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Oded Stark

Stressful Integration

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Abstract

This paper considers the integration of economies as a merger of populations. The premise is that the merger of groups of people alters their social landscape and their comparators. The paper identifies the effect of the merger on aggregate distress. A merger is shown to increase aggregate distress, measured as total relative deprivation: the social distress of a merged population is greater than the sum of the social distress of the constituent populations when apart. Physiological evidence from neighboring disciplines points to an increase in societal stress upon merger.

Keywords: Merger of populations; Revision of social space; Aggregate relative deprivation; Societal distress

JEL classification: D04; D63; F55; H53; P51

"A house may be large or small; as long as the surrounding houses are equally small, it satisfies all social demands for a dwelling. But if a palace arises beside the little house, the house shrinks into a hut." (Karl Marx, 1849, p. 33).

1. Introduction

We study the integration of economies, which we view as a merger of populations and the revision of social space and the comparison set. Specifically, we measure social distress by aggregate relative deprivation; and we show that (except in the special case in which the merged populations have identical income distributions) a merger increases aggregate relative deprivation. We refer to this result as "superadditivity."[1]

When populations merge, the social environment of the individuals who constitute the merged population changes: people who were previously outside the individuals' social domain are brought in. Mergers of populations occur in many spheres of life, at different times and places. They arise as a result of administrative considerations or naturally, they are imposed or chosen. Conquests bring hitherto disparate populations into one, provinces consolidate into regions, adjacent villages that experience population growth melt into one town, schools and school classes are joined, firms concentrate production from two plants in one, branches of a bank amalgamate, East Germany and West Germany become united Germany, European countries integrate. A typical driving force of integration is a presumption of economic gain.[2] With the help of specific examples, Stark (2010) and Stark et al. (2012b) raise the possibility that the revision of social space associated with the integration of societies can chip away at the sense of wellbeing of the societies involved. In the present paper we go beyond those specific examples and provide a generalized proof of this regularity. If, as we argue, integration brings in its wake social distress, then a compensating or higher economic gain is required to make integration desirable. Put differently, for economic integration to be worthwhile for the merged populations, the anticipated boost in productivity needs to be high enough to offset the strain on the individuals in the merged population.

[1] The superadditivity property and its proof reported in the present paper go beyond the examples displayed in Stark (2010) and in Stark et al. (2012b) and, as such, support the notion that the preliminary and specific findings reported in Stark (2010) and in Stark et al. (2012b) are robust, and more general.

[2] For a discussion from a macroeconomic perspective of the benefits from the integration of nations and regions, see Rivera-Batiz and Romer (1991). For empirical assessments of the economic consequences of European integration see, for example, Henrekson et al. (1997), and Beckfield (2009).

In Section 2 we present measures of individual and aggregate relative deprivation and we show that the aggregate relative deprivation of merged populations is larger than or equal to the sum of the pre-merger levels of the aggregate relative deprivation of the constituent populations (a superadditivity result). We are not aware of any dedicated study that sought to quantify social distress in two separate human populations, and subsequently in the merged population. However, experimental physiological evidence regarding mergers in groups of monkeys exists. The evidence is of an increase in social distress upon a merger. We present this evidence in Section 3. In Section 4 we provide discussion and conclusions. In the Appendix we present a brief account of the background and rationale of the measure of relative deprivation on which our analysis draws, and we provide a proof of the superadditivity claim.[3]

2. A measure of deprivation and the superadditivity of aggregate relative deprivation (*ARD*) with respect to the merger of two populations

We measure the distress of a population by the sum of the levels of distress experienced by the individuals who constitute the population. We refer to this sum as the aggregate relative deprivation (*ARD*) of the population. In our definition of relative deprivation we resort to income-based comparisons: an individual feels relatively deprived when others in his comparison group earn more than he does. To concentrate on essentials, we assume that the comparison group of each individual consists of all members of his population. Specifically, we measure the distress of an individual by the extra income units that others in the population have, we sum up these excesses, and we normalize by the size of the population. This procedure enables us to say, in alignment with intuition, that in a two-person population the distress of an individual earning 10 when another individual earns 14, which is $\frac{1}{2}(14-10)=2$, is greater than the distress that the individual experiences in a five-person population when each of the other four individuals earns 11, namely $\frac{1}{5}[4(11-10)]=\frac{4}{5}$, even though the total excess of incomes in each of these cases is the same. This approach tracks the seminal work of Runciman (1966) and its articulation by Yitzhaki (1979), and Hey and Lambert (1980); a detailed description is in the Appendix.

