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Exploring early age mortality through higher order Gini indices

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Abstract

Advancements in modern medicine have significantly prolonged human life, thereby raising the expected age at which mortality occurs. Moreover, people are generally dying closer to the mean age of mortality. In our paper we extend the previous studies on measurements of human mortality by proposing the implementation of the higher-order Gini indices to gauge the early-age mortality levels. We will show that the higher-order Gini indices, along with certain derived metrics, provide useful measures of early-age mortality. We also present historical results, data analyzed over time, for selected countries.

Key words: human lifespan, higher-order Gini indices, Lorenz curve, early-age mortality.

1. Introduction and Previous Studies

There is an extensive body of literature on the Gini Index and its application to assess inequalities in human lifespan. The study, Llorca(2000), develops a formal demographic derivation of the Gini coefficient of age of death distributions, establishing a direct framework for quantifying inequality. In a global context, the paper Smits(2009) shows that the lifespan inequality varies significantly across populations even when life expectancy is similar. Further demographic research confirms that Gini-based measures are widely used to study variability in age-at-death distributions, showing differences across populations and time periods.

Large-scale studies using global mortality datasets document cross-country variation in lifespan inequality beyond differences in life expectancy alone, see Jorda(2024). Comparative mortality analyses similarly show that populations with similar lifespan may still exhibit distinct age at death structures, reinforcing the importance of distribution-sensitive approaches, see Seaman(2016).

Despite this extensive literature, existing approaches primarily focus on summarizing age-at-death distributions and do not explicitly isolate the intensity of early-age mortality within the inequality structure. As a result, the standard Gini-based measure may underrepresent the contribution of infant mortality to overall lifespan inequality, particularly in settings where early deaths contribute a significant share of total mortality. Early-age mortality in this study refers to deaths occurring at various age categories during specific timeframes.

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These stages are demographically and epidemiologically distinct from adult mortality, as they are more strongly influenced by health-system access, poverty levels, wealth and income distributions in society, and other environmental factors. The standard Gini Index assigns equal weight across all ages and therefore does not explicitly distinguish premature deaths from deaths occurring at older ages, see Ramos(2018).

To address this limitation, this paper contributes by introducing higher-order Gini indices as an extension of the classical framework. These indices take into account the lower age-at-death distribution, increasing sensitivity to early-age mortality while preserving the foundation of inequality measurement. In doing so, the approach provides a refined tool that captures not only overall lifespan inequality but also the intensity and structure of premature mortality within populations.

2. Some Measurements of Premature Mortality

Various diverse methods are being implemented to assess the level of premature mortality in a society. One can measure the infant mortality rate (or under the age 5 mortality rate), another option is the life expectancy at birth. The Years of Potential Life Lost, YPLL, is defined as $\text{YPLL} = \sum_n (R - x_n)$. Here, R is some fixed chosen reference age (typically set to 75 years). The value x_n is the age at death for each person. Only deaths before the reference age are counted. For example, for somebody that dies at 40 years of age the contribution to YPLL is $75 - 40 = 30$ years.

Another widely used metric, the Years of Life Lost YLL, is geared to assess the premature mortality in a society. Here, we have $\text{YLL} = \sum_n D(n)L(n)$ where $D(n)$ is the number of deaths at the age n and $L(n)$ is the remaining life expectancy at the age n. For example, if there are 10 deaths at the age of 70 years and the life expectancy for a 70-year-old is 85 years then the addition to the YYL value is $(10)(85-70) = 150$ years. For more on this subject we refer the reader to Martinez(2019). The metric Years of Life Lost is closely related to Keyfitz entropy, see Keyfitz(2005).

