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Unequal uncertainties and uncertain inequalities: an axiomatic approach [☆]

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Abstract

In this paper, we provide an axiomatic characterization of social welfare functions for uncertain incomes. Our most general result is that a small number of reasonable assumptions regarding welfare orderings under uncertainty rule out pure ex ante as well as pure ex post evaluations. Any social welfare function that satisfies these axioms should lie *strictly* between the ex ante and the ex post evaluations of income distributions. We also provide an axiomatic characterization of the weighted average of the minimum and the maximum of ex post and ex ante evaluations.

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1. Introduction

Consider a society divided into two sectors of equal size—say, sector *A* and sector *B*. Sector *A* corresponds to domestic services that cannot be traded at the international level while sector *B* corresponds to manufacturing industries that can be traded. The government decides if international trade is allowed or not. If no

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international trade is permitted, whatever happens, wages remain equal to \$1000 a month in both sectors. In contrast, if international trade is allowed, wages in sector *B* depend on an exogenous shock on international demand, which can be positive or negative, with unknown probabilities. If the shock is positive, wages in sector *B* are \$1500 a month, whereas if the shock is negative, wages are only \$600 a month. In other words, trade is assumed to increase simultaneously total income, inequality and uncertainty. The two possible policies can be represented by the following tables:

No trade	Sector A	Sector B	Trade	Sector A	Sector B
Shock > 0	1000	1000	Shock > 0	1000	1500
Shock < 0	1000	1000	Shock < 0	1000	600

The government must decide whether or not to allow international trade. Clearly, the policy which should be chosen depends on the inequality and uncertainty aversions that characterize this particular society. The optimal policy, however, also depends on when individuals' welfare is evaluated, namely *before* (ex ante) or *after* (ex post) the resolution of uncertainty. For sufficiently low risk aversion, trade is certainly the best policy ex ante, since it increases the expected earnings in sector *B* without decreasing them in sector *A*. On the other hand, for sufficiently high inequality aversion, trade is also no doubt the worst policy ex post, since it decreases the lowest wages during bad periods, without increasing them during favorable periods.

More generally, when comparing uncertain income distributions, should we look at the expected income of each person, and consider that the distribution where the inequality of expected incomes is the lowest as the best one? Or should we look at the level of inequalities associated to each possible state of the world, and consider the distribution where the expected level of inequality is the lowest as the best solution?

This problem is not new and has sometimes been labelled as the “timing-effect problem”: the outcome of an allocation procedure depends on whether individuals' utility levels are evaluated before or after the resolution of uncertainty.¹ As stated by Myerson,

The moral of this story is that simply specifying a social welfare function may not be enough to fully determine a procedure for collective decision making. One must also specify *when* the individuals' preferences or utility levels should be evaluated; before or after the resolution of uncertainties. The timing of social welfare analysis may make a difference. The timing-effect is often an issue in moral debate, as when people argue about whether a social system should be judged with respect to its actual income distribution or with respect to its distribution of economic opportunities (p. 884).

To the best of our knowledge, the principles that should be followed to answer this question have not yet been identified in the economic literature. Whereas an

¹See for instance Broome [3], Diamond [5], Myerson [10] and Hammond [8], among others, for theoretical work on the timing effect. See Yaari and Bar-Hillel [12] for empirical evidence about the importance of beliefs in distributional issues.

extensive body of literature exists on inequality measurement when no uncertainty is involved, very little has been written on inequality measurement under uncertainty, with the important exception of Ben Porath et al. [2].

As stated by Ben Porath et al. [2], the crucial issue for measuring inequality under uncertainty is to simultaneously take into account the inequality of expected incomes and the expected inequalities of actual incomes. In this paper, we propose a simple axiomatic characterization of social welfare rankings under uncertainty that captures these two dimensions.

The paper is organized in the following way. Section 2 introduces notation and provides an axiomatic characterization of social welfare functions under uncertainty. Our most general result is that a small number of reasonable assumptions regarding welfare orderings under uncertainty rule out pure ex ante and pure ex post evaluations. Any social welfare function that satisfies these axioms should remain *strictly* between the ex ante and the ex post evaluations of income distributions. Section 3 provides a reasonable strengthening of our basic axioms which leads to a more complete characterization of admissible social welfare functions. In Section 4, we analyze how the set of welfare functions axiomatized in this paper compares with the family of min-of-means functionals introduced by Ben Porath et al. [2]. Finally, Section 5 gives our conclusions. All the proofs are gathered in the appendix.

2. A general class of social preferences under uncertainty

In order to better understand the difficulties raised by uncertainty in evaluating income distributions, let us examine the canonical examples given by Ben Porath et al. [2]. Consider a society with two individuals, a and b , facing two equally likely possible states of the world, s and t , and assume that the planner has to choose among the three following social policies, P_1 , P_2 and P_3 :

P_1	a	b	P_2	a	b	P_3	a	b
s	0	0	s	1	0	s	1	0
t	1	1	t	0	1	t	1	0

As argued by Ben Porath et al. [2], P_2 and P_3 are ex post equivalent, since in both cases, whatever the state of the world, the final income distribution is $(0, 1)$ (or $(1, 0)$ which, assuming anonymity, is equivalent). On the other hand, P_3 gives 1 for sure to one individual, and 0 to the other, while P_2 provides both individuals with the same ex ante income prospects. On these grounds, for a sufficiently low level of uncertainty aversion, it is reasonable to think that P_2 should be ranked above P_3 . As for P_1 , on the other hand, both individuals face the same income prospects like in P_2 ; but in P_1 , there is no ex post inequality, whatever the state of the world. This could lead one to prefer P_1 over P_2 .²

²As in Gilboa et al. [7], we consider preferences over final allocations: we do not claim that one could not obtain a policy that is strictly preferred to P_1 by way of ex post transfers among individuals in P_2 .

This example makes clear that there is no hope for providing a reasonable social welfare function over income distributions under uncertainty by simply reducing the problem under consideration to a problem of a choice over uncertain aggregated incomes (say, e.g., by computing a traditional social welfare function à la Atkinson–Kolm–Sen in each state, and then reducing the problem to a single decision maker’s choice among prospects of welfare). Similarly, reducing the problem by first aggregating individuals’ income prospects, and then considering a classical social welfare function defined on these aggregated incomes would not be a reasonable solution. The first procedure would lead us to neglect *ex ante* considerations and to judge P_2 and P_3 as equivalent. In contrast, the second procedure would lead us to neglect *ex post* considerations and to see P_1 and P_2 as equivalent. In other words, these procedures would fail to simultaneously take into account the *ex ante* and the *ex post* income distributions.

Ben Porath et al. [2] suggest solving this problem by considering a linear combination of the two procedures described above, specifically, a linear combination of the expected Gini index and the Gini index of expected income. This solution captures both *ex ante* and *ex post* inequalities. Furthermore, it is a natural generalization of the principles commonly used for evaluating inequality under certainty on the one hand, and for decision making under uncertainty on the other hand. However, the procedure suggested by Ben Porath et al. [2] is not the only possible evaluation principle that takes into account both *ex ante* and *ex post* inequalities. Any functional that is increasing in both individuals’ expected income and snapshot inequalities (say, measured by the Gini index) has the same nice property, provided that it takes its values between the expected Gini and the Gini of the expectation. Furthermore, it is unclear why we should restrict ourselves, as Ben Porath et al. [2] did, to decision makers who behave in accordance with the multiple priors model.³

There is hence a need for an axiomatic characterization of inequality measurement under uncertainty, which can encompass Ben Porath et al. [2] proposal, and make clear why this specific functional should be used. In this section, we propose a set of axioms which capture what we think to be the basic requirements for any reasonable evaluation of welfare under uncertainty, and identify the corresponding general class of preferences.

2.1. Notation

Let $S = \{1, \dots, s\}$ and $K = \{1, \dots, n\}$ be respectively a finite set of states of the world, and a finite set of individuals. Let \mathcal{F} denote the set of non-negative real-valued functions on $S \times K$. An element f of \mathcal{F} corresponds to a $(s \times n)$ non-negative real-valued matrix. For every $k \geq 0$, we will denote by \mathbf{k} the $(s \times n)$ matrix with all entries equal to k .

³The multiple priors model assumes that social preferences are concave. It is unclear why preferences over uncertain outcomes should necessarily be concave.

In this paper, we interpret \mathcal{F} as a set of income distributions under uncertainty. For each f in \mathcal{F} , $f_{\sigma i}$ denotes i 's income if state σ occurs, while f_{σ} is the row vector that represents the income distribution in state σ , and $f_{\cdot i}$ the column vector that represents individual i 's income profile. Furthermore, \mathbf{f}_{σ} denotes the $(s \times n)$ matrix with all rows equal to f_{σ} , whereas $\mathbf{f}_{\cdot i}$ denotes the $(s \times n)$ matrix with all columns equal to $f_{\cdot i}$. The set of \mathbf{f}_{σ} matrices represents situations where there is no uncertainty: the income distribution is the same in each possible state of the world. In contrast, the $\mathbf{f}_{\cdot i}$ matrices characterize situations where there is no inequality: each individual is faced with the same income prospects.

In the sequel, we adopt the following convention: vectors of \mathbb{R}_+^n and \mathbb{R}_+^{n+s} are considered as row vectors, whereas vectors of \mathbb{R}_+^s are considered as column vectors. For $(x_1, \dots, x_p), (y_1, \dots, y_p) \in \mathbb{R}^p$, $(x_1, \dots, x_p) > (y_1, \dots, y_p)$ means that $x_i \geq y_i$ for all i , and there exists at least one j such that $x_j > y_j$.

Finally, we use the following definitions. A function $\phi : \mathbb{R}^q \rightarrow \mathbb{R}$, with $q \in \mathbb{N}$, is increasing if for all $x, y \in \mathbb{R}^q$, $x > y$ implies $\phi(x) > \phi(y)$. We say that ϕ is homogeneous if, for all $\theta > 0$, and all $x \in \mathbb{R}^q$, $\phi(\theta x) = \theta \phi(x)$. We say that ϕ is homogeneous of degree 0 if for all $\theta > 0$, and all $x \in \mathbb{R}^q$, $\phi(\theta x) = \phi(x)$. We say that ϕ is affine if, for all $x \in \mathbb{R}^q$, all $\theta > 0$ and all $\eta \in \mathbb{R}$, $\phi(\theta x + \eta \mathbf{1}_q) = \theta \phi(x) + \eta$, where $\mathbf{1}_q$ denotes the unit vector in \mathbb{R}^q . We say that ϕ is a similarity transformation if there exists $\theta > 0$ such that $\phi(x) = \theta x$ for all $x \in \mathbb{R}^q$. Finally, if $\phi : A \rightarrow B_{\phi}$ and $\psi : A \rightarrow B_{\psi}$ are two functions, $\mathfrak{I}(\phi, \psi) = \{(x, y) \in B_{\phi} \times B_{\psi} \mid \exists z \in A \text{ s.t. } \phi(z) = x \text{ and } \psi(z) = y\}$.

Following the literature on inequality measurement (see, e.g., [1,9,11]) we do not make any assumptions about individuals' preferences. The issue is not to aggregate individuals' preferences, but to propose principles for defining a reasonable collective attitude towards inequality under uncertainty.

2.2. The structure of social welfare preferences under uncertainty

We assume that there is a complete, continuous preorder on \mathcal{F} . This is the usual basic axiom in the field of normative inequality measurement.

Axiom 1 (ORD). There is a complete, continuous preorder on \mathcal{F} , denoted as \succsim .

The preorder \succsim can be interpreted as the decision maker's preference relation over \mathcal{F} (one can see this "decision maker" as anybody behind the veil of ignorance). As usual, \sim and \succ will stand for the symmetric and asymmetric part of \succsim , respectively.