[3] In the Conclusions section we remark on the robustness of the superadditivity result to alternative specifications of relative deprivation.

Formally, for an ordered vector of incomes in population *P* of size n, $x=\left(x_1,...,x_n\right)$, where $x_1 \le x_2 \le ... \le x_n$, the relative deprivation of the *i*-th individual whose income is x_i, $i=1,2,...,n$, is defined as the weighted sum of the excesses of incomes higher than x_i such that each excess is weighted by its relative incidence, namely

$$RD\left(x_i,x\right) \equiv \frac{1}{n}\sum_{j=i+1}^{n}\left(x_j - x_i\right) \tag{1}$$

where it is understood that $RD\left(x_n,x\right)=0$. To ease the analysis that follows, an alternative representation of the relative deprivation measure is helpful.

Lemma 1. Let $F\left(x_i\right)$ be the fraction of those in the population *P* whose incomes are smaller than or equal to x_i. The relative deprivation of an individual earning x_i in population *P* with an income vector $x=\left(x_1,...,x_n\right)$ is equal to the fraction of those whose incomes are higher than x_i times their mean excess income, namely,

$$RD\left(x_i,x\right)=\left[1-F(x_i)\right]\cdot E\left(x_j - x_i \mid x_j > x_i\right). \tag{2}$$

Proof. We multiply $\frac{1}{n}$ in (1) by the number of the individuals who earn more than x_i, and we divide $\sum_{j=i+1}^{n}\left(x_j - x_i\right)$ in (1) by the same number. We then obtain two ratios: the first is the fraction of the population who earn more than the individual, namely $\left[1-F(x_i)\right]$; the second is mean excess income, namely $E\left(x_j - x_i \mid x_j > x_i\right)$. □

Lemma 1 highlights the difference between a low rank - an ordinal measure of distress - and our measure of relative deprivation: a given rank with a raised income of a higher-ranked individual does not change rank-based distress, but is associated with increased distress when measured by relative deprivation. In addition, even though when calculating relative deprivation comparisons are made with incomes “on the right,” events “on the left” do matter, as when the number of individuals with lower incomes changes, which in turn changes the fraction of those whose incomes are higher. In addition, it is trivial to show that the second term in (2) can be replaced by the excess over x_i of the mean income of those whose incomes are higher than x_i.

The aggregate relative deprivation is, in turn, the sum of the individual levels of relative deprivation

$$ARD(x) = \sum_{i=1}^{n} RD\left(x_i, x\right) = \sum_{i=1}^{n} \frac{\sum_{j=i+1}^{n}\left(x_j - x_i\right)}{n}. \tag{3}$$

$ARD(x)$ is our index of the level of "distress" of population *P*. (For several usages of this measure in recent related work, see Stark, 2010; Stark and Fan, 2011; Stark and Hyll, 2011; Fan and Stark, 2011; Stark et al., 2012a; and Stark et al., 2012b.)

We now consider two populations, P_1 and P_2, with ordered income vectors $x^1 = \left(x_i^1\right)$ and $x^2 = \left(x_i^2\right)$ of dimensions n_1 and n_2, respectively. Total population size is $n = n_1 + n_2$. The ordered income vector of the merged population is denoted $x^1 \circ x^2$, and is the *n*-dimensional income vector obtained by concatenating the two income vectors and ordering the resulting *n* components from lowest to highest.

The effect of a merger on aggregate relative deprivation, which changes from $ARD(x^1) + ARD(x^2)$ to $ARD\left(x^1 \circ x^2\right)$, is not intuitively obvious, even in simple cases. For example, assume that all the incomes of P_1 are lower than all the incomes of P_2 $(\max_i x_i^1 < \min_i x_i^2)$. Upon a merger, the relative deprivation of each member of P_1 increases, since both the fraction of those whose incomes are higher (the first term in Eq. (2)) and the mean excess incomes of those whose incomes are higher (the second term in Eq. (2)) increase after the merger. On the other hand, for each member of P_2 (except the one(s) with the highest income), the fraction of those whose incomes are higher decreases, and the mean excess income of those whose incomes are higher remains unchanged. As a result, the relative deprivation of each member of P_2 (except the one(s) with the highest income) decreases. In other words, the merger has caused an increase in the aggregate relative deprivation for members of one population and a decrease in the aggregate relative deprivation for members of the other population. It is therefore impossible to intuitively sign the difference between $ARD\left(x^1 \circ x^2\right)$ and $ARD\left(x^1\right) + ARD\left(x^2\right)$.[4]

