

The limit of discounted utilitarianism

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This paper presents an infinite-horizon version of intergenerational utilitarianism. By studying discounted utilitarianism as the discount factor tends to one, we obtain a new welfare criterion: limit-discounted utilitarianism (LDU). We show that LDU meets standard assumptions of efficiency, equity, and interpersonal comparability, but allows us to compare more pairs of utility streams than commonly-used utilitarian criteria, including the overtaking criterion and the catching-up criterion. We also introduce a principle of compensation for postponements of utility streams and use it to characterize the LDU criterion on a restricted domain.

KEYWORDS. Utilitarianism, intergenerational equity, time preference.

JEL CLASSIFICATION. D63, D70, D90.

1. INTRODUCTION

Utilitarianism is the normative theory which asserts that the best social policy among a set of alternatives is the one that generates the greatest total welfare, where total welfare is often defined as the sum of the utilities for all members of society. This notion of maximizing aggregate utility becomes problematic for an infinite-horizon society. The problem of aggregating infinite utility streams $u = (u_1, u_2, \dots)$, representing the utilities of present and future generations, has occupied philosophers and economists for more than a century. Discounted utilitarianism provides a popular criterion for the evaluation of such streams. However, since discounting means assigning smaller weights to future generations, discounted utilitarianism has also been the subject of heavy criticism.¹ For instance, Ramsey (1928, p. 543) calls discounting future generations' utilities an "ethically indefensible" practice that "arises merely from the weakness of the imagination". In his axiomatic approach to discounted utilitarianism, Koopmans (1960) formally defines time preference through the concept of *impatience*. Subsequently, a long tradition in welfare economics studies social preferences that combine the Strong Pareto axiom

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¹This criticism goes back at least to Sidgwick (1907) and Pigou (1920).

with Anonymity, that is, invariance under transformations that swap the utility levels of any two generations.² The formulation of criteria that meet the two requirements turns out to be associated with complications, the full extent of which has only been understood recently. Firstly, on the set of infinite utility streams, complete and transitive preferences that satisfy Strong Pareto and Anonymity are not representable by social welfare functions.³ Secondly, such preferences cannot be obtained by constructive methods. In other words, all explicit descriptions of transitive preferences satisfying Strong Pareto and Anonymity are incomplete.⁴

The literature on intergenerational preferences satisfying Strong Pareto and Anonymity therefore uses incomplete preferences. A *social welfare relation* (SWR) is a binary relation that is reflexive and transitive, but not necessarily complete. The most often used utilitarian SWRs rank infinite streams on the basis of their partial sums over a finite horizon tending to infinity.⁵ This is the case, for instance, for the overtaking criterion (von Weizsäcker, 1965), the catching-up criterion (Gale, 1967), and the utilitarian SWR of Basu and Mitra (2007).⁶ This paper investigates an alternative approach.⁷ By studying discounted utilitarianism as the discount factor tends to one, we obtain a new welfare criterion: *limit-discounted utilitarianism* (LDU). In the limit, any two generations are treated equally, so this approach also avoids the critique of Ramsey (1928). Our main results include:

The Compensation Principle. Social welfare relations that satisfy the Anonymity axiom cannot exhibit impatience in the traditional sense of Koopmans (1960).⁸ However, in the literature stemming from his seminal contribution, many authors have argued for the appropriateness of a more inclusive concept of social time preference. The most common argument points out that the overtaking and catching-up criterion do not exhibit impatience in the sense of Koopmans (1960), and rank $(1, 0, 1, 0, \dots)$ above $(0, 1, 0, 1, \dots)$; see, for example, Lauwers (1995), Fleurbaey and Michel (2003), and Heal (2005). This literature advocates anonymity axioms involving classes of infinite permutations that make $(1, 0, 1, 0, \dots)$ equivalent to $(0, 1, 0, 1, \dots)$. Recently, several authors (including B. Dutta (2008) and Asheim et al. (2010)) have remarked that the equivalence of the two periodic streams means a violation of either Strong Pareto or Stationarity, two often combined conditions in intertemporal contexts. The Compensation Principle addresses an aspect of time preference — the effect of postponing utility streams — in a way that does not conflict with these conditions. Informally, the principle says that a utility stream can be postponed for one generation if the infinite-horizon society is compensated by the average utility over all generations. The precise formulation is in Section 2, where we also motivate the average as the suitable compensation. If $u = (1, 0, 1, 0, \dots)$, the Compensation Principle says that u is equivalent to $(1/2, u)$, which makes u strictly preferred to $(0, u) = (0, 1, 0, 1, \dots)$ by tran-

²Precise definitions of axioms from previous literature are in Section 2.

³Diamond's (1965) version of this result was obtained under an additional continuity assumption on the social welfare function. The general impossibility theorem, without this assumption, is due to Basu and Mitra (2003).

⁴The existence of complete, transitive binary relations satisfying Strong Pareto and Anonymity was established by Svensson (1980). Zame (2007, Theorem 4) and Lauwers (2010, p. 33) show that Svensson's existence theorem cannot be proved without using the Axiom of Choice.

⁵Formally, $\liminf_{T \rightarrow \infty} \sum_{t=1}^T (u_t - v_t) \geq 0$ must hold if $u = (u_1, u_2, \dots)$ is at least as good as $v = (v_1, v_2, \dots)$.

⁶The former would be more appropriately described as the SWRs induced by the overtaking and catching-up criterion. For convenience, the expressions SWR, criterion, and welfare criterion will be used synonymously.

⁷Discounting with discount factors tending to one has been used extensively in the literature on stochastic games and dynamic optimization; see, e.g., Liggett and Lippman (1969), Lippman (1969), Dutta (1991), Sennott (1999), and Bishop et al. (2014). Basu and Mitra (2007, pp. 360-361) defend the relevance of vanishing discount rates for intergenerational equity in a "robustness check" of their welfare criterion. They attribute the idea behind the robustness check to Jörgen Weibull. Limit-discounted utilitarianism can be seen as a concretization of their line of thought.

⁸Koopmans's definition (see Koopmans, 1960, Def. 1) is stated for pre-orders defined by social welfare functions. According to Banerjee and Mitra's (2007, Sec. 2.2.2) more general ordinal formulation, impatience is displayed by strictly preferring a stream u with $u_s > u_t$ for some $s < t$ to the stream v obtained by switching u_s and u_t . With Anonymity, the two streams are equivalent.

sitivity and Strong Pareto. In short, the Compensation Principle provides a new perspective on time preference in a widely discussed collection of examples.

A characterization. Theorem 1 shows that Strong Pareto, the Compensation Principle, and Additivity (a standard translation invariance axiom) characterize limit-discounted utilitarianism on the set of pairs of utility streams with a summable or eventually periodic difference.