Within this framework, we are now going to introduce four axioms which in our view, should be satisfied by any plausible social preference over uncertain income distributions.

The first axiom is a standard monotonicity requirement: if f provides each individual with a higher income than g in each state of the world, then f should be preferred to g .

Axiom 2 (MON). For all f, g in \mathcal{F} , if $f_{\sigma i} > g_{\sigma i}$ for all σ in S and all i in K , then $f \succ g$.

Any preorder \succsim on \mathcal{F} naturally induces two preorders \succsim_a and \succsim_p on \mathbb{R}_+^S and \mathbb{R}_+^n respectively, defined as: $f_{\cdot i} \succsim_a g_{\cdot i}$ if and only if $\mathbf{f}_{\cdot i} \succsim \mathbf{g}_{\cdot i}$, and $f_{\sigma} \succsim_p g_{\sigma}$ if and only if $\mathbf{f}_{\sigma} \succsim \mathbf{g}_{\sigma}$. The preorder \succsim_p captures the decision maker’s preferences in the absence of uncertainty, i.e., when the income distribution does not depend on the state of the world. In contrast, \succsim_a captures the decision maker’s preferences in the absence of inequality, i.e., when each individual faces the same income prospects. In other words \succsim_a and \succsim_p represent preorders on individual income profiles and snapshot income distributions, respectively.

Let us assume that f and g are such that (a) f_{σ} is preferred to g_{σ} for all σ (with respect to \succsim_p), and (b) $f_{\cdot i}$ is preferred to $g_{\cdot i}$ for all i (with respect to \succsim_a). In other words, f is preferred to g ex post regardless of the state of the world and f is also preferred to g ex ante regardless of the individual on which we focus. In such a case, it is reasonable to assume that f is preferred to g with respect to \succsim . This property corresponds to the following axiom of dominance.

Axiom 3 (DOM). Let $f, g \in \mathcal{F}$. If for all $\sigma \in S$, $f_{\sigma} \succsim_p g_{\sigma}$, and for all $i \in K$, $f_{\cdot i} \succsim_a g_{\cdot i}$, then $f \succsim g$. If, moreover, there exists $\sigma \in S$ or $i \in K$ such that $f_{\sigma} \succ_p g_{\sigma}$ or $f_{\cdot i} \succ_a g_{\cdot i}$, then $f \succ g$.

(DOM) should not be understood as providing a rule for aggregating individuals’ preferences. By construction, \succsim_a does not represent individuals’ preferences but the collective attitude towards uncertainty, exactly as \succsim_p represents the collective attitude towards inequality. When these principles imply that (a) any individual is better off in f than in g , and (b) any snapshot distribution of f is better than the corresponding snapshot distribution in g , then (DOM) simply requires the decision maker to prefer f to g .

Now, let us assume that the uncertain income $f_{\sigma i}$ of individual i in state σ can be represented as the combination of individual fixed effects that do not depend on the state of the nature, captured by λ_i , on the one hand, and effects that depend on the state of the nature μ_{σ} , but that are the same for all individuals, on the other hand. In other words, $f_{\sigma i} = \lambda_i \mu_{\sigma}$, for all $i \in K$ and all $\sigma \in S$. In such a case, we can reasonably focus on preorders which satisfy the following property: if the distribution of individual (sure) fixed effects is the same for two matrices f and g , but the random variable that generates the variability of individuals’ income across states of nature in f is preferred (with respect to \succsim_a) to the one that generates the variability of the individuals’ income across states of nature in g , then f is preferred to g . This requirement is formally stated in the following Conditional Dominance Axiom.

Axiom 4 (CDOM). $\forall \lambda \in \mathbb{R}_+^n, \lambda \neq 0, \mu, \nu \in \mathbb{R}_+^S, \mu \lambda \succsim_a \nu \lambda \Leftrightarrow \mu \succsim_a \nu$.

Lastly, we will require that \succsim be homogeneous. This axiom is of course debatable; however, this assumption is quite standard in the field of inequality measurement.⁴

⁴Homogeneity is a potentially problematic property when there is a positive minimum of subsistence.

Axiom 5 (HOM). $\forall f, g \in \mathcal{F}, \forall \theta > 0, f \succ g \Leftrightarrow \theta f \succ \theta g$.

The following lemma will prove to be useful in the sequel.

Lemma 1. *Assume Axioms (ORD), (MON), (CDOM) and (HOM) hold. There then exists a homogeneous function I which represents \succ , and two homogeneous functions I_a and I_p which represent \succ_a and \succ_p , respectively, such that*

$$\forall \mu \in \mathbb{R}_+^s, \lambda \in \mathbb{R}_+^n, \quad I(\mu\lambda) = I_a(\mu)I_p(\lambda).$$

Our first basic finding is that any homogeneous continuous complete social evaluation of the elements of \mathcal{F} that satisfies the dominance and monotonicity axioms introduced in this section should necessarily remain between two very crucial bounds, namely the evaluation of the social welfare distribution before the resolution of uncertainties and the evaluation of the social welfare distribution after the resolution of uncertainty. In order to state this result, we will need the following notation. Following Ben Porath et al. [2], for all f in \mathcal{F} , and any function $I_a : \mathbb{R}_+^s \rightarrow \mathbb{R}_+$ and $I_p : \mathbb{R}_+^n \rightarrow \mathbb{R}_+$, we will denote by $(I_a * I_p)(f)$ the iterative application of I_a to the results of I_p applied to the rows of f , and by $(I_p * I_a)(f)$ the iterative application of I_p to the results of I_a applied to the columns of f . $(I_a * I_p)$ is hence obtained by first evaluating social welfare in each possible state of the world (through I_p), and then evaluating the distribution of these welfares through I_a . On the other hand, $(I_p * I_a)$ is obtained by first evaluating each individual's welfare by I_a , and then computing through I_p the social value of the distribution of these individual welfares. Formally, we use the following notation: $I_a(f) = (I_a(f_{\cdot 1}), \dots, I_a(f_{\cdot n}))$, $I_p(f) = (I_p(f_{1\cdot}), \dots, I_p(f_{s\cdot}))$, and $(I_a * I_p)(f) = I_a(I_p(f))$, $(I_p * I_a)(f) = I_p(I_a(f))$. This is a slight abuse in notation, but there is no risk of confusion between $I_a(f_{\cdot i})$ ($I_p(f_{\sigma\cdot})$), which is a function from \mathbb{R}_+^s (\mathbb{R}_+^n) to \mathbb{R}_+ , and I_a (I_p), which is a function from \mathcal{F} to \mathbb{R}_+^s (\mathbb{R}_+^n). Our result then reads as follows.

Theorem 1. *Axioms (ORD), (MON), (DOM), (CDOM) and (HOM) are satisfied if, and only if, there exist a continuous, increasing, homogeneous function $I : \mathcal{F} \rightarrow \mathbb{R}_+$ which represents \succ , two continuous, increasing and homogeneous functions $I_a : \mathbb{R}_+^s \rightarrow \mathbb{R}_+$ and $I_p : \mathbb{R}_+^n \rightarrow \mathbb{R}_+$, which represent \succ_a and \succ_p , respectively, and a continuous, increasing and homogeneous function $\Psi : \mathfrak{Z}(I_p, I_a) \rightarrow \mathbb{R}_+$, such that the following hold:*

1. $\forall f, g \in \mathcal{F}, f \succ g \Leftrightarrow I(f) = \Psi(I_p(f), I_a(f)) \geq \Psi(I_p(g), I_a(g)) = I(g)$.
2. *If $(I_a * I_p)(f) = (I_p * I_a)(f)$ then $I(f) = \Psi(I_p(f), I_a(f)) = (I_a * I_p)(f)$.*
3. *If $(I_a * I_p)(f) \neq (I_p * I_a)(f)$ then*

$$\min\{(I_a * I_p)(f), (I_p * I_a)(f)\} < I(f) < \max\{(I_a * I_p)(f), (I_p * I_a)(f)\}.$$

Moreover, Ψ is unique given I_a and I_p , and I_a and I_p are each unique up to a similarity transformation.

The symmetry of the representation theorem might at first sight seem surprising, since Axiom (CDOM) is not symmetric. However, once homogeneity is assumed, (CDOM) implies its symmetric counterpart, as Lemma 1 clearly shows. This is stated formally in the following remark.

Remark 1. Axioms (ORD), (CDOM) and (HOM) imply that for all $\lambda, \hat{\lambda} \in \mathbb{R}_+^n$, $\mu \in \mathbb{R}_+^s$, $\mu \neq 0$, $\mu\lambda \succcurlyeq \mu\hat{\lambda} \Leftrightarrow \lambda \succcurlyeq_p \hat{\lambda}$.

The I_a function represents \succcurlyeq_a and reflects how the decision maker evaluates uncertain income profiles. Symmetrically, the I_p function represents \succcurlyeq_p and captures how the decision maker evaluates income distributions under certainty. Within this framework, $(I_a * I_p)$ represents the evaluation through I_a of the distribution of ex post social welfares, while $(I_p * I_a)$ represents the evaluation through I_p of the distribution of ex ante social welfares. These two functionals represent the two key dimensions of social welfare under uncertainty, namely, unequal uncertainties ($I_p * I_a$) and uncertain inequalities ($I_a * I_p$). The first one reflects ex post considerations while the second one only captures ex ante considerations. Theorem 1 shows that under plausible monotonicity and dominance assumptions, a continuous and homogeneous social evaluation cannot correspond to $(I_p * I_a)$ or $(I_a * I_p)$, but should necessarily remain strictly between these two bounds.

The social welfare functionals defined in Theorem 1 are such that for every f , $I(f)$ is a specific weighted-average of the iterative application of I_p to the results of I_a and of the iterative application of I_a to the results of I_p .⁵ This motivates the following definition of Weighted Cross-Iterative (WCI) functionals.

Definition 1. A continuous functional $I: \mathcal{F} \rightarrow \mathbb{R}_+$ is a *Weighted Cross-Iterative* (WCI) functional, if and only if, there exist two continuous, increasing and homogeneous functions $I_a: \mathbb{R}_+^s \rightarrow \mathbb{R}_+$ and $I_p: \mathbb{R}_+^n \rightarrow \mathbb{R}_+$, a function $\gamma: \mathcal{F} \rightarrow (0, 1)$ homogeneous of degree 0, such that the following hold:

- (i) $\forall f \in \mathcal{F}$, $I(f) = \gamma(f)(I_p * I_a)(f) + (1 - \gamma(f))(I_a * I_p)(f)$.
- (ii) $\forall f, g \in \mathcal{F}$, $(I_a(f), I_p(f)) > (I_a(g), I_p(g)) \Rightarrow I(f) > I(g)$.

We denote \mathcal{W} as the set of WCI functionals.

Using Definition 1, Theorem 1 can be restated as follows.

Theorem 2. Axioms (ORD), (MON), (DOM), (CDOM) and (HOM) are satisfied if, and only if, \succcurlyeq can be represented by $I \in \mathcal{W}$, with I_a and I_p representing \succcurlyeq_a and \succcurlyeq_p , respectively. Moreover, I_a and I_p are unique up to a similarity transformation, and $\gamma_{\{f \in \mathcal{F} | (I_a * I_p)(f) \neq (I_p * I_a)(f)\}}$ is unique.

⁵To be more specific, for each f , there exists $\gamma(f)$ in $(0, 1)$, such that $I(f) = \gamma(f)(I_p * I_a)(f) + (1 - \gamma(f))(I_a * I_p)(f)$.

Note that the functionals proposed by Ben Porath et al. [2], namely $I(f) = \alpha(G_p * E_a)(f) + (1 - \alpha)(E_a * G_p)(f)$, where E_a is the expectation (defined on \mathbb{R}_+^s) and G_p is a Gini functional (defined on \mathbb{R}_+^n), belong to \mathcal{W} . Of course, the class of WCI functionals is much larger, since WCI functionals do not necessarily give constant weights to uncertainty in social welfare, on the one hand, and to inequality in uncertain income profiles, on the other hand. Actually, the most striking feature of the functionals proposed by Ben Porath et al. [2] is precisely that these relative weights do not depend on the matrix f under consideration (they are always given by the same α and $(1 - \alpha)$).