[4] In a setting in which others could only bring negative externalities, a smaller population will always experience less aggregate relative deprivation. But in a setting such as ours when others joining in can confer both negative externalities and positive externalities, it is impossible to determine without proof whether the expansion of a

In the following claim we state and prove that the difference $ARD\left(x^1 \circ x^2\right) - ARD\left(x^1\right) - ARD\left(x^2\right)$ is in fact non-negative: a merger increases aggregate relative deprivation or leaves it unchanged. Namely, if we conceptualize the merger as an addition operation, then *ARD* is a superadditive function of the income vectors. (A function *H* is superadditive if for all *x*, *y* it satisfies $H(x+y) - H(x) - H(y) \geq 0$.)

Claim 1. Let P_1 and P_2 be two populations with ordered income vectors x^1 and x^2, and let $x^1 \circ x^2$ be the ordered vector of merged incomes. Then

$$ARD\left(x^1 \circ x^2\right) - ARD\left(x^1\right) - ARD\left(x^2\right) \geq 0 .$$

Proof. See the Appendix.

Because throughout we have kept incomes unchanged, the incomes of the members of a constituent population are not affected by its merger with another population: in our setting, a merger changes the social comparisons space that governs the sensing and calculation of relative income (relative deprivation), but it leaves absolute incomes intact. If we assume that individuals' wellbeing depends positively on absolute income and negatively on relative deprivation, a merger leads to deterioration in the aggregate wellbeing of at least one of the merged populations.

3. Physiological evidence

Considerable research has been done on the measurement of stress via the hormone cortisol that is secreted while under stress, and that can be measured in saliva or blood. For example, it emerges that chronic stress affects the neural system, and in turn the immune system. When stressed, people are more prone to depression and anxiety, and more likely to develop a host of bodily ills including heart disease, obesity, drug addiction, liability to infection, and rapid aging (Wilkinson and Pickett, 2009). At the societal level, when incomes are relatively equal, the level of stress is lower (Wilkinson and Pickett, 2009).

In the preceding section we identified a social-psychological source of societal stress. Can the "superadditivity result" be measured empirically through the device of cortisol

population will entail a reduction in aggregate relative deprivation or an increase. To see the variation in the externality repercussion even more starkly, note that when 3 joins 1 and 1, he confers a negative externality on the incumbents; when 3 joins 5 and 5, he confers neither a negative externality nor a positive externality on the incumbents; and when 3 joins 4 and 5, he confers a positive externality on incumbent 4.

concentrations? Whereas direct experimental evidence for humans is hard to generate and thus far non-existent, there is evidence regarding mergers in groups of monkeys. To begin with, evidence suggests that dominant monkeys (those above the median in social rank) typically have greater control over resources; subordinate monkeys often experience a shortage of resources, fewer coping strategies, and reproductive impairment (Czoty et al. (2009), and references provided therein). There are physiological and neurobiological differences between dominant and subordinate monkeys. Animals that are more socially stressed by the dominance of other animals exhibit a higher level of physiological stress as measured, for example, by cortisol (Sapolsky, 2005). Studies have revealed that the extent to which different monkeys in such hierarchies experience stress varies widely according to the particulars of the social structure, including the stability of hierarchies (Czoty et al. (2009), and references provided therein). Thus, we could consider two separate groups of monkeys. Suppose that for each group, blood or saliva samples are taken and cortisol concentration levels are recorded. Suppose that very soon after a merger of the two groups, cortisol concentration values are recorded again. Our hypothesis would be that the ensuing reshuffle of social rankings, with the original rankings of dominant and subordinate animals undergoing revision, results in an increase in the aggregate level of cortisol concentration. This will arise because, as the "superadditivity result" suggests, the overall extent of added subordination is greater than the overall extent of reduced subordination. If, however, a decrease in aggregate level of cortisol concentration is to be recorded, then our hypothesis will be rebuffed. So far, we could not identify studies that have followed this experimental protocol strictly.