Basic properties. Theorem 2 shows that besides Strong Pareto and Additivity, the limit-discounted utilitarian criterion satisfies Anonymity, Stationarity, and a continuity property relating preferences over infinite streams to preferences over long, finite-horizon truncations. This continuity requirement is a relaxation of a similar requirement in Brock's (1970) classical characterization of the overtaking criterion. Theorem 2 also shows that LDU meets the utilitarian requirement that summable streams with a larger sum are strictly preferred to those with a smaller sum; streams with equal finite sums are equivalent.

Comparison to other utilitarian criteria. The limit-discounted utilitarian criterion is closely related to the Abel summation method from the theory of divergent series. In Lemma 1, we generalize the classical theorem of Frobenius (1880) on the relationship between Abel and Cesàro summation to obtain a sufficient condition for comparability. Theorem 3 summarizes relations between our criterion and overtaking, catching-up, and the Basu-Mitra criterion: If u is weakly preferred to v according to any of these three criteria, then the same is true for LDU. For the Basu-Mitra criterion, the implication holds for strict preference as well. Example 2 contains a class of streams that can be ranked with LDU, but cannot be ranked using overtaking, catching-up, or the Basu-Mitra criterion. Finally, Example 4 provides a pair of streams that LDU does not compare.

2. INTRODUCING THE LIMIT-DISCOUNTED UTILITARIAN CRITERION

This section formally introduces our notion of limit-discounted utilitarianism and gives an axiomatic description of the limit-discounted utilitarian criterion. We also show that our criterion has a number of properties that are familiar from earlier literature.

The following notation will be used: $\mathbb{N} = \{1, 2, 3, \dots\}$ is the set of positive integers, \mathbb{R} the set of real numbers,

$$\mathcal{U} = \{u \in \mathbb{R}^{\mathbb{N}} : \sup_{t \in \mathbb{N}} |u_t| < +\infty\}$$

the set of bounded utility streams $u = (u_1, u_2, \dots)$, where u_t denotes the welfare level of generation $t \in \mathbb{N}$. A *social welfare relation* (SWR) is a reflexive and transitive binary relation \succsim on \mathcal{U} . For $u, v \in \mathcal{U}$, $u \succsim v$ means that society considers u to be at least as good as v . As usual, $u \sim v$ means that $u \succsim v$ and $v \succsim u$, whereas $u \succ v$ means that $u \succsim v$ but not $v \succsim u$.

Given $u \in \mathcal{U}$, the Abel sum

$$\lim_{\delta \rightarrow 1^-} \sum_{t=1}^{\infty} \delta^{t-1} u_t \tag{1}$$

will be denoted by $\sigma_A(u)$ if the limit (1) exists and is finite. It is easy to see that this limit, if it exists, is unaffected by switching any two entries of u . Abel summation thus provides a method for evaluating streams using discounting while treating each pair of generations equally. Our concept of limit-discounted utilitarianism builds on Abel summation and is formally defined as follows:

DEFINITION 1. The *limit-discounted utilitarian* (LDU) criterion is defined for all $u, v \in \mathcal{U}$ as

$$u \succsim_{\text{LDU}} v \iff \liminf_{\delta \rightarrow 1^-} \sum_{t=1}^{\infty} \delta^{t-1} (u_t - v_t) \geq 0. \tag{2}$$

Our first objective is to give an axiomatic description of the LDU criterion. We will do so on a domain that accommodates frequently discussed examples from recent literature, including all pairs $u, v \in \mathcal{U}$ of eventually periodic streams, namely:⁹

$$\mathcal{D} \equiv \{(u, v) \in \mathcal{U} \times \mathcal{U} : u - v \text{ is summable or eventually periodic}\}.$$

Our characterization result uses three properties of LDU. We show that for a SWR \succsim on \mathcal{U} with these three properties, every pair of streams in \mathcal{D} can be compared using \succsim , where $u \succsim v$ holds if and only if $u \succsim_{\text{LDU}} v$. The first two properties are the traditional assumptions of efficiency and interpersonal comparisons of utility, respectively:

Strong Pareto (SP): For all $u, v \in \mathcal{U}$, if $u_t \geq v_t$ for all $t \in \mathbb{N}$ and $u \neq v$, then $u \succ v$.

Additivity (Add): For all $u, v, \alpha \in \mathcal{U}$, $u \succsim v$ implies $u + \alpha \succsim v + \alpha$.

Several authors use assumptions on interpersonal comparisons that are weaker than Additivity.¹⁰ But since $u - v = (u + \alpha) - (v + \alpha)$ for all $u, v, \alpha \in \mathcal{U}$, Additivity is satisfied if weak preference $u \succsim v$ depends only on $u - v$. This is the case for all SWRs in this paper.

The third property is a principle of compensation for postponements of infinite utility streams. Given $u \in \mathcal{U}$ and $c \in \mathbb{R}$, call $(c, u) \equiv (c, u_1, u_2, \dots)$ the *postponement* of $u \in \mathcal{U}$ with *compensation* c .¹¹ The Compensation Principle says that if the average $\bar{u} \equiv \lim_{n \rightarrow \infty} \sum_{t=1}^n u_t / n$ of $u \in \mathcal{U}$ is well-defined, then $c = \bar{u}$ is a suitable compensation for a postponement of u :

Compensation Principle (CP): For all $u \in \mathcal{U}$, if \bar{u} is well-defined, then

$$(\bar{u}, u) \sim u.$$

Notice that if SWR \succsim satisfies Strong Pareto and $u = (a, a, a, \dots)$ is constant, then $u \succ (c, u)$ if $c < a$. In this case, $(c, u) \sim u$ can only hold if $c = a$, i.e., the average of u . Is there a more general rationale for this compensation level? We will return to this question below: assuming commonly-used conditions on intertemporal preferences, we show that the implication $(c, u) \sim u \Rightarrow c = \bar{u}$ holds on a larger set of streams. But let us first observe that the three properties characterize LDU on \mathcal{D} . All proofs are in the appendix.

THEOREM 1. *The binary relation \succsim_{LDU} defines a SWR that satisfies Strong Pareto, Additivity, and the Compensation Principle. Every SWR on \mathcal{U} with these three properties coincides with \succsim_{LDU} on \mathcal{D} .*

We sketch the proof of this theorem. For the second assertion, let \succsim be a SWR on \mathcal{U} with the three properties. The key observation is that given any $u, v \in \mathcal{U}$, the sequence $s = (s_1, s_2, \dots)$ of partial sums $s_n = \sum_{t=1}^n (u_t - v_t)$ satisfies $u - v = s - (0, s)$.¹² By Additivity, this means that if s is bounded (so that s and $(0, s)$ are both in \mathcal{U}), then $u \succsim v$ holds if and only if $s \succsim (0, s)$. Suppose, in addition, that \bar{s} is well-defined. We then have $(\bar{s}, s) \sim s$ by the Compensation Principle. Using Additivity and Strong Pareto, we are able to conclude (equations (18) to (20)) that

$$u \succsim v \iff \bar{s} \geq 0. \tag{3}$$

⁹Stream $u \in \mathcal{U}$ is *summable* if the series $\sum_{t=1}^{\infty} u_t$ converges, and *eventually periodic* (with period p) if there are $k, p \in \mathbb{N}$ with $u_{t+p} = u_t$ for all $t \geq k$.