Interestingly, Theorem 1 can be used to derive a very fundamental *partial ordering* over distributions of income under uncertainty: for any $f, g \in \mathcal{F}$, if

$$\max\{(I_a * I_p)(f), (I_p * I_a)(f)\} \leq \min\{(I_a * I_p)(g), (I_p * I_a)(g)\},$$

then $g \succ f$. If f exhibits both less uncertainty in social welfare and less inequality in uncertain profiles than g , then it should be preferred to g .

This result provides a very simple means for ranking a wide range of distributions of income under uncertainty. For instance, consider the three social policies P_1 , P_2 and P_3 defined at the beginning of this section. For the sake of simplicity, assume that I_a and I_p are symmetric.⁶ Then, if $I_p(1, 1) = I_a(1, 1) = 1$ (which is only a matter of normalization), we can easily check that $(I_a * I_p)(P_1) = (I_p * I_a)(P_2) = I_a(0, 1)$, $(I_a * I_p)(P_3) = (I_p * I_a)(P_3) = I_p(0, 1)$, $(I_a * I_p)(P_2) = I_p(0, 1)$ and $(I_p * I_a)(P_1) = I_a(0, 1)$. Therefore, only three cases are possible: $P_1 \succ P_2 \succ P_3$, $P_3 \succ P_2 \succ P_1$ or $P_1 \sim P_2 \sim P_3$. Which of these orderings holds depends on the relative weight of the inequality and uncertainty aversions. If we assume that I_a is the expectation and I_p the Gini index, we get $P_1 \succ P_2 \succ P_3$. This is so because the expectation is neutral towards risk.

3. Weighted cross-iterative functionals

In this section, we show that a reasonable strengthening of the requirements introduced in the previous section makes it possible to characterize interesting and easy-to-implement sub-classes within the set of WCI functionals. Therefore, hereafter, we assume that \succ can be represented by a WCI functional.

First, we are going to focus on WCI functionals that satisfy the following strengthening of (DOM), to which we refer to as an Average Dominance Axiom.⁷

Axiom 6 (ADOM). $\forall f, g \in \mathcal{F}$, if $(I_a * I_p)(f) \geq (I_a * I_p)(g)$ and $(I_p * I_a)(f) \geq (I_p * I_a)(g)$ then $I(f) \geq I(g)$.

⁶The symmetry of I_p can be seen as a requirement of impartiality, whereas the symmetry of I_a can be justified, in this example, when the two states are equally likely.

⁷Note that for any WCI functional, I , I_a and I_p are well-defined.

This Axiom corresponds to requirements that are clearly stronger than (DOM). Under (ADOM), we do not require uniform ex ante and ex post dominance to prefer f to g , but only average dominance. Axiom (ADOM) can be seen as an axiom that imposes some consistency in the principles that rule ex post and ex ante welfare evaluations. To compare two matrices from an ex post viewpoint, we must first evaluate each possible income distribution and then, in a second stage, compare the two sets of social welfare evaluations. Symmetrically, to compare two matrices from an ex ante viewpoint, we must first evaluate income profiles for each individual, and then, in a second stage, compare the two distributions of income profile evaluations. In a sense, axiom (ADOM) says that the principles that rule the first stage of the ex post comparison should be the same as those which rule the second stage of the ex ante comparison, and vice versa. To put it differently, since each possible income distribution is evaluated through I_p , the distribution of income profiles should also be evaluated through I_p . Symmetrically, since each individual's income profile is evaluated through I_a , the social welfare evaluation profiles should also be evaluated through I_a .

In addition to axiom (ADOM), we will require \succsim to be additive, meaning that adding the same intercept to two matrices does not modify their ranking.

Axiom 7 (ADD). For all $f, g \in \mathcal{F}$, $\eta \in \mathbb{R}_+$, $f \succsim g \Rightarrow f + \eta \mathbf{1} \succsim g + \eta \mathbf{1}$.

This is a standard assumption regarding social welfare orderings. We could have introduced (ADD) earlier in the text. To be more specific, we could have introduced (ADD) instead of (HOM) in the previous section: substituting (ADD) for (HOM) in the list of axioms used in Theorem 1 leads to the same general class of social preferences (where homogeneity is replaced by unit translatability).

The following theorem characterizes WCI functionals which satisfy (ADOM) and (ADD).

Theorem 3. Suppose that \succsim can be represented by a WCI functional I . Then \succsim satisfies Axioms (ADOM) and (ADD) if, and only if, I_a and I_p are affine, and there exist $\alpha, \beta \in (0, 1)$, such that:

$$I(f) = \begin{cases} \alpha(I_p * I_a)(f) + (1 - \alpha)(I_a * I_p)(f), & \text{if } (I_a * I_p)(f) \geq (I_p * I_a)(f), \\ \beta(I_p * I_a)(f) + (1 - \beta)(I_a * I_p)(f), & \text{if } (I_p * I_a)(f) \geq (I_a * I_p)(f). \end{cases}$$

Moreover, α and β are unique.

The set of such I is denoted \mathcal{W}_1 . Once (ADOM) and (ADD) are satisfied, the weight given to ex ante evaluations only depends on whether they are more important or less important than ex post ones, and *vice versa*.

Axiom (ADOM) can be strengthened by assuming that the two fundamental dimensions of welfare, namely inequality in uncertainties and uncertainty in inequalities are of commensurate value and equally important. The following axiom of Global Dominance requires that if the best dimension of a matrix f is better than

the best dimension of a matrix g , and the worst dimension of f is also better than the worst dimension of g , then f is better than g .

Axiom 8 (GDOM). For all f, g in \mathcal{F} , if

$$\begin{cases} \max\{(I_a * I_p)(f), (I_p * I_a)(f)\} \geq \max\{(I_a * I_p)(g), (I_p * I_a)(g)\}, \\ \min\{(I_a * I_p)(f), (I_p * I_a)(f)\} \geq \min\{(I_a * I_p)(g), (I_p * I_a)(g)\} \end{cases}$$

then, $I(f) \geq I(g)$.

Note that when (GDOM) is satisfied, (ADOM) is also satisfied.

Replacing Axiom (ADOM) by Axiom (GDOM) in Theorem 3 leads to the characterization of the *Weighted Max-Min* functionals, i.e., of WCI functionals that can be written as a weighted average of the maximum and the minimum of $(I_p * I_a)(f)$ and $(I_a * I_p)(f)$.

Theorem 4. Suppose that \succsim can be represented by a WCI functional I . Then \succsim satisfies Axioms (GDOM) and (ADD) if, and only if, I_a and I_p are affine and there exists $\delta \in (0, 1)$, such that:

$$I(f) = \delta \min\{(I_a * I_p)(f), (I_p * I_a)(f)\} + (1 - \delta) \max\{(I_a * I_p)(f), (I_p * I_a)(f)\}.$$

Moreover, δ is unique.

The set of such I is denoted as \mathcal{W}_2 . Once (GDOM) is satisfied, the weights put on the two possible welfare evaluations do not depend on whether they correspond to ex post or ex ante considerations, but only on whether they are the most or the least important. Observe that we have $\mathcal{W}_2 \subset \mathcal{W}_1 \subset \mathcal{W}$.

4. Weighted cross-iterative functionals and Ben-Porath et al.’s proposal

As noted above, Ben Porath et al. [2] have proposed a specific sub-class of WCI functionals, namely the functionals that can be written as $I(f) = \alpha(I_p * I_a)(f) + (1 - \alpha)(I_a * I_p)(f)$, where I_a and I_p are what they call min-of-means functionals.

Min-of-means functionals are well-known in decision theory under the name of the multiple priors model, and were first introduced by Gilboa and Schmeidler [7]. Special notation is needed in order to define these functionals. Let \mathcal{P}_K and \mathcal{P}_S be the spaces of probability vectors on K and S , respectively. For any $f_\sigma \in \mathbb{R}_+^n$ and $q \in \mathcal{P}_K$, let $q \cdot f_\sigma = \sum_i q_i f_{\sigma i}$. Similarly, for any $f_{\cdot i} \in \mathbb{R}_+^s$, and $q \in \mathcal{P}_S$, let $q \cdot f_{\cdot i} = \sum_\sigma q_\sigma f_{\sigma i}$. Min-of-means functionals are defined as follows.

Definition 2. A functional $I_a : \mathbb{R}_+^s \rightarrow \mathbb{R}_+$ ($I_p : \mathbb{R}_+^n \rightarrow \mathbb{R}_+$) is a *min-of-means* functional if, and only if, there exists a compact and convex subset \mathcal{C}_{I_a} (\mathcal{C}_{I_p}) of \mathcal{P}_S (\mathcal{P}_K), such that for all $f_{\cdot i} \in \mathbb{R}_+^s$ ($f_\sigma \in \mathbb{R}_+^n$), $I_a(f_{\cdot i}) = \min_{q \in \mathcal{C}_{I_a}} q \cdot f_{\cdot i}$ ($I_p(f_\sigma) = \min_{q \in \mathcal{C}_{I_p}} q \cdot f_\sigma$).

The class of functionals \mathcal{W}_3 proposed by Ben-Porath et al. can then be defined as

$$\mathcal{W}_3 = \{I \in \mathcal{W} \mid I_a, I_p \text{ are min-of-means functionals and } \forall f, g \in \mathcal{F}, \gamma(f) = \gamma(g)\}.$$

Any functional in \mathcal{W}_3 clearly belongs to \mathcal{W}_1 , meaning $\mathcal{W}_3 \subset \mathcal{W}_1$. In contrast, elements of \mathcal{W}_3 do not necessarily satisfy (GDOM), and there exist functionals in \mathcal{W}_3 which do not belong to \mathcal{W}_2 (i.e., $\mathcal{W}_3 \not\subseteq \mathcal{W}_2$).

Any I in \mathcal{W}_3 gives the same weight to ex ante inequalities regardless of whether they are more or less important than ex post ones and vice versa. In contrast, any I in \mathcal{W}_2 systematically puts more emphasis on the dominant source of inequality.

Before exploring the relationship between these two classes of functionals, it may be useful to define a special subset of the set of min-of-means functionals, namely the generalized minimum operators. We say that a min-of-means functional $I_a : \mathbb{R}_+^S \rightarrow \mathbb{R}_+$ is a *generalized minimum operator* if there exist $k \in S$ and $S_0 = \{\sigma_1, \dots, \sigma_k\} \subseteq S$ such that for all $\mu = (\mu_1, \dots, \mu_s) \in \mathbb{R}_+^S$, $I_a(\mu) = \min_{\sigma \in S_0} \mu_\sigma$. Similarly, $I_p : \mathbb{R}_+^K \rightarrow \mathbb{R}_+$ is a *generalized minimum operator* if there exist $k \in K$ and $K_0 = \{i_1, \dots, i_k\} \subseteq K$ such that for all $\lambda = (\lambda_1, \dots, \lambda_n) \in \mathbb{R}_+^n$, $I_p(\lambda) = \min_{i \in K_0} \lambda_i$.

The following theorem examines the conditions under which an element of \mathcal{W}_3 satisfies the axioms introduced in this paper and belongs to \mathcal{W}_2 .