Evidence that appears to come close to what we would ideally like to have is to be found in a study by Shively and Clarkson (1994). An experiment involving 42 female macaque monkeys sought to measure the physiological ramifications of subordination, given the background evidence that socially subordinate females are stressed, as exhibited, for example, by their adrenal glands hyper-secreting cortisol. It was hypothesized that since social subordination causes stress, a change in social status will result in a change in stress level. If dominants became subordinates, increased stress would be expected, whereas if subordinates became dominants, decreased stress would be expected. The experiment involved a reshuffling (alas, not merging) of the groups of four into which the monkeys were distributed initially, such that subordination and dominance changed. The results were quite powerful: among initially dominant females, those that became subordinate had 500% higher level of a measure of stress than those that did not change social status. Thus, females that changed social status had heightened stress, with those that were initially dominant and became subordinate being most deleteriously affected.

Using a different methodology, Tung et al. (2012) also found a strong physiological link between social status and stress. Tung et al. (2012) conducted an experiment involving 49 female macaque monkeys, divided initially into 10 groups. Social status was manipulated by the order in which a female was introduced into a social group, given the empirically established fact that earlier introduction confers a higher rank. Yet, seven females changed ranks within their groups; although rank hierarchies tend to be stable, ranks sometimes change, particularly on the replacement of individuals within a group. Using a procedure in which subordinance and dominance were experimentally assigned, Tung et al. (2012) tested for association between social rank and gene regulation. The underlying research question was whether subordinance (the change from higher to lower social status) triggers a physiological response (stress). Out of 6,097 genes considered in each female, about 16% were rank-associated genes. Here too, as in the Shively and Clarkson (1994) experiment, the results were quite powerful: changes in social status mapped onto gene expression of rank-related genes such that lower status resulted in greater stress and immune compromise. In addition, the Tung et al. (2012) experiment revealed that the physiological repercussions associated with social rank changed rapidly when social rank was revised.

In sum, experiments investigating primates suggest that the merger of populations brings in its wake an increase of social distress.

4. Discussion and conclusions

Processes and policies that integrate economic entities also revise the social landscape of the people who populate the entities. We have considered the case in which the form that the revision takes is an expansion - be it the result of closer proximity to others, more intensive social interactions, or reduced barriers to the flow of information. We have argued that a consequence of the changing social milieu casts a shadow on the anticipated economic gains. It is no surprise then that following the fall of the Berlin wall, East Germans did not report increase in subjective wellbeing, despite the powerful positive income (wealth) effect arising from conversion of their nearly useless East German Mark at a one-to-one rate with the mighty West German Deutschmark. There were no language, travel, or media access restrictions to prevent the political unification being accompanied by a redrawing of the social borders.[5]

An increase in aggregate relative deprivation is a downside to the integration of economies. It puts a strain on the individuals in the merged population, casting a shadow over the production and trade (scale and scope) benefits anticipated from integration. An increase in relative deprivation can itself cause an adverse physiological reaction such as psychosomatic stress, and could lead to social unrest and a collective response in the form of public protest.

Although we have deliberately excluded from this paper a discussion of the possible responses of individuals to higher relative deprivation, it is worth mentioning that one possible response could be to work harder (cf. Stark and Hyll, 2011). For example, in the case of the merger of populations P_1 and P_2 with income vectors $x^1 = (1, 2)$ and $x^2 = (3, 4)$, individual "2" would end up sensing no higher relative deprivation than prior to the merger if he were to earn two additional units of income, and individual "1" would likewise end up sensing no higher relative deprivation than prior to the merger if he were to earn two additional units of income (that is, once individual "2" earns 4 units of income). These additional income units could be obtained by putting in more work effort. However, our main argument that merger damages wellbeing could still stand if the additional effort put in by individuals "2" and "1," which was considered not worth the gain in income prior to the merger, taxes more than the income gain rewards.

Our analysis is essentially of the "comparative statics" type, with the revision of the social landscape occurring at the time of the merger, and the expected increase in incomes in the wake of the merger yet to come. Introducing dynamics need not erode our main argument, however. The revision of the comparison group could be gradual and coincide with the processes of scale economies and scope economies taking hold. Still, as long as the latter processes do not result in sufficient convergence of incomes, the former process could still damage the post-merger sense of wellbeing.

[5] Easterlin and Plagnol (2008) report that the life satisfaction of East Germans declined sharply after the 1991 unification, thereafter gradually recovered, but not enough - even at the 1999 post-unification satisfaction peak - to reach the 1990 level. This account is in line with the perspective that East Germans experienced the full brunt of relative deprivation right after unification, and that the subsequent increase in their absolute incomes was still not enough to offset the deleterious effect of relative deprivation from comparing themselves with the wealthier West Germans.