3. Gini Index and Lifespan Inequality

The Gini Index is most commonly associated with wealth distribution. In economic discussions Gini reports detail the distribution of wealth in societies. A Gini Index of zero signifies perfect equality where everyone possesses an equal amount of wealth. Conversely, as the Gini Index approaches one, a greater proportion of the population tends to hold a lower percentage of the total wealth, indicating increasing inequality. The Gini Index can also be applied to analyze the distribution of lifespans within a society. In this context we equate wealth with the length of people's lives. A Gini Index of zero would mean that everyone lives until the same age, which coincides with the mean expected lifespan.

Conversely, as the Gini Index approaches one it suggests that despite having possibly the same expected lifespan, people are dying at increasingly varied ages. The length of a person's life is now considered to be the wealth. Hence, the collective wealth of a society is construed as the aggregate of all ages of the deceased individuals. The division of this

wealth held among the proportion of people is given by the Lorenz curve. The Gini Index is then computed from the difference between the Lorenz curve and the perfect line of equality.

A statistic closely related to the Gini Index is the Gini Mean Difference, Yitzhaki(1998). Conceptually, the Gini Mean Difference measures the anticipated disparity between the ages of two randomly selected deceased individuals. If the Gini Mean Difference is calculated prior, the Gini Index can be obtained by dividing the Gini Mean Difference by twice the expected lifespan. Equivalently, the Gini Index measures the expected difference in the ages of two random deaths in proportion to the expected lifespan, which is then divided by two.

We explain the implications of a Gini Index value of $G = 0.125$. Consider a society where the expected lifespan is 80 years with the Gini Mean Difference of 20 years. This signifies that if two random deaths are selected in this society, the anticipated age difference between the deceased is 20 years. The Gini Index of 0.125 can thus be interpreted as the ratio of 20 to 80, divided by two. Now, envision a parallel society with an expected lifespan of only 60 years. In such a scenario, the same Gini Index of 0.125 would result in a Gini Mean Difference of only 15 years.

An interesting interpretation of the Gini Index can be found in Farris(2010). Suppose we collect the ages of two random deaths in a society and then record the lower one. It turns out that the expected value for the lower age is given by

$$Y_2 = (1-G)\,\mu$$

where μ is the expected lifespan. The anticipated decline for the younger of the two randomly selected ages is μG. It is important to realize that the expected lifespan in our analysis is not the same as the life expectancy.

4. The Lorenz Curve

Assume X is a non-negative continuous random variable with the distribution function $F(x)$. Here, $F(x)$ is the proportion of the population holding at most x units of the quantity of interest, in our setting, it is the age at dying. We define the substitution

$$p = F(x)\ ;\ dp = f(x)\,dx\ ;\ x = F^{-1}(p)\ ;\ \frac{dL}{dp} = s(p) = \frac{x}{\mu}$$

where

$$\mu = \int_0^\infty x f(x)\,dx$$

is the expected lifespan. The Lorenz function is defined as

$$L(p) = \frac{1}{\mu}\int_0^{F^{-1}(p)} t f(t)\,dt$$

and its graph is referred to as the Lorenz curve. In the context of the Lorenz curve there is a notion of the Gini Index. It is defined as

$$G = 2\int_0^1 p - L(p)\,dp$$

understood as twice the area between the curves $y = p$ and $y = L(p)$. The Gini Index can be interpreted via the Gini Mean Difference, which is defined as

$$\begin{aligned} GMD &= E\left(|X_1 - X_2|\right) \\ &= \int_0^\infty \int_0^\infty |x_1 - x_2| f(x_2) f(x_1)\,dx_2\,dx_1 \end{aligned}$$

It can be shown that $GMD = 2\mu G$. The maximum value for the Gini Mean Difference is 2μ, since the maximum value for the Gini Index is one. Thus, one can think of the Gini Index as the Gini Mean Difference as a ratio to its maximum possible attainable value. For more details, the reader can see La Haye, Zizler (2020).