Theorem 5. *Assume $I \in \mathcal{W}_3$. Then, $I \in \mathcal{W}_2$ if and only if at least one of the two following conditions is satisfied:*

- (i) $\forall f \in \mathcal{F}, I(f) = \frac{1}{2}(I_p * I_a)(f) + \frac{1}{2}(I_a * I_p)(f)$;
- (ii) *At least one of I_a and I_p is either (a) a mathematical expectation with respect to a given probability measure or (b) a generalized minimum operator.*

A potentially interesting subclass of \mathcal{W}_3 is the set of symmetric min-of-means (i.e., such that for all $f \in \mathcal{F}, I(f) = I(f')$ for all f' such that f' is obtained by a permutation of the rows and the columns of f). The symmetry assumption may be relevant whenever the states of the world are equally likely. Given that the only symmetric generalized minimum operator is the minimum operator (on all the components) and that the only symmetric probability vector is the uniform one (i.e., the vector whose all components are equal), Theorem 5 has the following corollary.

Corollary 1. *Assume $I \in \mathcal{W}_3$ and I is symmetric. Then $I \in \mathcal{W}_2$ if and only if at least one of the two following conditions is satisfied:*

- (i) $\forall f \in \mathcal{F}, I(f) = \frac{1}{2}(I_p * I_a)(f) + \frac{1}{2}(I_a * I_p)(f)$.
- (ii) *At least one of I_a and I_p is either (a) the mathematical expectation with respect to the uniform distribution or (b) the minimum operator.*

Generally speaking, once we exclude the specific cases of risk (or inequality) neutrality and extreme egalitarianism (or extreme aversion to risk), the only functionals that belong simultaneously to \mathcal{W}_2 and \mathcal{W}_3 are the arithmetic means of ex ante and ex post social welfare evaluation (through min-of-means). The key feature of these functionals is that any given shifts in ex post levels of social welfare can actually be compensated by symmetric shifts in ex ante levels of individual welfares, i.e., by shifts whose social evaluation is the same as the evaluation of the ex post shifts in absolute value.

To make this property explicit, let us define, for each vector u in \mathbb{R}_+^n , the set $\mathcal{S}(u)$ of vectors v of \mathbb{R}_+^n , such that for some constant $k > 0$, the matrix $\mathbf{u}_\sigma + \mathbf{k}$ with all rows equal to $u + k\mathbf{1}_n$ (i.e., a matrix with no uncertainty, where only inequality matters) is equivalent to the matrix $\mathbf{v}_i + \mathbf{k}$ with all columns equal to $v + k\mathbf{1}_s$ (i.e., a matrix with no inequality, where only uncertainty matters).⁸ Formally:

$$\mathcal{S}(u) = \{v \in \mathbb{R}_+^n \mid \exists k > 0, \text{ s.t. } \mathbf{v}_i + \mathbf{k} \sim \mathbf{u}_\sigma + \mathbf{k}\}.$$

Then, for any matrix $f \in \mathcal{F}$, one can define the set $\mathcal{E}(f) \subseteq \mathcal{F}$ of matrices that are obtained from f by shifts in ex post levels of social welfare and shifts in ex ante levels of individual welfares, whose social evaluations are the same. Formally,

$$\mathcal{E}(f) = \{g \in \mathcal{F} \mid \exists u \in \mathbb{R}_+^n, v \in \mathcal{S}(u), \text{ s.t. } (I_a(g), I_p(g)) = (I_a(f) - u, I_p(f) + v)\}.$$

We can now state formally the desired Axiom of symmetry.

Axiom 9 (SYM). $\forall f \in \mathcal{F}, g \in \mathcal{E}(f) \Rightarrow f \sim g.$

As it turns out, the preorder \succsim can be represented by a WCI functional and satisfies Axioms (ADD) and (SYM) if, and only if, it can be represented by the arithmetic mean of ex ante and ex post welfare evaluations.

Theorem 6. *Suppose that \succsim can be represented by a WCI functional I . Then \succsim satisfies Axioms (ADD) and (SYM) if, and only if, I_a and I_p are affine, and:*

$$I(f) = \frac{1}{2}(I_p * I_a)(f) + \frac{1}{2}(I_a * I_p)(f).$$

5. Conclusion

In this paper, we show that under some reasonable monotonicity and dominance assumptions, any continuous homogeneous social welfare function should lie strictly between the ex ante and the ex post evaluations of income distributions. We propose the weighted average of the minimum and the maximum of ex post and ex ante evaluations as a new means for evaluating welfare under uncertainty.

⁸We denote by k_σ the vector of \mathbb{R}_+^n with all entries equal to k , and by k_i the vector of \mathbb{R}_+^s with all entries equal to k .

Clearly, this new evaluation tool can be used in a potentially very large set of contexts. The usual practice is to rank public policies according to their impact on either the observed distribution of income or on the distribution of expected income. Once we do not neglect macroeconomic uncertainty, we should not rely on either pure ex ante or pure ex post considerations, but on one of the mixtures that are axiomatized in this paper.

At a very general level, our paper can be understood as an attempt to evaluate income distributions when it is not indifferent whether income varies across states of the world or across individuals. We think that this approach could be generalized to any problem of welfare evaluation where the *sources* of income variability matter. One such problem is the evaluation of income distributions according to the principle of equality of opportunity. This principle requires giving different weights to inequalities generated by circumstances beyond the control of individuals on the one hand, and on the other hand, to inequalities generated by actions that reflect individuals' own free volition. We speculate that the axiomatization and design of new means for implementing this principle can be obtained following a very similar route as the one used in this paper. This issue is part of our research agenda.

Appendix A

Proof of Lemma 1. By Debreu [4], Axiom (ORD) implies that there exists a continuous function $I: \mathcal{F} \rightarrow \mathbb{R}$ representing \succsim . We can, therefore, define I_a and I_p , representing \succsim_a and \succsim_p , respectively, as follows: $I_a(f_i) = I(\mathbf{f}_i)$, and $I_p(f_\sigma) = I(\mathbf{f}_\sigma)$, for all $f_i \in \mathbb{R}_+^s$ and $f_\sigma \in \mathbb{R}_+^n$. Furthermore, we can, without loss of generality, normalize I such that $I(\mathbf{1}) = 1$, where $\mathbf{1}$ is the matrix in \mathcal{F} whose elements are all equal to 1. Axiom (HOM) implies that I can be chosen to be homogeneous, from which it follows that I_a and I_p are homogeneous too. Moreover, by continuity of I , $I(\mathbf{0}) = 0$, where $\mathbf{0}$ is the $(s \times n)$ matrix with all entries equal to 0. Therefore, by Axiom (MON), $I(f) \geq 0$ for all f in \mathcal{F} . This obviously implies that $I_a(\mu) \geq 0$ for all $\mu \in \mathbb{R}_+^s$, and $I_p(\lambda) \geq 0$ for all $\lambda \in \mathbb{R}_+^n$.

Let $f = \mu\lambda \in \mathcal{F}$, with $\mu \in \mathbb{R}_+^s$ and $\lambda \in \mathbb{R}_+^n$, $\lambda \neq 0$. Define g by: $g_{\sigma i} = I_a(\mu)\lambda_i$, for all $\sigma \in S$ and all $i \in K$. Observe that $g = v\lambda$, with $v = (I_a(\mu), \dots, I_a(\mu)) \in \mathbb{R}_+^s$. By homogeneity of I_a , and given the normalization choice $I(\mathbf{1}) = 1$, we have: $I_a(v) = I_a(\mu)$. Therefore, by Axiom (CDOM), we have $f \sim g$, i.e., $I(f) = I(g)$. But, by homogeneity of I , $I(g) = I_a(\mu)I(\mathbf{h}_\sigma)$, with $\mathbf{h}_\sigma = \lambda$ for every σ . Since, by definition of I_p , $I(\mathbf{h}_\sigma) = I_p(\lambda)$, we get: $I(g) = I_a(\mu)I_p(\lambda) = I(f)$, the desired result. \square

Proof of Theorem 1. First, we prove the “only if” part of the theorem.

Claim A.1. Axioms (ORD), (MON), (DOM) and (HOM) imply that there exist a continuous, increasing, homogeneous function I which represents \succsim , two continuous, increasing and homogeneous functions $I_a: \mathbb{R}_+^s \rightarrow \mathbb{R}_+$ and $I_p: \mathbb{R}_+^n \rightarrow \mathbb{R}_+$, which represent \succsim_a and \succsim_p , respectively, a continuous, increasing and homogeneous function

$\Psi : \mathfrak{I}(I_p, I_a) \rightarrow \mathbb{R}_+$, such that $\forall f, g \in \mathcal{F}$:

$$f \succcurlyeq g \Leftrightarrow I(f) = \Psi(I_p(f), I_a(f)) \geq \Psi(I_p(g), I_a(g)) = I(g).$$

Proof. By Debreu [4], Axiom (ORD) holds if, and only if, there exists a continuous function $I : \mathcal{F} \rightarrow \mathbb{R}$ such that I represents \succcurlyeq . Furthermore, Axiom (MON) implies that I is increasing.

Without loss of generality, we can choose I such that $I(\mathbf{1}) = 1$. Axiom (HOM) implies that I can be chosen to be homogeneous, i.e., such that $I(\theta f) = \theta I(f)$ for all $\theta > 0$ and $f \in \mathcal{F}$. The homogeneity and the continuity of I imply that $I(\mathbf{0}) = 0$. Therefore, by Axiom (MON), $I(f) \geq 0$ for all f in \mathcal{F} , i.e., I takes its values in \mathbb{R}_+ .

Considering the restriction of I on sets of matrices \mathbf{f}_σ and \mathbf{f}_i respectively, Axiom (ORD) implies that there exist two non-negative continuous functions I_p and I_a representing \succcurlyeq_p and \succcurlyeq_a respectively, and that these functions are increasing and homogeneous, since I is.

Now, for any $x \in \mathfrak{I}(I_p, I_a)$, let $\Gamma(x) = \{f \in \mathcal{F} \mid (I_p(f), I_a(f)) = x\}$.⁹ Axiom (DOM) implies that if two matrices f and g are such that $I_p(f) = I_p(g)$ and $I_a(f) = I_a(g)$, then $f \sim g$, and therefore $I(f) = I(g)$. Hence, for all $x \in \mathfrak{I}(I_p, I_a)$, and all $f, g \in \Gamma(x)$, $I(f) = I(g)$. Now define $\Psi : \mathfrak{I}(I_p, I_a) \rightarrow \mathbb{R}_+$ by: $\Psi(x) = I(f)|_{f \in \Gamma(x)}$. For any $f \in \mathcal{F}$, $I(f) = \Psi(I_p(f), I_a(f))$.

Using (DOM) and the fact that I_a and I_p are homogenous, it is straightforward to show that Ψ is homogenous and increasing too. We now prove the continuity of Ψ . Let $x^{(k)} \in \mathfrak{I}(I_p, I_a)$, be a sequence such that $\lim_{k \rightarrow \infty} x^{(k)} = x \in \mathfrak{I}(I_p, I_a)$. We are going to show that $\lim_{k \rightarrow \infty} \Psi(x^{(k)}) = \Psi(x)$.

Let $f^{(k)}$ be a sequence such that $f^{(k)} \in \Gamma(x^{(k)})$ for all k , and $f \in \Gamma(x)$. Given that $\lim_{k \rightarrow \infty} x^{(k)} = x$, for any $\varepsilon > 0$ there exists $N \in \mathbb{N}$ such that, for any $k > N$,

$$(1 - \varepsilon)x < x^{(k)} < (1 + \varepsilon)x.$$

Thus, given that I_a and I_p are homogenous, we have

$$(I_p((1 - \varepsilon)f), I_a((1 - \varepsilon)f)) < (I_p(f^{(k)}), I_a(f^{(k)})) < (I_p((1 + \varepsilon)f), I_a((1 + \varepsilon)f)),$$

and therefore by Axiom (DOM):

$$I((1 - \varepsilon)f) < I(f^{(k)}) < I((1 + \varepsilon)f).$$

Finally, homogeneity of I implies: $(1 - \varepsilon)I(f) < I(f^{(k)}) < (1 + \varepsilon)I(f)$, which implies that $\lim_{k \rightarrow \infty} I(f^{(k)}) = I(f)$. Thus, $\lim_{k \rightarrow \infty} \Psi(x^{(k)}) = \Psi(x)$. \square

Claim A.2. Axioms (ORD), (MON), (DOM), (CDOM) and (HOM) imply that, for all $f, g \in \mathcal{F}$ such that $(I_a * I_p)(f) \neq (I_p * I_a)(f)$,

$$\min\{(I_a * I_p)(f), (I_p * I_a)(f)\} < I(f) < \max\{(I_a * I_p)(f), (I_p * I_a)(f)\}.$$

⁹ Recall that $\mathfrak{I}(I_p, I_a) = \{z \in \mathbb{R}_+^{s+n} \mid \exists f \in \mathcal{F}, (I_p(f), I_a(f)) = z\}$.