We did not differentiate individuals by their distaste for relative deprivation. In some contexts, the assumption of uniformity in preferences is inadequate. Revisiting again the example of the reunification of Germany, several studies have shown that the taste for equal income distribution is significantly stronger for East Germans than for West Germans, in a large part because living under communism shaped preferences in a distinct manner (Corneo, 2001; Alesina and Fuchs-Schündeln, 2007). Then, in a merger such as that of the East German population with the West German population, the increase in aggregate relative deprivation will be greater than was postulated throughout the current paper.

The "superadditivity result" that we derived in this paper (Claim 1) is for a specific measure of a population's aggregate relative deprivation (Eq. (3)). Recalling the discussion in Section 2, the appeal of this measure is that it emanates from a solid social-psychological foundation, it rests on a sound axiomatic basis, and it was shown to be empirically significant (cf. the Appendix). Still, a population's aggregate relative deprivation could be measured in a variety of ways and by different indices. For example, it is easy to show that the "superadditivity result" is robust with respect to two other measures (specifications) of relative deprivation: the aggregate of the excesses of incomes, and the distance from the highest income in the population. The proofs are in the Appendix.

Finally, the superadditivity property could be considered as an axiom of deprivation indices. In this case, incorporating this axiom in the characterization of these indices could yield insights about deprivation, and lead to a new class of deprivation indices.

Appendix

A brief foray into relative deprivation

Our analysis is based on the sociological-psychological concepts of relative deprivation and reference groups, which are fitting tools for studying comparisons that affect an individual's behavior, in this case comparisons with related individuals whose incomes are higher than his own income (cf. the large literature spanning from Duesenberry, 1949, up to, for example, Clark, Frijters, and Shields, 2008). An individual has an unpleasant sense of being relatively deprived when lacking a desired good and perceiving others in his reference group as possessing that good (Runciman, 1966).[6] Given the income distribution of the individual's reference group, the individual's relative deprivation is the sum of the deprivation caused by every income unit that he lacks (Yitzhaki, 1979; Hey and Lambert, 1980; Ebert and Moyes, 2000; Bossert and D'Ambrosio, 2006; and Stark and Hyll, 2011). Frank (1985) argues that the concern for status shapes our view of public policy and the nature of government itself. He offers a status-driven explanation of observed consumption patterns, alluding in particular to the tendency of people (especially at low income levels) to invest too little in safety and insurance, and too much in positional goods, namely goods of a value that depends on how they compare with what is owned by others. In a sense, such behavior is a coping mechanism aimed at reducing relative deprivation.

The pioneering study in modern times that opened the flood gate to research on relative deprivation and reference groups is the 1949 two-volume set of Stouffer et al. *Studies in Social Psychology in World War II: The American Soldier.* The research of Stouffer et al. was followed by a large social-psychological literature (several references are provided below). Economics has caught up relatively late, and only somewhat. This is rather surprising because eminent economists in the past understood well that people compare themselves to others around them, and that social comparisons are of paramount importance for individuals' happiness, motivations, and actions. Even Adam Smith (1776, p. 465) pointed to the social aspects of the necessities of life, and stressed the *relative* nature of poverty. Karl Marx's (1849, p. 33) noted the social nature of utility, and the impact of an individual's relative position on his satisfaction. Paul Samuelson (1973, p. 218), one of the founders of modern neoclassical economics, pointed out that an individual's utility depends on what he consumes in relation to what others consume.

[6] In Runciman's (1966) theory of *RD*, an individual's reference group is the group of individuals with whom the individual compares himself (cf. Singer, 1981).

Modern-day evidence from econometric studies, experimental economics, social psychology, and neuroscience indicates that humans routinely compare themselves with other individuals who constitute their "comparison" or "reference" group, and that the outcome of that engagement impinges on their sense of wellbeing. Consequently, economic processes are impacted, and economic realizations differ from what they would have been had comparisons with others not mattered. Using a large data set collected as part of the European Social Survey, Clark and Senik (2010) find that income comparisons are acknowledged as at least somewhat important by a majority of Europeans; are mostly upward; and are associated with lower levels of happiness. Matching data on local earnings with data from the National Survey of Families and Households, Luttmer (2005) finds that higher earnings of neighbors are associated with lower levels of self-reported happiness in the US.

The relative income hypothesis, formulated by Duesenberry (1949), posits that the individual looks upward when making comparisons,[7] and is related to Thorstein Veblen's (1899) concept of *pecuniary emulation*.