¹⁰These include the Partial Unit Comparability axiom in Basu and Mitra (2007) and Partial and Finite Translation Scale Invariance axiom in Asheim (2010) and Asheim et al. (2010), respectively.

¹¹Heal (2005, p. 1115) refers to $(0, u)$ as the postponement of u . Koopmans et al. (1964) refer to (c, u) as the postponement of u with “insertion” c .

¹²That is, for each t : $s_{t+1} - s_t = u_{t+1} - v_{t+1}$.

The average of s is, by definition, the Cesàro-sum of the series $\sum_{t=1}^{\infty} (u_t - v_t)$. By the theorem of Frobenius (see Duren, 2012, p. 180), the series is Abel-summable to the same sum:

$$\sigma_A(u - v) = \bar{s}. \quad (4)$$

Combining (3) and (4) gives

$$u \succsim v \iff u \succsim_{\text{LDU}} v.$$

This argument takes care of the case when $d = u - v$ is summable or eventually periodic with average $\bar{d} = 0$ (Case 1 in the proof), as \bar{s} is defined in this case. A monotonicity argument reduces the case when $\bar{d} \neq 0$ (Case 2) to the zero-average case.

Let us note that (4) gives us an interpretation of the Compensation Principle in terms of the loss that society incurs when a stream is postponed with $c = 0$. To elaborate, suppose $u \in \mathcal{U}$ has a well-defined average and let $v = (0, u)$. We then have $s_n = \sum_{t=1}^n (u_t - v_t) = u_n$ for all $n \geq 1$, so the partial sums have average $\bar{s} = \bar{u}$, which by (4) means that $\sigma_A(u - v) = \bar{u}$. In other words, in terms of Abel-summation, postponing u with compensation $c = 0$ incurs a loss of \bar{u} whenever \bar{u} is well-defined. For example, postponing $u = (1, 1, 1, \dots)$ incurs a loss of $\bar{u} = 1$ and postponing $w = (1, 0, 1, 0, \dots)$ incurs a loss of $\bar{w} = 1/2$.

We now turn to the properties mentioned in the introduction. These properties will not only help us relate LDU to established utilitarian SWRs, which is the topic of the next section. They will also allow us to provide axiomatic support for the Compensation Principle. The Anonymity axiom says that preferences are unaffected by switching the utility levels of any two generations:

Anonymity (Ano): For all $u, v \in \mathcal{U}$, if there are $s, t \in \mathbb{N}$ with $u_s = v_t, u_t = v_s$, and if $u_i = v_i$ for all other $i \in \mathbb{N}$, then $u \sim v$.

Stationarity is Koopmans's (1960) condition for dynamic consistency — preferences are independent of the first generation if the first generation receives identical utility levels in the social states specified by u and v :¹³

Stationarity (Stat): For all $u, v \in \mathcal{U}$ and $c \in \mathbb{R}$, $u \succsim v$ if and only if $(c, u) \succsim (c, v)$.

The compensation level in the Compensation Principle can in part be justified by Stationarity and the following property:

Total Utility (TU): For all $u, v \in \mathcal{U}$, if $u - v$ is summable, then

$$u \succsim v \text{ if and only if } \sum_{t=1}^{\infty} (u_t - v_t) \geq 0. \quad (5)$$

If \succsim is a stationary SWR with this property and u is eventually periodic, then $(c, u) \sim u$ can only hold if $c = \bar{u}$. To illustrate the argument with a simple example, let $u = (a, b, a, b, \dots)$, so that u is periodic with period 2. If $(c, u) \sim u$, then we have $(c, c, u) \sim (c, u)$ by Stationarity and hence

$$(c, c, u) \sim u \quad (6)$$

by transitivity. Since $(c, c, u) - u = (c - a, c - b, 0, 0, \dots)$, combining (5) and (6) gives $(c - a) + (c - b) = 0$, i.e., $c = (a + b)/2$, the average of $u = (a, b, a, b, \dots)$. Here we only needed to assume that (5) holds when $u - v$ has at most a finite number of nonzero entries, and for this it is enough to

¹³Also Asheim et al. (2010) stress the relevance of Stationarity for intergenerational utilitarianism. They motivate their extension of Basu and Mitra's relation (10) by the desirability of retaining this axiom.

impose Strong Pareto, Additivity, and Anonymity.¹⁴ So if we add Stationarity to this axiom set, then $(c, u) \sim u$ implies $c = \bar{u}$ for all eventually periodic u (Proposition 1 in Appendix A.1).

This implication (if $(c, u) \sim u$, then $c = \bar{u}$) holds on a larger set of streams, including all convergent and consequently all summable streams, if we add a continuity assumption to the axioms above. We defer the precise definition of this set of streams to Appendix A.1. The continuity assumption in question relates preferences over infinite streams to preferences over long, finite-horizon truncations: for $u \in \mathcal{U}$ and $n \in \mathbb{N}$, we write $u_{[n]} = (u_1, u_2, \dots, u_n, 0, 0, \dots)$ and define¹⁵

Continuity (Cont): For all $u, v \in \mathcal{U}$, if there is an $N \in \mathbb{N}$ with $u_{[n]} \succ v_{[n]}$ for all $n \geq N$, then $u \succsim v$.

A similar axiom is used by Brock (1970), who writes that his condition captures the idea that “decisions on infinite programs are consistent with decisions on finite programs of length n if n is large enough”. For a discussion of the two axioms and their relation to the Total Utility property, see Jonsson and Voorneveld (2015).

THEOREM 2. *The LDU criterion satisfies Anonymity, Stationarity, Total Utility, and Continuity.*

The first three properties in Theorem 2 are easily verified. Anonymity is implied by the Total Utility property, which in turn is a direct consequence of Abel’s theorem. To verify that LDU satisfies Continuity, we use a generalization of the Frobenius theorem that relates upper and lower Cesàro and Abel-limits.¹⁶ For $d \in \mathcal{U}$ and $\delta \in (0, 1)$, define $s_n = \sum_{t=1}^n d_t$, $n \geq 1$, and

$$C_n(d) = \frac{s_1 + s_2 + \dots + s_n}{n}, \quad (7)$$

$$\sigma_\delta(d) = \sum_{t=1}^{\infty} \delta^{t-1} d_t. \quad (8)$$

Many properties of the LDU criterion are consequences of the following result:

LEMMA 1. *For $d \in \mathcal{U}$,*

$$\liminf_{n \rightarrow \infty} C_n(d) \leq \liminf_{\delta \rightarrow 1^-} \sigma_\delta(d) \leq \limsup_{\delta \rightarrow 1^-} \sigma_\delta(d) \leq \limsup_{n \rightarrow \infty} C_n(d). \quad (9)$$

This result will also help us in the next section when we compare our criterion to the over-taking criterion and the catching-up criterion.