Proof. Let $f \in \mathcal{F}$, with $f \neq \mathbf{0}$ and define g and h as follows: $g_{\sigma i} = \frac{I_a(f_i)I_p(f_\sigma)}{(I_a * I_p)(f)}$ and $h_{\sigma i} = \frac{I_a(f_i)I_p(f_\sigma)}{(I_p * I_a)(f)}$, for all σ in S and all i in K .¹⁰ Observe that, since $f \neq \mathbf{0}$, Axiom (MON) implies that g and h are well defined.

First, let us assume that $(I_a * I_p)(f) < (I_p * I_a)(f)$. We get: $I_a(g_i) = \frac{I_a(f_i)}{(I_a * I_p)(f)}(I_a * I_p)(f)$ for all i in K by homogeneity of I_a . Therefore: $I_a(g_i) = I_a(f_i)$ for all i in K . On the other hand, $I_p(g_\sigma) = \frac{I_p(f_\sigma)}{(I_a * I_p)(f)}(I_p * I_a)(f)$ for all i in K , by homogeneity of I_p , which implies $I_p(g_\sigma) > I_p(f_\sigma)$ for all σ in S , since $(I_a * I_p)(f) < (I_p * I_a)(f)$. Therefore, it follows from Claim A.1 that $g > f$.

Observe that $g = \frac{1}{(I_a * I_p)(f)} \mu_1 \lambda_1$, with $\lambda_1 = (I_a(f_1), \dots, I_a(f_n))$ and $\mu_1 = (I_p(f_1), \dots, I_p(f_s))$. Therefore, by homogeneity of I , and using Lemma 1, we have $I(g) = \frac{1}{(I_a * I_p)(f)} I_a(\mu_1) I_p(\lambda_1)$. By definition, $I_a(\mu_1) = (I_a * I_p)(f)$, and $I_p(\lambda_1) = (I_p * I_a)(f)$. Therefore, $I(g) = (I_p * I_a)(f)$, which implies: $I(f) < (I_p * I_a)(f)$.

On the other hand, $I_a(h_i) = \frac{I_a(f_i)}{(I_p * I_a)(f)}(I_a * I_p)(f)$ for all i in K , by homogeneity of I_a . Therefore, $I_a(h_i) < I_a(f_i)$ for all i in K since $(I_a * I_p)(f) < (I_p * I_a)(f)$, and $I_p(h_\sigma) = \frac{I_p(f_\sigma)}{(I_p * I_a)(f)}(I_p * I_a)(f)$ for all i in K , by homogeneity of I_p , which implies $I_p(h_\sigma) = I_p(f_\sigma)$ for all σ in S . Therefore, it follows from Claim A.1 that $f > h$.

By homogeneity of I , $I(h) = \frac{1}{(I_p * I_a)(f)} I(\lambda_1 \mu_1)$. Therefore, using again Lemma 1, we get: $I(h) = (I_a * I_p)(f)$. Therefore, $I(f) > (I_a * I_p)(f)$, from which it follows that $(I_a * I_p)(f) < I(f) < (I_p * I_a)(f)$.

Using a symmetrical argument, we can show that if $(I_a * I_p)(f) > (I_p * I_a)(f)$, then $(I_p * I_a)(f) < I(f) < (I_a * I_p)(f)$. \square

Claim A.3. Axioms (ORD), (MON), (DOM), (CDOM) and (HOM) imply that for all $f \in \mathcal{F}$,

$$(I_a * I_p)(f) = (I_p * I_a)(f) \Rightarrow I(f) = \Psi(I_p(f), I_a(f)) = (I_a * I_p)(f).$$

Proof. Assume that $(I_a * I_p)(f) = (I_p * I_a)(f)$. Using the same notation as in Claim A.2, we clearly get that $f \sim g \sim h$ and therefore, $(I_a * I_p)(f) = (I_p * I_a)(f) = I(f)$. \square

Claim A.4. I_a and I_p are unique up to a similarity transformation.

Proof. Due to the symmetry of the problem, we will focus on I_a (the proof for I_p is similar).

Let us assume that there exist two homogeneous functionals I_a and \hat{I}_a that represent \succsim_a . Let $\tilde{I}_a = \frac{I_a(1, \dots, 1)}{\hat{I}_a(1, \dots, 1)} \hat{I}_a$. Then, $\tilde{I}_a(1, \dots, 1) = I_a(1, \dots, 1)$. Assume there exists $\mu \in \mathbb{R}_+^S$ such that $I_a(\mu) \neq \tilde{I}_a(\mu)$. Without loss of generality, let $\tilde{I}_a(\mu) = \xi > I_a(\mu) = \zeta$.

¹⁰Observe that $I(\mathbf{0}) = (I_a * I_p)(\mathbf{0}) = (I_p * I_a)(\mathbf{0}) = 0$, and therefore, condition (2) of the theorem is obviously satisfied in this case.

Let us consider $\mu_1 = (\frac{\xi}{I_a(1, \dots, 1)}, \dots, \frac{\xi}{I_a(1, \dots, 1)})$. By definition of \tilde{I}_a , $\tilde{I}_a(\mu_1) = \frac{I_a(1, \dots, 1)}{I_a(1, \dots, 1)} \hat{I}_a(\mu_1)$. The homogeneity of \hat{I}_a then implies: $\tilde{I}_a(\mu_1) = \xi$. Therefore, $\mu \sim_a \mu_1$.

Similarly, let us define $\mu_2 = (\frac{\zeta}{I_a(1, \dots, 1)}, \dots, \frac{\zeta}{I_a(1, \dots, 1)})$. Using Axiom (HOM) again, one gets $I_a(\mu_2) = \zeta$. Hence, $\mu_2 \sim_a \mu$.

Since $\mu_1 \sim_a \mu$ and $\mu_2 \sim_a \mu$, we finally get $\mu_1 \sim_a \mu_2$, which contradicts the increasingness of \succsim_a , since $\xi > \zeta$. \square

Claim A.5. Given I_a and I_p , Ψ is unique up to a similarity transformation.

Proof. Assume that there exist two homogeneous functionals Ψ_1 and Ψ_2 such that $\Psi_1(I_a, I_p)$ and $\Psi_2(I_a, I_p)$ both represent \succsim . Since I_a and I_p are defined up to a similarity transformation, we can assume without loss of generality that $I_a(1, \dots, 1) = I_p(1, \dots, 1) = 1$. Let $\Psi_3 = \frac{\Psi_1(1, \dots, 1)}{\Psi_2(1, \dots, 1)} \Psi_2$. Then, $\Psi_3(1, \dots, 1) = \Psi_1(1, \dots, 1)$. Assume there exists f in \mathcal{F} such that $\Psi_3(I_a(f), I_p(f)) \neq \Psi_1(I_a(f), I_p(f))$. Without loss of generality, let $\Psi_3(I_a(f), I_p(f)) = \xi > \Psi_1(I_a(f), I_p(f)) = \zeta$.

Now, define g as follows: $g_{\sigma i} = \frac{\xi}{\Psi_1(1, \dots, 1)}$ for all σ and all i . By homogeneity of Ψ_3 , and given the normalization of I_a and I_p , $\Psi_3(I_a(g), I_p(g)) = \xi$. Therefore, $g \sim f$.

Similarly, let h be defined by: $h_{\sigma i} = \frac{\zeta}{\Psi_1(1, \dots, 1)}$ for all σ and all i . By homogeneity of Ψ_1 , and given the normalization of I_a and I_p , $\Psi_1(I_a(h), I_p(h)) = \zeta$. Therefore, $h \sim f$.

Since $g \sim f$ and $h \sim f$, we finally get $g \sim f$, which contradicts Axiom (MON), since $\xi > \zeta$. Hence, $\Psi_3 = \Psi_1$. Therefore, Ψ is unique up to a similarity transformation. \square

We will now turn to the “if” part of the theorem.

Axiom (ORD) is obviously satisfied. Since Ψ , I_a and I_p are homogeneous, Axiom (HOM) is satisfied. Furthermore, since Ψ is increasing, Axiom (DOM) holds, and since I_a and I_p are increasing, Axiom (MON) holds too.

Now, let $f = \mu\lambda$ and $g = \nu\lambda$ as in Axiom (CDOM), with $\mu \succsim_a \nu$. Homogeneity of I_a and I_p imply $I_a(f_i) = I_a(\mu)\lambda_i$ for all $i \in K$ and $I_p(f_\sigma) = I_p(\lambda)\mu_\sigma$ for all $\sigma \in S$. Therefore, by homogeneity of I_a and I_p , we have $(I_a * I_p)(f) = (I_p * I_a)(f) = I_a(\mu)I_p(\lambda)$. Hence, by condition (1) in the theorem, it follows that $I(f) = I_a(\mu)I_p(\lambda)$. Similarly, $I(g) = I_a(\nu)I_p(\lambda)$. Observe that $I_p(\lambda) > 0$, because $\lambda \neq 0$ and I_p is homogeneous and increasing. Therefore, $I(f) \geq I(g)$, if and only if, $I_a(\mu) \geq I_a(\nu)$, i.e., $\mu \succsim_a \nu$: Axiom (CDOM) is hence satisfied.

Finally, any similarity transformation of I_a and I_p also leads to a functional representing \succsim (with Ψ being appropriately adjusted), which completes the proof. \square

Proof of Theorem 2. Assume that I satisfies the conditions of Theorem 2. Then, for all f in \mathcal{F} , we can define, using Theorem 1:

$$\begin{cases} \gamma(f) = \frac{I(f) - (I_a * I_p)(f)}{(I_p * I_a)(f) - (I_a * I_p)(f)} & \text{if } (I_p * I_a)(f) \neq (I_a * I_p)(f), \\ \gamma(f) = \frac{1}{2} & \text{if } (I_p * I_a)(f) = (I_a * I_p)(f). \end{cases}$$

Clearly $\gamma(f)$ belongs to $(0, 1)$, is homogenous of degree zero and satisfies,

$$I(f) = \gamma(f)(I_p * I_a)(f) + (1 - \gamma(f))(I_a * I_p)(f), \quad \forall f \in \mathcal{F}.$$

Furthermore, condition (1) in Theorem 1 and the requirement that Ψ be increasing imply that for all f, g in \mathcal{F} , such that $(I_a(f), I_p(f)) > (I_a(g), I_p(g))$, $I(f) > I(g)$, i.e., condition (ii) of Definition 1 is satisfied. Therefore, if I satisfies the conditions of Theorem 2, it can be written as a WCI functional.

Uniqueness up to a similarity transformation of I_a and I_p are proven as in Theorem 1. The uniqueness of $\gamma_{\{(f \in \mathcal{F} | (I_a * I_p)(f) \neq (I_p * I_a)(f))\}}$ is straightforward.

Conversely, any WCI functional with I_a and I_p (representing respectively \succsim_a and \succsim_p), obviously satisfies the conditions imposed on I in Theorem 1. \square

Proof of Theorem 3. We first prove the “only if” part of the theorem.