The *theoretical possibility* that behavior is modulated by individuals deriving satisfaction from looking down does not appear to have much of a basis. Andolfatto (2002) shows that while the utility of an individual rises in his own consumption, it declines in the consumption of any of his neighbors if that consumption falls below some minimal level; individuals are adversely affected by the material wellbeing of others in their reference group when this wellbeing is sufficiently lower than theirs. Frey and Stutzer (2002) and Walker and Smith (2002) marshaled a large body of evidence that overwhelmingly supports the "upward comparison" view.

To incorporate the distaste for low relative income in individuals' preferences, it is necessary to quantify this distaste, and to revise the received utility characterization of individuals' preferences. Runciman (1966, p. 19) writes as follows: "The more people a man sees promoted when he is not promoted himself, the more people he may compare himself with in a situation where the comparison will make him feel deprived," implying that the deprivation from not having income x is an increasing function of the fraction of people in the reference group who have x.

[7] The empirical findings support the relative income hypothesis. Duesenberry (1949) found that individuals' savings rates depend on their positions in the income distribution, and that the incomes of the richer people affect the behavior of the poorer ones (but not *vice versa*). Schor (1998) showed that, keeping annual and permanent income constant, the individuals whose incomes are lower than the incomes of others in their community saved significantly less than those who are relatively better off in their community.

Whether we draw on the axiomatic representations of Ebert and Moyes (2000) and Bossert and D'Ambrosio (2006) or on the social-psychological literature (notably Runciman, 1966), we end with the measure of relative deprivation that we have employed in the body of this paper. For several usages of this measure in recent related work see Stark (2010), Stark and Fan (2011), Stark and Hyll (2011), Fan and Stark (2011), Stark et al. (2012a), and Stark et al. (2012b).

Proof of Claim 1. We first show that the double sum in the definition of the aggregate relative deprivation (Eq. (3)) can be reduced to a single sum.

Proposition 1. For an ordered income vector $x=\left(x_i\right)$, we have

$$ARD(x)=\sum_{i=1}^{n}a(i,n)x_i \tag{A1}$$

where

$$a(i,n)=\frac{2i-1-n}{n} \tag{A2}$$

and

$$\sum_{i=1}^{k}a(i,n)=k\left(\frac{k}{n}-1\right),\ \mathrm{k}=1,2,...,n. \tag{A3}$$

Proof. From Eq. (3) we have that

$$\begin{aligned}
nARD(x) &= \sum_{i=1}^{n}\sum_{j=i+1}^{n}\left(x_j-x_i\right)\\
&= \sum_{i=1}^{n}\sum_{j=i+1}^{n}x_j-\sum_{i=1}^{n}\sum_{j=i+1}^{n}x_i\\
&= \sum_{i=1}^{n}(i-1)x_i-\sum_{i=1}^{n}(n-i)x_i\\
&= \sum_{i=1}^{n}(2i-1-n)x_i
\end{aligned}$$

which is equivalent to Eq. (A1). Equation (A3) follows trivially from the definition of $a(\mathrm{i},n)$ in Eq. (A2). □

Before proceeding, we introduce a notation that will be used to denote the connection between the ordering of the concatenated income vector and the ordering of the income vectors of the populations when apart.

As $x^1 = \left(x_1^1, ..., x_{n_1}^1\right)$ and $x^2 = \left(x_1^2, ..., x_{n_2}^2\right)$ are the ordered income vectors of the merged populations, we write the ordered income vector of the resultant population as

$$x^1 \circ x^2 = \left(x_{\nu(1)}^{\varphi(1)}, x_{\nu(2)}^{\varphi(2)}, ..., x_{\nu(n)}^{\varphi(n)}\right),$$

where $n = n_1 + n_2$, $\varphi(k)$ is 1 (or 2) if the *k*-th overall smallest income belonging to population P_1 (or P_2), and $\nu(k)$ is the rank (from smallest to largest) within $P_{\varphi(k)}$ of this *k*-th overall smallest income.