¹⁴ See Basu and Mitra (2007, Lemma 1) or Jonsson and Voorneveld (2015, Lemma 1).

¹⁵ Our convention of considering streams with $u_t = 0$ for $t \geq n$ follows Brock (1970) and Basu and Mitra (2007). With Additivity, replacing the zeros by any other numbers would give the same condition as long as generations $t > n$ receive the same welfare in the two social states. For instance, if Additivity is satisfied, then Continuity is equivalent to a relaxation of the “weak preference continuity” axiom in Asheim and Tungodden (2004, p. 223): for all $u, v \in \mathcal{U}$, if there is an $N \in \mathbb{N}$ with $(u_1, \dots, u_n, v_{n+1}, v_{n+2}, \dots) \succ v$ for all $n \geq N$, then $u \succsim v$.

¹⁶ The inequalities in Lemma 1 are well-known from the literature on stochastic games; see Lippman (1969), Bishop et al. (2014) and Sennott (1999). These references do not contain a proof of the result in the generality that we stated it. Our proof is a slightly rewritten version of one suggested by an anonymous referee.

3. COMPARISON TO OTHER UTILITARIAN CRITERIA

In this section, we compare the limit-discounted utilitarian criterion to three other utilitarian social welfare relations:¹⁷ the criterion \succsim_{BM} of Basu and Mitra (2007) where

$$u \succsim_{\text{BM}} v \iff \text{there is a } T_0 \in \mathbb{N} \text{ with } \sum_{t=1}^{T_0} (u_t - v_t) \geq 0 \quad (10)$$

and $u_t - v_t \geq 0$ for all $t \geq T_0$,

the *overtaking* criterion \succsim_{W} of von Weizsäcker (1965) where

$$u \succsim_{\text{W}} v \iff \text{there is a } T_0 \in \mathbb{N} \text{ with } \sum_{t=1}^T (u_t - v_t) \geq 0 \text{ for all } T \geq T_0, \quad (11)$$

and the *catching-up* criterion \succsim_{G} of Gale (1967) where

$$u \succsim_{\text{G}} v \iff \liminf_{T \rightarrow \infty} \sum_{t=1}^T (u_t - v_t) \geq 0. \quad (12)$$

Our discussion will address the following (related) questions: Which properties from the previous section do these criteria satisfy? And to what extent do preferences according to LDU agree with those of the other criteria?

Table 1 lists the properties of LDU established in the previous section and indicates which of these properties are satisfied by overtaking, catching-up, and the Basu-Mitra criterion.

		SP	Add	CP	Ano	Stat	Cont	TU
LDU	\succsim_{LDU}	+	+	+	+	+	+	+
Basu-Mitra	\succsim_{BM}	+	+	-	+	+	-	-
<i>overtaking</i>	\succsim_{W}	+	+	-	+	+	+	-
<i>catching-up</i>	\succsim_{G}	+	+	-	+	+	+	+

Table 1: Social welfare relations and properties they do (+) or do not (-) satisfy.

The properties that are satisfied by the three criteria are straightforward to verify and known from the literature.¹⁸ We illustrate violations of properties in two examples where the overtaking criterion \succsim_{W} and the catching-up criterion \succsim_{G} have been criticized.¹⁹

EXAMPLE 1. Let $u \in \mathcal{U}$ be a summable stream with strictly positive entries and let $v = (0, u)$. Then $\sum_{t=1}^T (u_t - v_t) = u_T > 0$ for all $T \geq 1$. So u is strictly preferred to $v = (0, u)$ under overtaking. Since the two streams have the same sum, this example illustrates that overtaking does not have the Total Utility property. Nor does the Basu-Mitra criterion, which cannot compare

¹⁷Our definitions of the overtaking and catching-up criterion follow Gale (1967).

¹⁸See Basu and Mitra (2007) and Jonsson and Voorneveld (2015).

¹⁹Basu and Mitra (2007, p. 361) consider a version of Example 1. Versions of Example 2 have been discussed by, among others, Lauwers (1995, p. 348), Lauwers (1997, p. 225), Fleurbaey and Michel (2003, p. 783), Asheim and Tungodden (2004, p. 229), Heal (2005, p. 1115), Banerjee (2006, p. 333), Basu and Mitra (2007, p. 360), Dutta (2008, Sec. IV), Asheim et al. (2010, p. 520), and Asheim and Banerjee (2010, p. 164).

u and v .²⁰ LDU and catching-up do have the Total Utility property: they find u and $(0, u)$ equivalent.

The next example shows that the Compensation Principle and Strong Pareto allow us to compare streams that have appeared frequently in the literature, but which are not comparable using overtaking, catching-up, or the Basu-Mitra criterion.

EXAMPLE 2. Consider the periodic stream $u = (1, 0, 1, 0, \dots)$ and let $v = (c, u)$ for some real number c . Since $u - v = (1 - c, -1, 1, -1, \dots)$, Basu and Mitra's criterion does not compare u and v for any value of c . We have

$$\sum_{t=1}^T (u_t - v_t) = -\sum_{t=1}^T (v_t - u_t) = \begin{cases} -c + 1 & \text{if } T \text{ is odd,} \\ -c & \text{if } T \text{ is even.} \end{cases}$$

So u and v are not comparable with the overtaking criterion or the catching-up criterion if $c \in (0, 1)$. Both criteria rank u above v if $c \leq 0$. In particular, they prefer $(1, 0, 1, 0, \dots)$ to $(0, 1, 0, 1, \dots)$. The LDU criterion compares u and v for all c . Indeed, for $\delta \in (0, 1)$,

$$\sum_{t=1}^{\infty} \delta^{t-1} (u_t - v_t) = \sum_{t=1}^{\infty} (-\delta)^{t-1} - c = \frac{1}{1 + \delta} - c.$$

Letting δ go to one, the Abel sum of $\sum_{t=1}^{\infty} (u_t - v_t)$ is $1/2 - c$. This means that $u \sim_{\text{LDU}} v$ if $c = 1/2$, $u \succ_{\text{LDU}} v$ if $c < 1/2$, and $v \succ_{\text{LDU}} u$ if $c > 1/2$. From the axioms: we have $u \sim_{\text{LDU}} v$ for $c = 1/2$ by the Compensation Principle and therefore strict preference for all other c by Strong Pareto.

The next example contains a pair of streams over which catching-up has a strict preference, but LDU is indifferent; Example 1 gave a corresponding result for overtaking.

EXAMPLE 3. Define $u \in \mathcal{U}$ by setting $u_t = 1$ if $t = 2^n$ for some $n \in \mathbb{N}$ and $u_t = 0$ otherwise. Then $u - (0, u) = (u_1, u_2 - u_1, u_3 - u_2, \dots)$ has partial sums $s_n = u_n$, which means that $u \succ_G (0, u)$. But since $\bar{u} = 0$, the Compensation Principle implies that $u \sim_{\text{LDU}} (0, u)$.