By definition, if I is a WCI, there exists a function $\gamma : \mathcal{F} \rightarrow (0, 1)$ homogeneous of degree 0, and two homogeneous increasing functions I_a and I_p , which represent respectively \succsim_a and \succsim_p , such that \succsim can be represented by $I(f) = \gamma(f)(I_p * I_a)(f) + (1 - \gamma(f))(I_a * I_p)(f)$. Without loss of generality, we can normalize I such that $I(\mathbf{1}) = 1$.

The proof goes through three steps.

Claim A.6. $\forall f \in \mathcal{F}$ such that $(I_p * I_a)(f) \neq (I_a * I_p)(f)$, $\forall \theta > 0, \forall \eta \in \mathbb{R}_+, \gamma(\theta f + \eta \mathbf{1}) = \gamma(f)$.

Proof. For any $f \in \mathcal{F}, \theta > 0, \eta \in \mathbb{R}_+$, the homogeneity of I and Axiom (ADD) imply: $I(\theta f + \eta \mathbf{1}) = \theta I(f) + \eta$. In other words, I is affine.

Next, let $\mu \in \mathbb{R}_+^s, \theta > 0$ and $\eta \geq 0$, and define $f_\mu \in \mathcal{F}$ by $f_{\cdot i} = \mu$ for all $i \in K$. By definition of I_a , we have $I_a(\theta \mu + (\eta, \dots, \eta)) = I(\theta f_\mu + \eta \mathbf{1})$. Because I is affine, $I(\theta f_\mu + \eta \mathbf{1}) = \theta I(f_\mu) + \eta$. Finally, the definition of I_a implies $I(f_\mu) = I_a(\mu)$. Therefore, $I_a(\theta \mu + (\eta, \dots, \eta)) = \theta I_a(\mu) + \eta$. In other words, $I_a : \mathbb{R}_+^s \rightarrow \mathbb{R}_+$ is also affine. An analogous argument shows that $I_p : \mathbb{R}_+^s \rightarrow \mathbb{R}_+$ is affine. Thus, for all $f \in \mathcal{F}$,

$$\begin{aligned} (I_a * I_p)(\theta f + \eta \mathbf{1}) &= I_a(I_p(\theta f + \eta \mathbf{1})) = I_a(\theta I_p(f) + (\eta, \dots, \eta)) \\ &= \theta(I_a * I_p)(f) + \eta, \end{aligned}$$

where the first equality follows from the definition of $(I_a * I_p)$, the second equality is due to the fact that I_p is affine, and the last equality follows from the fact that I_a is affine. Therefore, $(I_a * I_p)$ is also affine. By a symmetric argument, one shows that $(I_p * I_a)$ is affine, too.

Therefore, we can write

$$\begin{aligned} I(\theta f + \eta \mathbf{1}) &= \gamma(\theta f + \eta \mathbf{1})(I_p * I_a)(\theta f + \eta \mathbf{1}) + (1 - \gamma(\theta f + \eta \mathbf{1}))(I_a * I_p)(\theta f + \eta \mathbf{1}) \\ &= \gamma(\theta f + \eta \mathbf{1})[\theta(I_p * I_a)(f) + \eta] + (1 - \gamma(\theta f + \eta \mathbf{1}))[\theta(I_a * I_p)(f) + \eta] \\ &= \theta[\gamma(\theta f + \eta \mathbf{1})(I_p * I_a)(f) + (1 - \gamma(\theta f + \eta \mathbf{1}))(I_a * I_p)(f)] + \eta. \end{aligned}$$

We can also write, however

$$I(\theta f + \eta \mathbf{1}) = \theta I(f) + \eta = \theta[\gamma(f)(I_p * I_a)(f) + (1 - \gamma(f))(I_a * I_p)(f)] + \eta.$$

Comparing the two expressions for $I(\theta f + \eta \mathbf{1})$, we obtain

$$\begin{aligned} & \theta[\gamma(f)(I_p * I_a)(f) + (1 - \gamma(f))(I_a * I_p)(f)] + \eta \\ &= \theta[\gamma(\theta f + \eta \mathbf{1})(I_p * I_a)(f) + (1 - \gamma(\theta f + \eta \mathbf{1}))(I_a * I_p)(f)] + \eta. \end{aligned}$$

Assuming $(I_p * I_a)(f) \neq (I_a * I_p)(f)$, this implies $\gamma(\theta f + \eta \mathbf{1}) = \gamma(f)$. \square

Claim A.7. Let $f, g \in \mathcal{F}$. If $(I_a * I_p)(g) = (I_a * I_p)(f)$, $(I_p * I_a)(f) = (I_p * I_a)(g)$, and $(I_a * I_p)(f) \neq (I_p * I_a)(f)$ then $\gamma(f) = \gamma(g)$.

Proof. By Axiom (ADOM), if $(I_a * I_p)(g) = (I_a * I_p)(f)$ and $(I_p * I_a)(f) = (I_p * I_a)(g)$, then $I(f) = I(g)$. Therefore: $\gamma(f)(I_p * I_a)(f) + (1 - \gamma(f))(I_a * I_p)(f) = \gamma(g)(I_p * I_a)(g) + (1 - \gamma(g))(I_a * I_p)(g)$, which implies $\gamma(f) = \gamma(g)$ since $(I_a * I_p)(g) = (I_a * I_p)(f)$, $(I_p * I_a)(f) = (I_p * I_a)(g)$ and $(I_a * I_p)(f) \neq (I_p * I_a)(f)$. \square

Claim A.8. Let $f, g \in \mathcal{F}$. If either $(I_a * I_p)(f) < (I_p * I_a)(f)$ and $(I_a * I_p)(g) < (I_p * I_a)(g)$, or $(I_a * I_p)(f) > (I_p * I_a)(f)$ and $(I_a * I_p)(g) > (I_p * I_a)(g)$ then $\gamma(f) = \gamma(g)$.

Proof. Let $f, g \in \mathcal{F}$ be such that either $(I_a * I_p)(f) < (I_p * I_a)(f)$ and $(I_a * I_p)(g) < (I_p * I_a)(g)$, or $(I_a * I_p)(f) > (I_p * I_a)(f)$ and $(I_a * I_p)(g) > (I_p * I_a)(g)$. Let us define h by

$$\begin{aligned} h &= \frac{(I_p * I_a)(f) - (I_a * I_p)(f)}{(I_p * I_a)(g) - (I_a * I_p)(g)} g \\ &+ \frac{(I_p * I_a)(g)(I_a * I_p)(f) - (I_p * I_a)(f)(I_a * I_p)(g)}{(I_p * I_a)(g) - (I_a * I_p)(g)} \mathbf{1} + \eta \mathbf{1}, \end{aligned}$$

where $\eta > 0$ is chosen such that $h \in \mathcal{F}$.

Because $(I_a * I_p)$ is affine, we have

$$\begin{aligned} (I_a * I_p)(h) &= \frac{(I_p * I_a)(f) - (I_a * I_p)(f)}{(I_p * I_a)(g) - (I_a * I_p)(g)} (I_a * I_p)(g) \\ &+ \frac{(I_p * I_a)(g)(I_a * I_p)(f) - (I_p * I_a)(f)(I_a * I_p)(g)}{(I_p * I_a)(g) - (I_a * I_p)(g)} + \eta \\ &= \frac{(I_p * I_a)(g)(I_a * I_p)(f) - (I_a * I_p)(f)(I_a * I_p)(g)}{(I_p * I_a)(g) - (I_a * I_p)(g)} + \eta \\ &= (I_a * I_p)(f) + \eta. \end{aligned}$$

Similarly, one can show that $(I_p * I_a)(h) = (I_p * I_a)(f) + \eta$. Therefore, $(I_a * I_p)(h) \neq (I_p * I_a)(h)$ (recall that we assumed $(I_a * I_p)(f) \neq (I_p * I_a)(f)$). Claim A.6 implies $\gamma(h) = \gamma(g)$. Since either $(I_a * I_p)(f) < (I_p * I_a)(f)$ or $(I_a * I_p)(f) > (I_p * I_a)(f)$, Claim A.7 implies $\gamma(f) = \gamma(h)$. Hence, $\gamma(f) = \gamma(g)$. \square

Claim A.8 implies that $\gamma(f)$ only depends on the ordering of $(I_a * I_p)(f)$ and $(I_p * I_a)(f)$, which completes the proof of the “necessary” part of the theorem.¹¹

We now turn to the “sufficiency” part of the theorem. Because I is clearly affine, Axiom (ADD) is satisfied. We now check axiom (ADOM). Let $f, g \in \mathcal{F}$ be such that $(I_a * I_p)(f) \geq (I_a * I_p)(g)$ and $(I_p * I_a)(f) \geq (I_p * I_a)(g)$. Two cases may occur: either (i) f and g are evaluated with the same weights, or (ii) they are evaluated with different weights. Case (i) arises when $[(I_a * I_p)(f) - (I_p * I_a)(f)][(I_a * I_p)(g) - (I_p * I_a)(g)] \geq 0$, whereas case (ii) may arise when $[(I_a * I_p)(f) - (I_p * I_a)(f)][(I_a * I_p)(g) - (I_p * I_a)(g)] < 0$. Let us first consider case (i). Without loss of generality, let us assume that $(I_a * I_p)(f) \geq (I_p * I_a)(f)$. We then have: $I(f) = \alpha(I_p * I_a)(f) + (1 - \alpha)(I_a * I_p)(f)$, and $I(g) = \alpha(I_p * I_a)(g) + (1 - \alpha)(I_a * I_p)(g)$. Because, by assumption, $(I_a * I_p)(f) \geq (I_a * I_p)(g)$ and $(I_p * I_a)(f) \geq (I_p * I_a)(g)$, we get $I(f) \geq I(g)$, which implies that Axiom (ADOM) is satisfied.

Consider now case (ii). Without loss of generality, assume that $(I_a * I_p)(f) > (I_p * I_a)(f)$ and $(I_p * I_a)(g) > (I_a * I_p)(g)$. We then have

$$\begin{aligned} I(f) &= \alpha(I_p * I_a)(f) + (1 - \alpha)(I_a * I_p)(f) \geq \alpha(I_p * I_a)(f) + (1 - \alpha)(I_p * I_a)(f) \\ &= (I_p * I_a)(f), \end{aligned}$$

and

$$\begin{aligned} I(g) &= \beta(I_p * I_a)(g) + (1 - \beta)(I_a * I_p)(g) \leq \beta(I_p * I_a)(g) + (1 - \beta)(I_p * I_a)(g) \\ &= (I_p * I_a)(g). \end{aligned}$$

But we have, by assumption, $(I_p * I_a)(f) \geq (I_p * I_a)(g)$. Therefore, $I(f) \geq I(g)$, which implies that Axiom (ADOM) is satisfied. \square

Proof of Theorem 4. The “if” part of the Theorem is straightforward. We hence only prove the “only if” part.

Since Axiom (GDOM) is satisfied, so is Axiom (ADOM). It follows from Theorem 3 that there exist $\alpha, \beta \in (0, 1)$, such that

$$I(f) = \begin{cases} \alpha(I_p * I_a)(f) + (1 - \alpha)(I_a * I_p)(f), & \text{if } (I_a * I_p)(f) \geq (I_p * I_a)(f), \\ \beta(I_p * I_a)(f) + (1 - \beta)(I_a * I_p)(f), & \text{if } (I_p * I_a)(f) \geq (I_a * I_p)(f), \end{cases}$$

where I_a and I_p are affine.