Because $x_{\nu(1)}^{\varphi(1)}$ is the smallest income in the merged population we have that

$$\left(\varphi(1), \nu(1)\right) = \begin{cases} (1,1) \text{ if } x_1^1 \le x_1^2 \\ (2,1) \text{ otherwise.} \end{cases}$$

We define

$$\sigma(k) \equiv \sum_{i=1}^{k} \varphi\left(i\right) - k,$$

which is the number of incomes from P_2 among the first *k* incomes of the merged population. For example, $\sigma(1) = 0$ if $\varphi(1) = 1$, and $\sigma(1) = 1$ if $\varphi(1) = 2$. With this notation, the first k incomes of the merged population are made up of $k - \sigma(k)$ incomes from P_1, and of $\sigma(k)$ incomes from P_2. The $\nu(k+1)$'s and $\varphi(k+1)$'s are therefore defined recursively as

$$\left(\varphi(k+1), \nu(k+1)\right) \equiv \begin{cases} \left(1, k+1-\sigma(k)\right) \text{ if } x_{k+1-\sigma(k)}^1 \le x_{\sigma(k)+1}^2 \\ \left(2, \sigma(k)+1\right) \text{ otherwise.} \end{cases}$$

We define for $k = 1, 2, ..., n$ the number $h_l(k)$ of incomes in the *l*-th population ($l = 1, 2$) that are less than or equal to $x_{\nu(k)}^{\varphi(k)}$, the *k*-th lowest income in the merged population. We note that $h_1(k) + h_2(k) = k$.

We now prove the superadditivity result by providing a non-negative closed-form expression for $ARD\left(x^1 \circ x^2\right) - ARD\left(x^1\right) - ARD\left(x^2\right)$; that is, we show that

$$ARD\left(x^1 \circ x^2\right) - ARD\left(x^1\right) - ARD\left(x^2\right) = \Phi$$

where

$$\Phi = \sum_{j=1}^{n-1}\left(x_{\nu(j+1)}^{\varphi(j+1)} - x_{\nu(j)}^{\varphi(j)}\right)\frac{\left(n_1 h_2(j) - n_2 h_1(j)\right)^2}{n n_1 n_2} \geq 0.$$

Using Eq. (A1) we have that

$$\begin{aligned} &ARD\left(x^1 \circ x^2\right) - ARD\left(x^1\right) - ARD\left(x^2\right) = \sum_{k=1}^{n} a\left(k,n\right) x_{\nu(k)}^{\varphi(k)} \\ &-\sum_{m=1}^{n_1} a\left(m,n_1\right) x_m^1 - \sum_{p=1}^{n_2} a\left(p,n_2\right) x_p^2 = \sum_{k=1}^{n} b(k) x_{\nu(k)}^{\varphi(k)}, \end{aligned} \tag{A4}$$

where

$$b(k) = a\left(k,n\right) - a\left(\nu(k), n_{\varphi(k)}\right).$$

The partial sums $z(q) = \sum_{k=1}^{q} b(k)$ are

$$z(q) = \sum_{k=1}^{q} a\left(k,n\right) - \sum_{k=1}^{h_1(q)} a\left(k,n_1\right) - \sum_{k=1}^{h_2(q)} a\left(k,n_2\right).$$

We use Eq. (A3), $q = h_1(q) + h_2(q)$, and $n = n_1 + n_2$ to obtain

$$\begin{aligned} z(q) &= q\left(\frac{q}{n} - 1\right) - h_1(q)\left(\frac{h_1(q)}{n_1} - 1\right) - h_2(q)\left(\frac{h_2(q)}{n_2} - 1\right) \\ &= -\frac{\left(n_1 h_2(q) - n_2 h_1(q)\right)^2}{n n_1 n_2}. \end{aligned}$$

We note that $z(n) = \sum_{k=1}^{n} b(k) = 0$ because $h_1(n) = n_1$ and $h_2(n) = n_2$.

If we define the non-negative sequence $d(k)$, $k = 1, 2, \ldots, n,$ as

$$d(1) \equiv x_{\nu(1)}^{\varphi(1)},\ d(k) \equiv x_{\nu(k)}^{\varphi(k)} - x_{\nu(k-1)}^{\varphi(k-1)},\ k = 2, 3, \ldots, n$$

we have that

$$x_{\nu(k)}^{\varphi(k)} = \sum_{j=1}^{k} d(j),\ k = 1, 2, \ldots, n.$$

Bearing in mind that $\sum_{k=1}^{n} b(k)=0$ we return to Eq. (A4) and conclude that

$$\begin{aligned}\sum_{k=1}^{n} x_{\nu(k)}^{\varphi(k)} b(k) &= \sum_{k=1}^{n}\sum_{j=1}^{k} d(j)b(k) \\ &= \sum_{j=1}^{n} d(j)\sum_{k=j}^{n} b(k)\end{aligned}$$

$$\begin{aligned}&= \sum_{j=2}^{n} d(j)\left(\sum_{k=1}^{n} b(k) - \sum_{k=1}^{j-1} b(k)\right) \\ &= -\sum_{j=2}^{n} d(j) z(j-1) \\ &= \sum_{j=1}^{n-1}\left(x_{\nu(j+1)}^{\varphi(j+1)} - x_{\nu(j)}^{\varphi(j)}\right)\frac{\left(n_1 h_2(j) - n_2 h_1(j)\right)^2}{n n_1 n_2} \\ &= \Phi \geq 0,\end{aligned}$$

which completes the proof of the claim. □

Superadditivity when relative deprivation is the aggregate of the excesses of incomes