To describe to what degree LDU agrees with overtaking, catching up, and the Basu-Mitra criterion, we use the following terminology: Given two SWRs \succsim_A and \succsim_B on \mathcal{U} , say that \succsim_B *weakly extends* \succsim_A if for all $u, v \in \mathcal{U}$, $u \succsim_A v$ implies $u \succsim_B v$. If, in addition, for all $u, v \in \mathcal{U}$, $u \succ_A v$ implies $u \succ_B v$, we say that \succsim_B *extends* \succsim_A .

THEOREM 3. *The following relations hold between the LDU criterion \succsim_{LDU} , the Basu-Mitra criterion \succsim_{BM} , overtaking \succsim_{W} , and catching-up \succsim_{G} :*

- (i) \succsim_{LDU} *extends* \succsim_{BM} .
- (ii) \succsim_{LDU} *weakly extends* \succsim_{G} and \succsim_{G} *weakly extends* \succsim_{W} .
- (iii) \succsim_{LDU} *does not extend* \succsim_{W} : there are $u, v \in \mathcal{U}$ with $u \succ_{\text{W}} v$ and $u \sim_{\text{LDU}} v$.
- (iv) \succsim_{LDU} *does not extend* \succsim_{G} : there are $u, v \in \mathcal{U}$ with $u \succ_{\text{G}} v$ and $u \sim_{\text{LDU}} v$.

In summary, if a pair of streams can be compared using overtaking, catching-up, or the Basu-Mitra criterion, then the same is true for LDU. But we also saw that LDU can compare streams that have appeared frequently in the literature, but which are not comparable using any of these other criteria. The pairs of streams in Example 1 and 2 are all in \mathcal{D} . Theorem 1 shows that all pairs of streams in this domain can be compared using Additivity, Strong Pareto, and the Compensation Principle.

²⁰Since $\sum_{t=1}^{\infty} u_t = \sum_{t=1}^{\infty} v_t$ and $\sum_{t=1}^T (u_t - v_t) > 0$ for every T , there is no T_0 with $u_t \geq v_t$ for all $t \geq T_0$. Therefore, $u \not\succeq_{\text{BM}} v$ does not hold. Likewise, $v \not\succeq_{\text{BM}} u$ does not hold. This also shows that \succsim_{BM} violates Continuity: $u_{[n]} \succ_{\text{BM}} u_{[n]}$ for all n , but u and v are not comparable.

4. LIMITATIONS

We conclude our study of the LDU criterion by providing examples of streams that it does not allow us to rank. By means of these examples, we briefly discuss the extent to which LDU is characterized by properties that we have established.

Lemma 1 tells us that for all $u, v \in \mathcal{U}$,

$$\liminf_{\delta \rightarrow 1^-} \sigma_\delta(u - v) \geq \liminf_{n \rightarrow \infty} C_n(u - v). \quad (13)$$

If the partial sums $\sum_{t=1}^n (u_t - v_t)$, $n \geq 1$, are bounded below or above and $\lim_{\delta \rightarrow 1^-} \sigma_\delta(u - v)$ exists, then the inequality in (13) is an equality.²¹ That we may have strict inequality in (13) even with bounded partial sums was demonstrated by, among others, Liggett and Lippman (1969). We use an example from Bishop et al. (2014, Sec. 4) to define a pair of streams that \succsim_{LDU} does not to compare:

EXAMPLE 4. Define $a = (a_1, a_2, \dots) \in \mathcal{U}$ by

$$a_t = \begin{cases} 0 & \text{if } k! \leq t < 2k! \text{ for some } k \in \mathbb{N}, \\ 1 & \text{otherwise.} \end{cases}$$

We then have (Bishop et al., 2014, Proposition 2)

$$\liminf_{n \rightarrow \infty} \frac{1}{n} \sum_{t=1}^n a_t = 1/2 < \liminf_{\delta \rightarrow 1^-} (1 - \delta) \sigma_\delta(a) = 3/4 \quad (14)$$

and

$$\limsup_{n \rightarrow \infty} \frac{1}{n} \sum_{t=1}^n a_t = \limsup_{\delta \rightarrow 1^-} (1 - \delta) \sigma_\delta(a) = 1. \quad (15)$$

If we take $u = a - (0, a)$, then the partial sums of u equal $s_n = \sum_{t=1}^n u_t = a_n$, $n \geq 1$. Summation by parts gives that $\sigma_\delta(u) = (1 - \delta) \sigma_\delta(a)$. By (14) and (15),

$$\liminf_{n \rightarrow \infty} C_n(u) = 1/2 < \liminf_{\delta \rightarrow 1^-} \sigma_\delta(u) = 3/4 \quad \text{and} \quad \limsup_{n \rightarrow \infty} C_n(u) = \limsup_{\delta \rightarrow 1^-} \sigma_\delta(u) = 1.$$

Consequently, u and $v = (r, 0, 0, \dots)$ are not \succsim_{LDU} -comparable if $r \in (3/4, 1)$.

The arguments in the proof of Theorem 1 apply whenever the sequence $s = (s_1, s_2, \dots)$ of partial sums $s_n = \sum_{t=1}^n (u_t - v_t)$, $n \geq 1$, is bounded and has a well-defined average. But if \bar{s} is undefined, then the Compensation Principle does not help us compare s and $(0, s)$. Lemma 1 gives us that for all $u \in \mathcal{U}$ and $c \in \mathbb{R}$: $(c, u) \succsim_{\text{LDU}} u$ if $c \geq \limsup_{n \rightarrow \infty} \frac{1}{n} \sum_{t=1}^n u_t$, where $u \succsim_{\text{LDU}} (c, u)$ if $c \leq \liminf_{n \rightarrow \infty} \frac{1}{n} \sum_{t=1}^n u_t$. However, characterizing LDU on larger domains is made difficult by the complicated relations between upper and lower Abel- and Cesàro-limits (see Bishop et al. (2014) and Example 4 above). We leave this investigation for future work.

A. APPENDIX

This appendix contains all proofs. Proposition 1 in Section A.1 gives axiomatic support for using the average in our Compensation Principle. Section A.2 to A.5 contain proofs of Theorem 1, Lemma 1, Theorem 2, and Theorem 3, respectively. In the proofs, we refer to axioms using their abbreviations from Section 2.

²¹This follows from the Hardy-Littlewood theorem (Duren, 2012, p. 184).