We want to prove that $\alpha = (1 - \beta)$. Let $f \in \mathcal{F}$ be such that $(I_a * I_p)(f) > (I_p * I_a)(f)$. Now, let us define h as follows: $h = -f + (I_a * I_p)(f)\mathbf{1} + (I_p * I_a)(f)\mathbf{1} + \eta\mathbf{1}$, where $\eta > 0$ is chosen such that $h \in \mathcal{F}$. We can easily check that because $(I_a * I_p)$ and $(I_p * I_a)$ are affine (see the proof of Claim A.6, Theorem 3), $(I_a * I_p)(h) = (I_p * I_a)(f) + \eta$ and $(I_p * I_a)(h) = (I_a * I_p)(f) + \eta$. Therefore, $(I_p * I_a)(h) > (I_a * I_p)(h)$, which entails

$$I(h) = \beta(I_p * I_a)(h) + (1 - \beta)(I_a * I_p)(h).$$

¹¹Uniqueness of α and β directly follows from Theorem 2.

Now, define $g \in \mathcal{F}$ by $g = f + \eta \mathbf{1}$. We have, because $(I_a * I_p)$ and $(I_p * I_a)$ are affine: $(I_a * I_p)(g) = (I_a * I_p)(f) + \eta = (I_p * I_a)(h)$ and $(I_p * I_a)(g) = (I_p * I_a)(f) + \eta = (I_a * I_p)(h)$. Therefore Axiom (GDOM) implies that $I(g) = I(h)$. But because $(I_a * I_p)(g) > (I_p * I_a)(g)$, we have

$$I(g) = \alpha(I_p * I_a)(g) + (1 - \alpha)(I_a * I_p)(g) = \alpha(I_a * I_p)(h) + (1 - \alpha)(I_p * I_a)(h).$$

Therefore, we obtain

$$\beta(I_p * I_a)(h) + (1 - \beta)(I_a * I_p)(h) = \alpha(I_a * I_p)(h) + (1 - \alpha)(I_p * I_a)(h). \tag{A.1}$$

Finally, because $(I_p * I_a)(h) > (I_a * I_p)(h)$, Eq. (A.1) implies $\beta = (1 - \alpha)$, which completes the proof.¹² \square

Proof of Theorem 5. We first prove the “only if” part of the theorem.

Claim A.9. $I \in \mathcal{W}_2 \cap \mathcal{W}_3$ and $I(f) \neq \frac{1}{2}(I_p * I_a)(f) + \frac{1}{2}(I_a * I_p)(f)$ implies that either $(I_p * I_a)(f) \geq (I_a * I_p)(f)$ for all $f \in \mathcal{F}$, or $(I_a * I_p)(f) \geq (I_p * I_a)(f)$ for all $f \in \mathcal{F}$.

Proof. Let us assume $I \in \mathcal{W}_2 \cap \mathcal{W}_3$ and $I(f) \neq \frac{1}{2}(I_p * I_a)(f) + \frac{1}{2}(I_a * I_p)(f)$. In that case, there exist α and δ in $(0, 1) \setminus \{\frac{1}{2}\}$, such that, for all $f \in \mathcal{F}$,

$$I(f) = \alpha(I_p * I_a)(f) + (1 - \alpha)(I_a * I_p)(f), \tag{A.2}$$

and

$$I(f) = \delta \min\{(I_a * I_p)(f), (I_p * I_a)(f)\} + (1 - \delta) \times \max\{(I_a * I_p)(f), (I_p * I_a)(f)\}, \tag{A.3}$$

where (A.3) follows from Theorem 4. Let us assume that there exist f and g in \mathcal{F} , such that $(I_a * I_p)(f) > (I_p * I_a)(f)$ and $(I_a * I_p)(g) < (I_p * I_a)(g)$. Using Eqs. (A.2) and (A.3), $(I_a * I_p)(f) > (I_p * I_a)(f)$ implies $\alpha = \delta$, whereas $(I_a * I_p)(g) < (I_p * I_a)(g)$ implies $\alpha = (1 - \delta)$. But we assumed that $\alpha \neq \frac{1}{2}$ and $\delta \neq \frac{1}{2}$, which yields a contradiction. \square

Claim A.10. If for all $f \in \mathcal{F}$, $(I_a * I_p)(f) \leq (I_p * I_a)(f)$, then I_a is the mathematical expectation with respect to a given probability distribution, or I_p is a generalized minimum operator.

Proof. We first introduce some notations, definitions, and a preliminary result due to Ghirardato et al. [6].

We say that two vectors $\phi = (\phi_1, \dots, \phi_q)$ and $\psi = (\psi_1, \dots, \psi_q)$ of \mathbb{R}^q are comonotonic if for every $i, j \in \{1, \dots, q\}$, $(\phi_i - \phi_j)(\psi_i - \psi_j) \geq 0$. If there exist $\alpha \geq 0$ and $\beta \in \mathbb{R}$ such that either $\phi_i = \alpha\psi_i + \beta$ for all i , or $\psi_i = \alpha\phi_i + \beta$ for all i , or both, we say that ϕ and ψ are affinely related. Finally, let \mathcal{C} be the set of compact and convex sets of probability measures over \mathbb{R}^q .

¹²Uniqueness of δ directly follows from Theorem 2.

Affinely related vectors are important, because the min-of-means functionals are additive for affinely related vectors. More precisely, we have the following result, due to Ghirardato et al. [6] (Theorem 1 and Lemma 1).

Proposition (Ghirardato et al. [6]). *Let J_C denote the min-of-means functional defined on \mathbb{R}^q , with respect to the set of probability measures $C \in \mathcal{C}$. Then the following two statements are equivalent:*

- (i) ϕ and ψ in \mathbb{R}^q are affinely related;
- (ii) $J_C(\phi + \psi) = J_C(\phi) + J_C(\psi)$ for all $C \in \mathcal{C}$. Moreover, for a given $C \in \mathcal{C}$, the following two statements are equivalent:
- (iii) $J_C(\phi + \psi) = J_C(\phi) + J_C(\psi)$;
- (iv) $(\arg \min_{p \in C} p \cdot \phi) \cap (\arg \min_{p \in C} p \cdot \psi) \neq \emptyset$.

We can now turn to the proof of the claim. Assume that for all $f \in \mathcal{F}$, $(I_a * I_p)(f) \leq (I_p * I_a)(f)$ and that I_p is not a generalized minimum operator. We are going to show that I_a is then necessarily the mathematical expectation with respect to a given probability distribution in \mathcal{P}_S (i.e., C_{I_a} is a singleton).

Because I_p is not a generalized minimum operator, for all $\{i_1, \dots, i_k\} \subseteq K$, $C_{I_p} \neq co(e_{i_1}, \dots, e_{i_k})$, where for all $i \in K$, $e_i \in \mathbb{R}^n$ is such that its i th entry is equal to 1, whereas all its other entries are equal to zero.¹³

Let $K_1 = \{i \in K \mid e_i \notin C_{I_p}\}$. By construction, $K_1 \neq \emptyset$, otherwise we would have $C_{I_p} = co(e_1, \dots, e_K)$. Thus, it is possible to define $\bar{p} = \max_{\{p \in C_{I_p}, i \in K_1\}} p_i$. The \bar{p} parameter represents the largest weight given by elements of C_{I_p} to elements of K_1 .

We are going to prove that $0 < \bar{p} < 1$, and construct a vector λ such that $I_p(\lambda)$ depends on \bar{p} .

By definition of K_1 , any $i \in K_1$ is such that $p_i < 1$ for any $p \in C_{I_p}$. Thus, $\bar{p} < 1$. Furthermore, there exists at least one $i \in K_1$ and one $p \in C_{I_p}$ such that $p_i \neq 0$ (otherwise we would have $C_{I_p} = co(e_i)_{i \notin K_1}$). Thus, $\bar{p} > 0$.

Now, consider any j_0 in K_1 such that there exists \tilde{p} in C_{I_p} with $\tilde{p}_{j_0} = \bar{p}$. By construction, we have $\bar{p} = \max_{\{p \in C_{I_p}\}} p_{j_0}$. Define $\lambda \in \mathbb{R}^n$ by $\lambda_i = 1$ for all $i \neq j_0$, and $\lambda_{j_0} = 0$. Also define $C_{j_0} = \{p \in C_{I_p} \mid p_{j_0} = \bar{p}\}$. Given the definition of λ , $p \cdot \lambda = (1 - p_{j_0})$ for any p in C_{I_p} and therefore

$$\arg \min_{p \in C_{I_p}} p \cdot \lambda = \arg \min_{p \in C_{I_p}} (1 - p_{j_0}) = \arg \max_{p \in C_{I_p}} p_{j_0}.$$

But, because $\bar{p} = \max_{\{p \in C_{I_p}\}} p_{j_0}$, any $p \in \arg \max_{p \in C_{I_p}} p_{j_0}$ satisfies $p_{j_0} = \bar{p}$. Thus we have $\arg \min_{p \in C_{I_p}} p \cdot \lambda \subseteq C_{j_0}$.

¹³If λ and λ' are two vectors in \mathbb{R}_+^n , $co(\lambda, \lambda')$ denotes the convex hull of λ and λ' , i.e., $co(\lambda, \lambda') = \{\tilde{\lambda} \in \mathbb{R}_+^n \mid \exists \alpha \in [0, 1] \text{ s.t. } \tilde{\lambda} = \alpha \lambda + (1 - \alpha) \lambda'\}$.

Now, assume that there exist $\tilde{\mu}, \bar{\mu} \in \mathbb{R}_+^S$, such that

$$\left(\arg \min_{q \in C_{I_a}} q \cdot \bar{\mu} \right) \cap \left(\arg \min_{q \in C_{I_a}} q \cdot \tilde{\mu} \right) = \emptyset.$$

As discussed below, this amounts to assuming that I_a is not an expectation operator. Note that this assumption implies that neither $\tilde{\mu}$ nor $\bar{\mu}$ is a vector of zeros. Using \bar{p} and λ we are going to show that such an hypothesis contradicts the assumption that $(I_a * I_p)(f) \leq (I_p * I_a)(f)$ for all $f \in \mathcal{F}$.

Note that for all $\theta > 0$, $\arg \min_{q \in C_{I_a}} q \cdot \tilde{\mu} = \arg \min_{q \in C_{I_a}} q \cdot (\theta \tilde{\mu})$. Let $\theta > 0$ be such that $\theta \tilde{\mu}_\sigma > \bar{\mu}_\sigma$ for all $\sigma \in S$, and define $\mu = \theta \tilde{\mu}$. We have $\mu_\sigma > \bar{\mu}_\sigma$ for all $\sigma \in S$ and $(\arg \min_{q \in C_{I_a}} q \cdot \bar{\mu}) \cap (\arg \min_{q \in C_{I_a}} q \cdot \mu) = \emptyset$.

Let $f \in \mathcal{F}$ be defined by $f_i = \mu$ if $i \neq j_0$, and $f_{j_0} = \bar{\mu}$. For all $\sigma \in S$, $f_{\sigma i} = \mu_\sigma$ if $i \neq j_0$ and $f_{\sigma j_0} = \bar{\mu}_\sigma$. Therefore, $f_{\sigma i} = (\mu_\sigma - \bar{\mu}_\sigma)\lambda_i + \bar{\mu}_\sigma$, which means that f_σ and λ are affinely related for all $\sigma \in S$. Given this fact, the first part of the proposition (i.e., (i) \Rightarrow (ii)) implies that $I_p(f_\sigma + \lambda) = I_p(f_\sigma) + I_p(\lambda)$. Given this equality, the second part of the proposition (i.e., (iii) \Rightarrow (iv)) implies that

$$\left(\arg \min_{\tilde{p} \in C_{I_p}} \tilde{p} \cdot \lambda \right) \cap \left(\arg \min_{\tilde{p} \in C_{I_p}} \tilde{p} \cdot f_\sigma \right) \neq \emptyset.$$

Thus, given that $\arg \min_{p \in C_{I_p}} p \cdot \lambda \subseteq C_{j_0}$, there exists $p^* \in C_{j_0}$ such that $I_p(f_\sigma) = p^* \cdot f_\sigma$, which implies $I_p(f_\sigma) = (1 - \bar{p})\mu_\sigma + \bar{p} \bar{\mu}_\sigma$.