For an ordered vector of incomes in population P_1 of size n_1, $x^1=\left(x_1^1,...,x_{n_1}^1\right)$, where $x_1^1 \leq x_2^1 \leq ... \leq x_{n_1}^1$, let the relative deprivation of the individual with income x_i^1, $i=1,2,...,n_1$, be defined as

$$RD'\left(x_i^1, x^1\right) \equiv \sum_{k=i+1}^{n_1}\left(x_k^1 - x_i^1\right).$$

Then, the aggregate relative deprivation of population P_1, as the sum of the excesses of incomes, is

$$ARD'\left(x^1\right) \equiv \sum_{i=1}^{n_1-1} RD'\left(x_i^1, x^1\right) = \sum_{i=1}^{n_1-1}\sum_{k=i+1}^{n_1}\left(x_k^1 - x_i^1\right).$$

Or, equivalently

$$ARD'\left(x^1\right) = \sum_{i=1}^{n_1-1}\sum_{k=i+1}^{n_1}\left(x_k^1 - x_i^1\right) = \frac{1}{2}\sum_{i=1}^{n_1}\sum_{k=1}^{n_1}\left|x_k^1 - x_i^1\right|.$$

When a second population, P_2, with incomes $x^2=\left(x_1^2,...,x_{n_2}^2\right)$, merges with population P_1, we derive the superadditivity result once again.

Claim A1. $ARD'\left(x^1 \circ x^2\right) \geq ARD'\left(x^1\right) + ARD'\left(x^2\right)$.

Proof. We have that

$$ARD'\left(x^1 \circ x^2\right) = \frac{1}{2}\left[\sum_{i=1}^{n_1}\sum_{j=1}^{n_1}\left|x_j^1 - x_i^1\right| + \sum_{k=1}^{n_2}\sum_{l=1}^{n_2}\left|x_l^2 - x_k^2\right|\right] + \sum_{i=1}^{n_1}\sum_{k=1}^{n_2}\left|x_k^2 - x_i^1\right|.$$

Noting that $\frac{1}{2}\sum_{i=1}^{n_1}\sum_{j=1}^{n_1}\left|x_j^1 - x_i^1\right| = ARD'\left(x^1\right)$, that $\frac{1}{2}\sum_{k=1}^{n_2}\sum_{l=1}^{n_2}\left|x_l^2 - x_k^2\right| = ARD'\left(x^2\right)$, and that $\sum_{i=1}^{n_1}\sum_{k=1}^{n_2}\left|x_k^2 - x_i^1\right| \geq 0$, completes the proof. □

Superadditivity when relative deprivation is the distance from the highest income

In population P_1, let the relative deprivation of an individual with income x_i^1, $i = 1,2,...,n_1$, be defined as

$$RD''\left(x_i^1, x^1\right) \equiv \hat{x}^1 - x_i^1,$$

where $\hat{x}^1 = \max\left\{x_1^1,...,x_{n_1}^1\right\}$. The aggregate relative deprivation of population P_1, measured as the aggregate of the distances from the highest income, is

$$ARD''\left(x^1\right) \equiv \sum_{i=1}^{n_1}\left(\hat{x}^1 - x_i^1\right).$$

When a second population, P_2, the total relative deprivation of which is measured in the same way as that of population P_1, merges with population P_1, we obtain the superadditivity result once again. The reasoning is straightforward. Unless the two populations have each the same highest income, a merger results in exposure of members of one of the populations to a higher post-merger highest income, while members of the other population continue to be exposed to the same highest income as prior to the merger. Thus, the aggregated distances from the highest income in the merged population will not be less than the sum of the corresponding distances in the constituent populations when apart. For the sake of completeness, we state this result in the following claim.

Claim A2. $ARD''\left(x^1 \circ x^2\right) \geq ARD''\left(x^1\right) + ARD''\left(x^2\right)$.

Proof. The proof is contained in the preceding discussion. □

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