A.1 Motivating the Compensation Principle

We will argue that if a stream u on average gives each generation a utility of \bar{u} , then $c = \bar{u}$ is a reasonable compensation in a compensated postponement (c, u) of u : using some of our earlier axioms, Proposition 1 shows — on a fairly large set of well-behaved streams — that $(c, u) \sim u$ can only hold if $c = \bar{u}$. We will say that a stream $u \in \mathcal{U}$ has a *regular average* if (i) its average \bar{u} is well-defined and (ii) for every $\varepsilon > 0$ the average of u over sufficiently long, but finite segments of consecutive coordinates differs from \bar{u} by at most ε . That is, $u \in \mathcal{U}$ has a regular average if \bar{u} is well-defined and for every $\varepsilon > 0$ there is an $N \in \mathbb{N}$ such that

$$\left| \frac{1}{n} \sum_{t=t_0+1}^{t_0+n} u_t - \bar{u} \right| < \varepsilon \quad \text{for all } t_0 \in \mathbb{N} \text{ and } n \geq N.$$

For instance, the set of streams with a regular average contains all streams that are eventually periodic, summable, or convergent.²²

PROPOSITION 1. *Let \succsim be a SWR on \mathcal{U} that satisfies Strong Pareto, Anonymity, Additivity, and Stationarity. If $u \in \mathcal{U}$ is eventually periodic and $c \in \mathbb{R}$, then*

(i) $(c, u) \succsim u$ implies $c \geq \bar{u}$.

(ii) $u \succsim (c, u)$ implies $c \leq \bar{u}$.

(iii) $(c, u) \sim u$ implies $c = \bar{u}$.

If \succsim also satisfies Continuity, these implications hold for all $u \in \mathcal{U}$ with a regular average.

PROOF. Recall from footnote 14 that SP, Ano, and Add imply that for all $u, v \in \mathcal{U}$ where $u - v$ has only finitely many nonzero entries:

$$u \succsim v \iff \sum_{t=1}^{\infty} (u_t - v_t) \geq 0. \quad (16)$$

Assume that SWR \succsim on \mathcal{U} satisfies SP, Ano, Add, and Stat. Let $u \in \mathcal{U}$ be eventually periodic and let $c \in \mathbb{R}$. To prove (i), assume that $(c, u) \succsim u$. Since u is eventually periodic, there are $k, p \in \mathbb{N}$ with $u_{t+p} = u_t$ for $t \geq k$. If $p = 1$, then $u = (u_1, \dots, u_k, u_k, u_k, \dots)$ is eventually constant, so $(c, u) - u$ has a finite number of nonzero entries that sum to $c - u_k$. Since SP, Ano, and Add are satisfied, (16) implies that $c \geq u_k = \bar{u}$. If $p \geq 2$, we have $(c, c, u) \succsim (c, u) \succsim u$ by Stat and $(c, c, u) \succsim u$ by transitivity. Iterating (if $p > 2$) gives $(\underline{c}_p, u) \succsim u$, where \underline{c}_p is a short-cut notation for p consecutive coordinates equal to c . Since $u_t = (\underline{c}_p, u)_t$ for all $t > k + p$, the difference $(\underline{c}_p, u) - u$ has finitely many nonzero entries and sum $pc - \sum_{t=k+1}^{k+p} u_t$. By (16), $(\underline{c}_p, u) \succsim u$ implies that that this sum is nonnegative: $c \geq \sum_{t=k+1}^{k+p} u_t / p = \bar{u}$.

(ii): By Add, $u \succsim (c, u)$ implies $(-c, -u) \succsim -u$, which by (i) implies $-c \geq -\bar{u}$, so that $c \leq \bar{u}$.

(iii): This follows from (i) and (ii).

Now add axiom Cont. We prove implication (i) for streams with a regular average; (ii) and (iii) follow as above. So let $u \in \mathcal{U}$ and $c \in \mathbb{R}$ be such that u has regular average \bar{u} and $(c, u) \succsim u$. By Stat and transitivity, $(\underline{c}_N, u) \succsim u$ for all $N \in \mathbb{N}$. To prove that $c \geq \bar{u}$, suppose, to the contrary, that $c < \bar{u}$. We obtain a contradiction by showing that $u \succ (\underline{c}_N, u)$ for some $N \in \mathbb{N}$.

²²A stream with an average that is not regular is $u = (0, 1, 0, 0, 1, 1, 0, 0, 0, 1, 1, 1, \dots)$, consisting of a zero followed by a one, then two zeros followed by two ones, three zeros followed by three ones, etc. Its average is $1/2$. But it does not have a regular average: for every n , the stream contains infinitely many segments of n consecutive zeros (and n consecutive ones).

If $c < \bar{u}$, there are $b \in \mathbb{R}$ with $c < b < \bar{u}$ and $N \in \mathbb{N}$ such that the average of u over any $n \geq N$ consecutive generations differs from \bar{u} by at most $\varepsilon \equiv (\bar{u} - b)/2$. Let $d = u - (\underline{b}_N, u)$. For $n > N$:

$$\begin{aligned} \sum_{t=1}^n d_t &= u_n + u_{n-1} + \cdots + u_{n-N+1} - Nb \\ &= N((u_n + u_{n-1} + \cdots + u_{n-N+1})/N - b) \\ &\geq N(\bar{u} - \varepsilon - b) \\ &= N\varepsilon. \end{aligned}$$

Since $d_{[n]}$ has finitely many nonzero entries and positive sum, (16) implies that $d_{[n]} \succ (0, 0, 0, \dots)$ for all $n > N$. By Cont, we have $d \succsim (0, 0, 0, \dots)$. Hence $u \succsim (\underline{b}_N, u)$ by Add. By SP and $b > c$: $u \succ (\underline{c}_N, u)$, which is our contradiction. \square

A.2 Proof of Theorem 1

We start with a lemma linking Strong Pareto, Additivity, and the Compensation Principle to summability:

LEMMA 2. *Let the SWR \succsim satisfy Strong Pareto, Additivity, and the Compensation Principle. For $u, v \in \mathcal{U}$, if the series $\sum_{t=1}^{\infty} (u_t - v_t)$ is Cesàro-summable and has bounded partial sums, then*

$$u \succsim v \iff \lim_{n \rightarrow \infty} C_n(u - v) \geq 0. \quad (17)$$

In particular, \succsim has the Total Utility property.

PROOF. For u and v as in the lemma, Add gives $u \succsim v$ if and only if $u - v \succsim (0, 0, \dots)$. The sequence $s = (s_1, s_2, \dots)$ of partial sums $s_n = \sum_{t=1}^n (u_t - v_t)$, $n \in \mathbb{N}$, is bounded and $u - v = s - (0, s)$. So

$$u \succsim v \iff s - (0, s) \succsim (0, 0, \dots). \quad (18)$$

By CP, $s \sim (\bar{s}, s)$, where $\bar{s} = \lim_{n \rightarrow \infty} C_n(u - v)$ by definition (7). By Add, $s - (0, s) \sim (\bar{s}, s) - (0, s)$. Since

$$(\bar{s}, s) - (0, s) = (\bar{s}, 0, 0, \dots), \quad (19)$$

equation (18) implies

$$u \succsim v \iff (\bar{s}, 0, 0, \dots) \succsim (0, 0, 0, \dots). \quad (20)$$

By reflexivity and SP, $(\bar{s}, 0, 0, \dots) \succsim (0, 0, 0, \dots)$ holds if and only if $\bar{s} \geq 0$. With (20), this gives (17).