Now, let $r \in \arg \min_{\tilde{r} \in C_{I_a}} \tilde{r} \cdot I_p(f)$. We have then, by definition of I_a , $(I_a * I_p)(f) = r \cdot I_p(f)$, i.e.,

$$(I_a * I_p)(f) = \sum_{\sigma} r_{\sigma} [(1 - \bar{p})\mu_{\sigma} + \bar{p} \bar{\mu}_{\sigma}],$$

which can be written as

$$(I_a * I_p)(f) = (1 - \bar{p}) \sum_{\sigma} r_{\sigma} \mu_{\sigma} + \bar{p} \sum_{\sigma} r_{\sigma} \bar{\mu}_{\sigma}. \tag{A.4}$$

Next, observe that $I_a(f_i) = I_a(\mu)$ for all $i \neq j_0$ and $I_a(f_{j_0}) = I_a(\bar{\mu})$. Furthermore, given that $\mu_\sigma > \bar{\mu}_\sigma$ for all $\sigma \in S$, we have $I_a(\mu) > I_a(\bar{\mu})$. But it is easily checked that $I_a(f_i) = (I_a(\mu) - I_a(\bar{\mu}))\lambda_i + I_a(\bar{\mu})$, which means that $I_a(f)$ and λ are affinely related. Therefore, using the same arguments as above, there exists $\hat{p} \in C_{j_0}$ such that $(I_p * I_a)(f) = \hat{p} \cdot I_a(f) = (1 - \bar{p})I_a(\mu) + \bar{p}I_a(\bar{\mu})$.

Now, by definition of I_a , and since $r \in C_{I_a}$, we have $I_a(f_i) \leq r \cdot f_i$ for all $i \in K$. If none of these inequalities were strict, we would have $r \in \arg \min_{\tilde{r} \in C_{I_a}} \tilde{r} \cdot f_i$ for all $i \in K$, which would contradict $(\arg \min_{q \in C_{I_a}} q \cdot \bar{\mu}) \cap (\arg \min_{q \in C_{I_a}} q \cdot \mu) = \emptyset$. Thus, at least one of these inequalities is strict. This implies (recall that $0 < \bar{p} < 1$):

$$(I_p * I_a)(f) = (1 - \bar{p})I_a(\mu) + \bar{p}I_a(\bar{\mu}) < (1 - \bar{p})(r \cdot \mu) + \bar{p}(r \cdot \bar{\mu}).$$

But we have

$$(1 - \bar{p})(r \cdot \mu) + \bar{p}(r \cdot \bar{\mu}) = (1 - \bar{p}) \sum_{\sigma} r_{\sigma} \mu_{\sigma} + \bar{p} \sum_{\sigma} r_{\sigma} \bar{\mu}_{\sigma} = (I_a * I_p)(f),$$

where the last equality follows from Eq. (A.4). Therefore, $(I_p * I_a)(f) < (I_a * I_p)(f)$, a contradiction. Therefore, for all $\mu, \bar{\mu} \in \mathbb{R}_+^S$, $(\arg \min_{q \in C_{I_a}} q \cdot \mu) \cap (\arg \min_{q \in C_{I_a}} q \cdot \bar{\mu}) \neq \emptyset$. By the proposition, this implies that I_a is additive on \mathbb{R}_+^S , which implies that I_a is the expectation with respect to a given probability distribution. \square

Claim A.11. *If for all $f \in \mathcal{F}$, $(I_a * I_p)(f) \geq (I_p * I_a)(f)$, then I_p is the mathematical expectation with respect to a given probability distribution, or I_a is a generalized minimum operator.*

Proof. By symmetry, the proof is similar to the proof of Claim A.10.

The “only if” part of the theorem follows from Claims A.9–A.11.

We now turn to the “if” part of the theorem. In what follows, we assume that $I \in \mathcal{W}_3$.

First, assume that I_a is the mathematical expectation with respect to a given probability measure $q \in \mathcal{P}_S$. Then, for all $f \in \mathcal{F}$, $I_a(f) = (q \cdot f_{\cdot 1}, \dots, q \cdot f_{\cdot S}) = \sum_{\sigma} q_{\sigma} f_{\sigma}$, and therefore $(I_p * I_a)(f) = I_p(\sum_{\sigma} q_{\sigma} f_{\sigma})$. On the other hand, $(I_a * I_p)(f) = q \cdot I_p(f) = \sum_{\sigma} q_{\sigma} I_p(f_{\sigma})$. But any min-of-means functional is concave (see [7]). Therefore, by Jensen’s inequality: $\sum_{\sigma} q_{\sigma} I_p(f_{\sigma}) \leq I_p(\sum_{\sigma} q_{\sigma} f_{\sigma})$, and therefore $(I_a * I_p)(f) \leq (I_p * I_a)(f)$ for all $f \in \mathcal{F}$, which clearly implies that $I \in \mathcal{W}_2$.

By symmetry, if I_p is the mathematical expectation with respect to a given probability measure, the same argument leads to $(I_a * I_p)(f) \geq (I_p * I_a)(f)$ for all $f \in \mathcal{F}$, which clearly implies that $I \in \mathcal{W}_2$.

Now, assume that I_p is a generalized minimum operator. Then, there exists $K_0 = \{i_1, \dots, i_k\} \subseteq K$ such that $C_{I_p} = \text{co}(e_i)_{i \in K_0}$. In this case, for all $f \in \mathcal{F}$, and all $\sigma \in S$, $I_p(f_{\sigma}) = \min_{i \in K_0} f_{\sigma i}$. Therefore, $(I_a * I_p)(f) = I_a(\min_{i \in K_0} f_{1i}, \dots, \min_{i \in K_0} f_{Si})$, from which it follows by monotonicity of I_a that for all $j \in K_0$, $(I_a * I_p)(f) \leq I_a(f_j)$. But $(I_p * I_a)(f) = \min_{i \in K_0} I_a(f_{\cdot i})$. Therefore, there exists $j_0 \in K_0$ such that $(I_p * I_a)(f) = I_a(f_{j_0})$. Choosing $j = j_0$, it follows that $(I_a * I_p)(f) \leq (I_p * I_a)(f)$, for all $f \in \mathcal{F}$, which implies that $I \in \mathcal{W}_2$.

By symmetry, if I_a is a generalized minimum operator, the same argument leads to $(I_a * I_p)(f) \geq (I_p * I_a)(f)$ for all $f \in \mathcal{F}$, which clearly implies that $I \in \mathcal{W}_2$.

Finally, if $I(f) = \frac{1}{2}(I_p * I_a)(f) + \frac{1}{2}(I_a * I_p)(f)$ for all $f \in \mathcal{F}$, then trivially $I \in \mathcal{W}_2$. \square

Proof of Theorem 6. The “if” part of the Theorem is straightforward. We hence only prove the “only if” part.

Since $I \in \mathcal{W}$ and I satisfies Axiom (ADD), I_a and I_p are affine.

Let $f \in \mathcal{F}$ be such that $(I_p * I_a)(f) \neq (I_a * I_p)(f)$ and consider g defined by: $g_{\sigma i} = \frac{1}{2}I_a(f_{\cdot i}) + \frac{1}{2}I_p(f_{\sigma \cdot})$, for all i in K and all σ in S . We then obtain

$$I_a(g_{\cdot i}) = I_a(f_{\cdot i}) + \left[\frac{1}{2}(I_a * I_p)(f) - \frac{1}{2}I_a(f_{\cdot i}) \right], \quad \forall i \in K, \tag{A.5}$$

and

$$I_p(g_{\sigma \cdot}) = I_p(f_{\sigma \cdot}) + \left[\frac{1}{2}(I_p * I_a)(f) - \frac{1}{2}I_p(f_{\sigma \cdot}) \right], \quad \forall \sigma \in S. \tag{A.6}$$

Now, let us define $u \in \mathbb{R}^n$ by $u_i = \frac{1}{2}(I_a(f_{\cdot i}) - (I_a * I_p)(f))$, for all i in K , and $v \in \mathbb{R}^s$ by $v_\sigma = \frac{1}{2}((I_p * I_a)(f) - I_p(f_{\sigma \cdot}))$. We hence have: $I_a(g) = I_a(f) - u$ and $I_p(g) = I_p(f) + v$. Finally, let $k > 0$ be large enough to have $\mathbf{u}_\sigma + \mathbf{k}$ and $\mathbf{v}_i + \mathbf{k}$ in \mathcal{F} , where $\mathbf{u}_\sigma + \mathbf{k}$ ($\mathbf{v}_i + \mathbf{k}$) represents the matrix with all rows (columns) equal to $u + k\mathbf{1}_n$ ($v + k\mathbf{1}_s$).¹⁴

Without loss of generality, we assume that I is normalized with $I(\mathbf{1}) = 1$. Then, we can easily check that, since I_a and I_p are affine, $(I_a * I_p)(\mathbf{u}_\sigma + \mathbf{k}) = (I_p * I_a)(\mathbf{u}_\sigma + \mathbf{k}) = \frac{1}{2}[(I_p * I_a)(f) - (I_a * I_p)(f)] + k$, which implies, since I is a WCI functional, that $I(\mathbf{u}_\sigma + \mathbf{k}) = \frac{1}{2}[(I_p * I_a)(f) - (I_a * I_p)(f)] + k$. Similarly, $(I_a * I_p)(\mathbf{v}_i + \mathbf{k}) = (I_p * I_a)(\mathbf{v}_i + \mathbf{k}) = \frac{1}{2}[(I_p * I_a)(f) - (I_a * I_p)(f)] + k$. Therefore, $I(\mathbf{v}_i + \mathbf{k}) = \frac{1}{2}[(I_p * I_a)(f) - (I_a * I_p)(f)] + k$, from which it follows that $I(\mathbf{u}_\sigma + \mathbf{k}) = I(\mathbf{v}_i + \mathbf{k})$. Therefore, $v \in \mathcal{S}(u)$. Hence, by Axiom (SYM), we have $f \sim g$. Because I_a and I_p are affine, however, we obtain, using Eqs. (A.5) and (A.6):

$$\begin{aligned} (I_p * I_a)(g) &= (I_p * I_a)(f) + \frac{1}{2}(I_a * I_p)(f) - \frac{1}{2}(I_p * I_a)(f) \\ &= \frac{1}{2}(I_p * I_a)(f) + \frac{1}{2}(I_a * I_p)(f), \end{aligned}$$

and

$$\begin{aligned} (I_a * I_p)(g) &= (I_a * I_p)(f) + \frac{1}{2}(I_p * I_a)(f) - \frac{1}{2}(I_a * I_p)(f) \\ &= \frac{1}{2}(I_p * I_a)(f) + \frac{1}{2}(I_a * I_p)(f). \end{aligned}$$

Hence, by Theorem 1, $I(g) = \frac{1}{2}(I_a * I_p)(f) + \frac{1}{2}(I_p * I_a)(f)$. Therefore, $I(f) = \frac{1}{2}(I_a * I_p)(f) + \frac{1}{2}(I_p * I_a)(f)$. We can then conclude that, for all f such that $(I_a * I_p)(f) \neq (I_p * I_a)(f)$, $\gamma(f) = \frac{1}{2}$.

Finally, if $(I_a * I_p)(f) = (I_p * I_a)(f)$, one obviously get $I(f) = \frac{1}{2}(I_a * I_p)(f) + \frac{1}{2}(I_p * I_a)(f)$. \square

¹⁴ k should be chosen large enough to have $\frac{1}{2}(I_a * I_p)(f) - \frac{1}{2}I_a(f_{\cdot i}) + k > 0$ for all i , and $\frac{1}{2}(I_p * I_a)(f) - \frac{1}{2}I_p(f_{\sigma \cdot}) + k > 0$ for all σ .

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