circ F)(x_0, y_0) \in \mathbb{R}$,
2. for each fixed $y \in X$, $F(\cdot, y)$ is $(\preceq, C)$-continuous,
3. for each fixed $x \in X$, $F(x, \cdot)$ is $(\preccurlyeq)$-naturally quasi concave,
4. for all $x \in X$, $F(x, x) \preccurlyeq \{\theta_Y\}$,

then there exists $\bar{x} \in X$ such that $F(\bar{x}, y) \preccurlyeq \{\theta_Y\}$ for all $y \in X$.

Applications

Tammer's scalarization function

Definition

Let C be a proper closed convex cone in Y with $\mathrm{int}\, C \neq \emptyset$, $V, V' \in \mathcal{P}(Y) \backslash \{\emptyset\}$, and direction $k \in \mathrm{int}\, C$. For each $j = (3U), (3L)$, $I^{(j)}_{k,V'}(V) \colon \mathcal{P}(Y) \to \mathbb{R} \cup \{\pm\infty\}$ are defined by

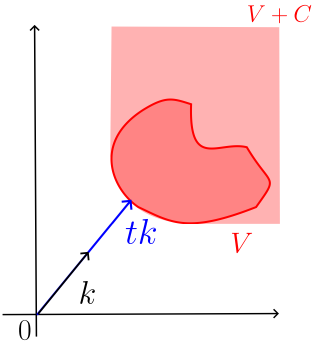
$$I^{(j)}_{k,V'}(V) := \inf\{t \in \mathbb{R} \mid V \preccurlyeq^{(j)}_{C} (tk + V')\}.$$

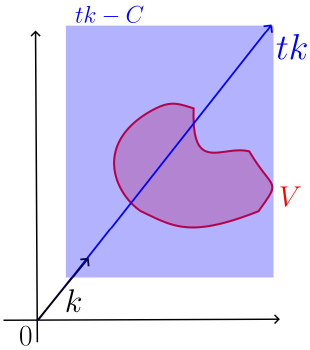
Example

$$I^{(3L)}_{k,\{\theta_Y\}}(V) := \inf\{t \in \mathbb{R} \mid V \preccurlyeq^{(3L)}_{C} (tk + V')\} = \inf\{t \in \mathbb{R} \mid tk \subset V + C\},$$
$$I^{(3U)}_{k,\{\theta_Y\}}(V) := \inf\{t \in \mathbb{R} \mid V \preccurlyeq^{(3U)}_{C} (tk + V')\} = \inf\{t \in \mathbb{R} \mid V \subset tk - C\}.$$

Example

$$I^{(3L)}_{k,\{\theta_Y\}}(V) := \inf\{t \in \mathbb{R} \mid V \preccurlyeq^{(3L)}_C (tk + V')\} = \inf\{t \in \mathbb{R} \mid tk \subset V + C\},$$
$$I^{(3U)}_{k,\{\theta_Y\}}(V) := \inf\{t \in \mathbb{R} \mid V \preccurlyeq^{(3U)}_C (tk + V')\} = \inf\{t \in \mathbb{R} \mid V \subset tk - C\}.$$





Hiriart-Urruty Oriented Distance

Definition (Hiriart-Urruty distance)

Let Y be a real normed vector space. For a set $A \subset Y$, let the oriented distance function $\Delta_A \colon Y \to \mathbb{R} \cup \{\pm\infty\}$ be defined by

$$\Delta_A(y) := d_A(y) - d_{Y \setminus A}(y),$$

$d_A(y) = \inf\{\|y - z\| \mid z \in A\}$, $d_\emptyset(y) := +\infty$, and $\|y\|$ denotes the norm of y in Y.

Definition

For the set $A \in Y$, let the functions $\mathcal{D}_A^+ \colon \mathcal{P}(Y) \to \mathbb{R} \cup \{\pm\infty\}$ and $\mathcal{D}_A^- \colon \mathcal{P}(Y) \to \mathbb{R} \cup \{\pm\infty\}$ be defined as

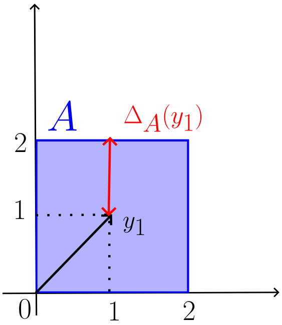
$$\mathcal{D}_A^+(B) := \sup\{\Delta_A(b) \mid b \in B\},\ B \in \mathcal{P}(Y),$$
$$\mathcal{D}_A^-(B) := \inf\{-\Delta_A(b) \mid b \in B\} = -\mathcal{D}_A^+(B),\ B \in \mathcal{P}(Y).$$

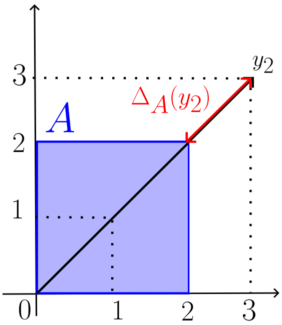
Hiriart-Urruty Oriented Distance

Example

Let $Y = \mathbb{R}^2$, $A = [0,2] \times [0.2]$, $y_1 = (1,1)$, and $y_2 = (3,3)$. Then,

$$\Delta_A(y_1) = d_A(y_1) - d_{Y\setminus A}(y_1) = 0 - 1 = -1,$$
$$\Delta_A(y_2) = d_A(y_2) - d_{Y\setminus A}(y_2) = 1 - 0 = \sqrt{2}.$$





Theorem

Let X be a nonempty compact convex subset of a topological vector space, Y a real normed vector space, C a closed convex cone in Y with $\operatorname{int} C \neq \emptyset$, and, $F\colon X \times X \to \mathcal{P}(Y)\backslash\{\emptyset\}$ a set-valued map. If F satisfies the following conditions:

1. there exists $x_0, y_0 \in X$ such that $(\varphi \circ F)(x_0, y_0) \in \mathbb{R}$,
2. for each fixed $y \in X$, $F(\cdot, y)$ is $(\preccurlyeq_2, C)$-continuous (that is, C-upper continuous),
3. for each fixed $x \in X$, $F(x, \cdot)$ is $(\preccurlyeq_C^{(3L)})$-naturally quasi concave,
4. for all $x \in X$, $F(x, x) \preccurlyeq_C^{(3L)} \{\theta_Y\}$,

then there exists $\bar{x} \in X$ such that $F(\bar{x}, y) \preccurlyeq_C^{(3L)} \{\theta_Y\}$ for all $y \in X$.

Conclusion

Conclusion

- We gave a new result of set-valued Fan-Takahashi inequalities via scalarization .
- Kuwano's result which is introduced at first implies the only (3L) type minimax inequality. This results in the same type minimax inequality holds while the scalarization function is the oriented distance function.
- We need to check other scalarization functions to satisfy our assumption.

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