For TU, if $\sum_{t=1}^{\infty} (u_t - v_t)$ is convergent, it is Cesàro-summable to the same sum. That is, s is bounded ($s \in \mathcal{U}$) and $\bar{s} = \sum_{t=1}^{\infty} (u_t - v_t)$. By (17), $u \succsim v$ if and only if $\sum_{t=1}^{\infty} (u_t - v_t) \geq 0$. \square

This leaves us properly equipped for the proof of Theorem 1:

Proof of Theorem 1. For $\delta \in (0, 1)$ and $u \in \mathcal{U}$, we use the notation $\sigma_{\delta}(u)$ for $\sum_{t=1}^{\infty} \delta^{t-1} u_t$. We first show that \succsim_{LDU} is a social welfare relation. It is reflexive: $\sigma_{\delta}(u - u) = \sigma_{\delta}(0, 0, \dots) = 0$ for all $u \in \mathcal{U}$ and $\delta \in (0, 1)$. It is transitive: let $u, v, w \in \mathcal{U}$ have $u \succsim_{\text{LDU}} v$ and $v \succsim_{\text{LDU}} w$. For each $\delta \in (0, 1)$, the discounted sums satisfy

$$\sigma_{\delta}(u - w) = \sigma_{\delta}(u - v) + \sigma_{\delta}(v - w),$$

so taking lower limits and using $u \succsim_{\text{LDU}} v$ and $v \succsim_{\text{LDU}} w$ gives

$$\liminf_{\delta \rightarrow 1^-} \sigma_\delta(u - w) \geq \liminf_{\delta \rightarrow 1^-} \sigma_\delta(u - v) + \liminf_{\delta \rightarrow 1^-} \sigma_\delta(v - w) \geq 0 + 0 = 0,$$

i.e., $u \succsim_{\text{LDU}} w$. We proceed to the axioms:

SP: If $u_t \geq v_t$ for all $t \in \mathbb{N}$ and $u_t > v_t$ for some $t \in \mathbb{N}$, the discounted sum $\sigma_\delta(u - v)$ is a positive, increasing function of $\delta \in (0, 1)$. So $\lim_{\delta \rightarrow 1^-} \sigma_\delta(u - v)$ exists in $(0, +\infty]$ and $\lim_{\delta \rightarrow 1^-} \sigma_\delta(v - u) = -\lim_{\delta \rightarrow 1^-} \sigma_\delta(u - v) \in [-\infty, 0)$. So $u \succ_{\text{LDU}} v$.

Add: For all $u, v, \alpha \in \mathcal{U}$, $(u + \alpha) - (v + \alpha) = u - v$.

CP: Let $u \in \mathcal{U}$ have a well-defined average \bar{u} and let $c \in \mathbb{R}$. We show that the discounted sum of $d = u - (c, u) = (u_1 - c, u_2 - u_1, u_3 - u_2, \dots)$ satisfies

$$\lim_{\delta \rightarrow 1^-} \sigma_\delta(u - (c, u)) = \bar{u} - c. \quad (21)$$

By Frobenius's theorem, it suffices to show that the series $\sum_{t=1}^{\infty} d_t$ is Cesàro-summable to $\bar{u} - c$, i.e., that its partial sums $s_n = \sum_{t=1}^n d_t$ satisfy

$$\frac{s_1 + \dots + s_n}{n} \rightarrow \bar{u} - c \text{ as } n \rightarrow \infty.$$

But that is easy: the partial sum of the first $n \in \mathbb{N}$ terms is $s_n = u_n - c$, so

$$\frac{s_1 + \dots + s_n}{n} = \frac{u_1 + \dots + u_n}{n} - c.$$

Since \bar{u} exists by assumption, the right-hand side tends to $\bar{u} - c$ as $n \rightarrow \infty$. This proves (21). It follows that $(c, u) \sim_{\text{LDU}} u$ if $c = \bar{u}$.

For the second assertion of the theorem, let SWR \succsim satisfy SP, Add, and CP. Let $(u, v) \in \mathcal{D}$. If $d \equiv u - v$ is summable, the Total Utility property (Lemma 2 for both \succsim_{LDU} and \succsim) implies that $u \succsim v$ if and only if $u \succsim_{\text{LDU}} v$.

So assume that d is eventually periodic: there are $p, T \in \mathbb{N}$ with $d_{t+p} = d_t$ for all $t \geq T$. For all $t \geq T$, we then have $\bar{d} = \sum_{i=t+1}^{t+p} d_i / p$, i.e., $p\bar{d} = \sum_{i=t+1}^{t+p} d_i$.

Case 1: If $\bar{d} = 0$, then $\sum_{i=t+1}^{t+p} d_i = 0$ for all $t \geq T$. Then $s_n = \sum_{t=1}^n d_t$, $n \geq 1$, is eventually periodic, so that s is bounded and \bar{s} is well-defined. Since both \succsim_{LDU} and \succsim satisfy the conditions of Lemma 2,

$$u \succsim v \iff \bar{s} \geq 0 \iff u \succsim_{\text{LDU}} v.$$

Case 2: If $\bar{d} \neq 0$, let's suppose that $\bar{d} > 0$: the argument when $\bar{d} < 0$ is similar. We show that $u \succ v$ and $u \succ_{\text{LDU}} v$ both hold.

Since $d = u - v$ is bounded, there is an $M \in [0, \infty)$ such that $-M \leq d_t \leq M$ for all $t \in \mathbb{N}$. Then also $-M \leq \bar{d} \leq M$. Because $\bar{d} > 0$ implies $s_n \rightarrow +\infty$, we can choose $N \geq T$ with $s_N \geq 2pM$. We abbreviate $k \in \mathbb{N}$ consecutive zero coordinates by $\underline{0}_k$ and define

$$u' = u - (\underline{0}_N, p\bar{d}, \underline{0}_{p-1}, p\bar{d}, \underline{0}_{p-1}, p\bar{d}, \underline{0}_{p-1}, \dots).$$

Since $u - v$ and $(\underline{0}_N, p\bar{d}, \underline{0}_{p-1}, p\bar{d}, \underline{0}_{p-1}, p\bar{d}, \underline{0}_{p-1}, \dots)$ are eventually periodic with period p and average \bar{d} , stream $u' - v$ is eventually periodic with period p and average 0. Arguing as in Case 1, its sequence of partial sums $s'_n = \sum_{t=1}^n (u'_t - v_t)$, $n \geq 1$, is bounded, i.e., $s' = (s'_1, s'_2, \dots) \in \mathcal{U}$, and eventually periodic with period p . We claim that $s'_n \geq 0$ for all $n > N$. By periodicity, it suffices to show that $s'_{N+k} \geq 0$ for all $k = 1, \dots, p$. By construction,

$$s'_{N+k} = s_N - p\bar{d} - \sum_{m=1}^k (u_{N+m} - v_{N+m}) \geq 2pM - pM - kM \geq 0.$$