5. Higher Order Ginis and Early-Age Mortality

We now introduce the higher-order Gini Indices, and its further derived metrics, into the lifespan inequality discussion. This will further expand the existing literature by strengthening its theoretical aspects. Higher-order Gini Indices will help to detect mortality at early ages. We will be able to detect societies and regions, currently and overtime, with an index reflecting early-age mortality as opposed to mortalities at later stages of life. In particular, we introduce the higher-order Gini Indices G_k that have been utilized in identifying instances of extreme poverty in a society. If we set $k = 2$ we define

$$G_2 = 6\int_0^1 (p - L(p))\,(1-p)\,dp$$

For small values of p the weight is close to one, thus detecting more early-age deaths. For p values close to one the weight is diminishing, as desired.

Similar to the case of the Gini Index G, there is an intuitive approach to understanding the higher-order Gini Index G_2. Consider a society in which three random deaths have been documented. We focus on the minimum age among these three mortalities and seek its expected value, denoted as Y_3. This represents the anticipated value of the lowest age among the three randomly selected ages at death. In Farris(2010), it was shown that

$$Y_3 = (1 - G_2)\,\mu$$

In particular, the expected drop for the lowest age of the three random deaths is given by μG_2. Clearly, we must have

$$G_2 \geq G$$

To generalize we take the expectation of the lowest of the k ages of the k random deaths

and denote it by Y_k. This is the expected value of the lowest of the k random ages at death. We get

$$Y_k = (1 - G_{k-1})\,\mu$$

where

$$G_k = k(k+1)\int_0^1 (p - L(p))\,(1-p)^{k-1}\,dp$$

the factor $k(k+1)$ insures the range of the index G_k is zero to one. The expected drop for the lowest age of the k random deaths is given by μG_k. For any $k \geq 2$ we have

$$1 \geq G_k \geq G_{k-1} \geq \cdots G_2 \geq G$$

Similarly, one can inquire about the expected value for the higher age of any two randomly chosen deaths. In particular, in the hypothetical family scenario, this would correspond to the expected lifespan of the person living longer out of the two people (random case). Denote this value by Z_2. If we seek the expected value for the highest age of three randomly chosen deaths then we obtain the value Z_3. Using results in Farris(2010) we have

$$Z_2 = (1+G)\,\mu$$

and in Zizler(2014) it was shown that

$$Z_3 = (1 - G_2 + 3G)\,\mu$$

The values Z_2 and Y_2 are symmetric, in particular $Z_2 - \mu = \mu - Y_2$. Analogous identity does not hold for Y_3 and Z_3. It is possible to extend these to higher values of k and define accordingly the quantities Z_k, the expected values for the highest age of k randomly chosen deaths.

The metrics Y_k and Z_k, derived from the Gini Index and the higher-order Gini Indices, will be shown to provide tangible methods to assess the inequality of the ages in dying, in particular, the Y_k value that assesses the early-age mortality. We put forth the following hypothetical scenario geared to provide an intuitive understanding of these metrics. Imagine someone plans to attend k random funerals and prior to attending they ponder the expected age in dying, the value Y_k, for the person that died earliest among the k people buried. The higher this expectation, the lower the rate of early-age mortality in society. Although not indicative of early-age mortality, one can ponder the expectation for the age of the longest living person among the k people that died. This expectation value is Z_k.

6. Example

We illustrate our metrics of interest on a fictitious example. Suppose a certain entity lives only for five years, ages of dying are indicated as follows.

We estimate that all deaths in the interval $0-1$ occur at 0.5 years of age, all deaths in the interval $1-2$ occur at 1.5 years of age, and so on, last all the deaths in the interval $4-5$

Table 1. Age at Dying

Age	Deaths
0-1	14
1-2	8
2-3	5
3-4	20
4-5	15

occur at 4.5 years of age. These assumptions yield a piece-wise linear Lorenz curve when interpolating this discrete example to the continuous model. We generate

$$\begin{aligned} p &= [0\ 0.2258\ 0.3548\ 0.4355\ 0.7581\ 1.0000] \\ L &= [0\ 0.0414\ 0.1124\ 0.1864\ 0.6006\ 1.0000] \end{aligned}$$

with the values $\mu = 2.7258$, $GMD = 1.6662$, $G = 0.3056$, $Y_2 = 1.8928$, $G_2 = 0.4850$, $Y_3 = 1.4038$, $G_3 = 0.5855$, $Y_4 = 1.1298$ and $Z_3 = 3.9028$.