Since $s'_n \geq 0$ for all $n > N$, $\bar{s}' \geq 0$. By CP, $s' \sim (\bar{s}', s')$, so $s' \succsim (0, s')$ by SP. By Add, $u' \succsim v$. By SP, $u \succ u'$. By transitivity, $u \succ v$. Since \succsim_{LDU} also satisfies Add, SP, and CP, the same arguments show that $u \succ_{\text{LDU}} v$. □

A.3 Proof of Lemma 1

We prove Lemma 1 slightly more generally, for all real sequences $d = (d_1, d_2, \dots)$ whose discounted sum $\sigma_\delta(d)$ is well-defined for each $\delta \in (0, 1)$. Let $s_n = \sum_{t=1}^n d_t$, $n \in \mathbb{N}$. In (9), note that all upper/lower limits are well-defined in $\mathbb{R} \cup \{-\infty, +\infty\}$ and that the second inequality holds: all infima and suprema are taken over nonempty sets. The first inequality in (9) implies the third using a sign change: $\limsup_{\delta \rightarrow 1^-} \sigma_\delta(d) = -\liminf_{\delta \rightarrow 1^-} \sigma_\delta(-d)$, $\limsup_{n \rightarrow \infty} C_n(d) = -\liminf_{n \rightarrow \infty} C_n(-d)$. So it suffices to prove the first inequality:

$$\liminf_{n \rightarrow \infty} C_n(d) \leq \liminf_{\delta \rightarrow 1^-} \sigma_\delta(d).$$

Summation by parts, first for the sequence d and then for its partial sums, gives

$$\begin{aligned} \sum_{n=1}^{\infty} \delta^{n-1} d_n &= d_1 + \sum_{n=2}^{\infty} \delta^{n-1} (s_n - s_{n-1}) \\ &= (1 - \delta) \sum_{n=1}^{\infty} \delta^{n-1} s_n \\ &= (1 - \delta)^2 \sum_{n=1}^{\infty} \delta^{n-1} (s_1 + \dots + s_n). \end{aligned}$$

So, recalling from (7) that $C_n(d) = (s_1 + \dots + s_n)/n$, the discounted sum equals

$$\sigma_\delta(d) = \sum_{n=1}^{\infty} \delta^{n-1} d_n = (1 - \delta)^2 \sum_{n=1}^{\infty} \delta^{n-1} n C_n(d). \quad (22)$$

Distinguish three cases. Firstly, if $\liminf_{n \rightarrow \infty} C_n(d) = +\infty$, then (22) and the equality

$$\sum_{n=1}^{\infty} n \delta^{n-1} = \frac{1}{(1 - \delta)^2} \quad (23)$$

immediately give that also $\liminf_{\delta \rightarrow 1^-} \sigma_\delta(d) = +\infty$. Secondly, if $\liminf_{n \rightarrow \infty} C_n(d) = -\infty$, the inequality $\liminf_{n \rightarrow \infty} C_n(d) \leq \liminf_{\delta \rightarrow 1^-} \sigma_\delta(d)$ holds trivially, since both lower limits are well-defined. Finally, suppose that $\liminf_{n \rightarrow \infty} C_n(d)$ is finite. For $\lambda \in \mathbb{R}$, (22) and (23) give

$$\sum_{n=1}^{\infty} \delta^{n-1} d_n - \lambda = (1 - \delta^2) \sum_{n=1}^{\infty} \delta^{n-1} n (C_n(d) - \lambda).$$

Take $\lambda = \liminf_{n \rightarrow \infty} C_n(d)$. By definition of λ , for each $\varepsilon > 0$ there is a T such that $C_n(d) - \lambda \geq -\varepsilon$ for all $n > T$. Then

$$\begin{aligned} \sum_{n=1}^{\infty} \delta^{n-1} d_n - \lambda &\geq (1 - \delta^2) \sum_{n=1}^T \delta^{n-1} n (C_n(d) - \lambda) - \varepsilon (1 - \delta^2) \sum_{n=T+1}^{\infty} \delta^{n-1} n \\ &\geq (1 - \delta^2) \sum_{n=1}^T \delta^{n-1} n (C_n(d) - \lambda) - \varepsilon. \end{aligned} \quad (24)$$

The first term in (24) tends to 0 as $\delta \rightarrow 1^-$, so $\liminf_{\delta \rightarrow 1^-} \sigma_\delta(d) - \lambda \geq -\varepsilon$. Since $\varepsilon > 0$ was arbitrary, $\liminf_{\delta \rightarrow 1^-} \sigma_\delta(d) \geq \lambda = \liminf_{n \rightarrow \infty} C_n(d)$.

A.4 Proof of Theorem 2

TU: If $u - v$ is summable, then $\sum_{t=1}^{\infty} (u_t - v_t) = \lim_{\delta \rightarrow 1^-} \sigma_{\delta}(u - v)$ by Abel's theorem; cf. Duren (2012, p. 76). (An indirect proof is given by Lemma 2.)

Ano: If $v \in \mathcal{U}$ is obtained from $u \in \mathcal{U}$ by permuting two coordinates, then $\sum_{t=1}^{\infty} (u_t - v_t) = 0$. So Ano follows from TU.

Stat: For all $u, v \in \mathcal{U}$, $\liminf_{\delta \rightarrow 1^-} \sigma_{\delta}(u - v) = (u_1 - v_1) + \liminf_{\delta \rightarrow 1^-} \sigma_{\delta}((u_2, u_3, \dots) - (v_2, v_3, \dots))$.

Cont: Let $u, v \in \mathcal{U}$ and $N \in \mathbb{N}$ be such that $u_{[n]} \succ_{\text{LDU}} v_{[n]}$ for all $n \geq N$. Since $u_{[n]}$ and $v_{[n]}$ are summable, $s_n = \sum_{t=1}^n (u_t - v_t) > 0$ for all $n \geq N$ by TU. By Lemma 1, $\liminf_{\delta \rightarrow 1^-} \sigma_{\delta}(u - v) \geq 0$, i.e., $u \succsim_{\text{LDU}} v$.

A.5 Proof of Theorem 3

(i): Since \succsim_{LDU} satisfies SP, Ano, and Add, it extends \succsim_{BM} ; see Basu and Mitra (2007, Theorem 1) or Jonsson and Voorneveld (2015, Theorem 6).

(ii): By definition, \succsim_{G} weakly extends \succsim_{W} . To see that \succsim_{LDU} extends \succsim_{G} , let $u, v \in \mathcal{U}$ have $u \succsim_{\text{G}} v$: the partial sums $s_n = \sum_{t=1}^n (u_t - v_t)$ of $u - v$ satisfy $\liminf_{n \rightarrow \infty} s_n \geq 0$. Consequently,

$$\liminf_{n \rightarrow \infty} C_n(u - v) = \liminf_{n \rightarrow \infty} \frac{s_1 + \dots + s_n}{n} \geq 0.$$

By Lemma 1, also $\liminf_{\delta \rightarrow 1^-} \sigma_{\delta}(u - v) \geq 0$. That is, $u \succsim_{\text{LDU}} v$.

Finally, (iii) was illustrated in Example 1, and (iv) in Example 3.

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