The method and approach utilized in this example will be extended to mortality data in various countries and over time.

7. Results from Selected Countries

The data from Our World in Data(2014) show that the universal mortality Gini Index hovers around $0.10 - 0.30$ across regions. We collected data from the Human Mortality Database(2024), giving us the number of people dying at various ages during specific time frames. This allowed us to calculate the Gini Index with accessible data.

We have done our analysis using data from 47 countries. The data provided are the total deaths in each age category at a given time. Here, we present some of the results from six countries for which data were available, namely, Canada, USA, Netherlands, Japan, Poland, and Italy. Each country has data spanning different decades. We have chosen these countries where the data were historically available in the early 1900's and even before, understanding this provides evidence from developed countries.

For each given country and a given time frame we compute the expected lifespan, the Gini Index, the higher-order Gini Indices and the corresponding derived metrics. A consistent trend across all selected countries is the significant rise in the expected lifespan over time. While this trend is not unexpected, what is remarkable is the steepness of the increase observed across all the countries examined. Furthermore, the Gini Index is decreasing over time in all of the countries involved indicating that people are dying closer to the expected lifespan.

We note that in the GMD calculation $GMD = 2\mu G$ we have an increasing μ over time. The decrease in G over time is powerful enough to force the decrease in GMD in recent

decades. To illustrate the incredible drop in the *GMD* over time, we point to the late 1800's in the Netherlands, where the Gini Mean Difference was higher than the expected lifespan at the time; the Gini Index was higher than 0.5.

As mentioned previously, the higher-order Order Ginis emphasize mortality at younger ages. The higher-order Ginis are dropping over time in all countries involved. This increases the Y_k values indicating a decrease in early-age mortality across the countries. To appreciate the advances in modern medicine, one only needs to look at the values Y_2, Y_3, and Y_4 during the decade 1850-1859 in the Netherlands and compare it to the decade 2010-2019 in the same country. Where the data are available, a drop in μ and the Y_k values (most likely attributed to the Second World War) was only detected in the Netherlands. It is interesting to note that the Z_3 values have been historically somewhat large, albeit rising to quite high values recently. This could point to the following conjecture: if an individual survived contagious diseases early in life, they were expected to live to a relatively high age.

8. Conclusion

In conclusion, our empirical studies for the selected countries show a detectable reduction in the higher-order Gini Indices. In particular, our empirical results using the derived metrics Y_k, show a dramatic decline in the early-age mortality. These findings build on previous studies and provide valuable novel contributions to the subject in both applied and theoretical contexts. In other words, this definite drop in the higher-order Gini Indices over time suggests enhanced longevity among younger cohorts. Furthermore, our study also provides empirical evidence that even though the expected lifespan is increasing over time there is a detectable sharp drop in the Gini Mean Difference in the latter part of the 20th century.

Improvements in early-age mortality, reductions in neonatal, infant, and under-five deaths, had significant implications for societies. These advances contributed to global population growth, economic development, and the expansion of education. Furthermore, societies have experienced changes in family structures and shifts in demographic age distributions over time.

9. Contribution Statement

We have introduced the higher-order Gini Indices into the analysis of lifespan inequality and measures of early-age mortality. We further developed metrics based on the higher-order Gini Indices to assess the levels of early-age mortality. We developed empirical studies in selected countries and thus enhanced previous studies done on the subject. The recommendation, derived from our empirical model, is to monitor whether the higher-order Gini Indices further drop over time or reach a stabilization point; similarly observations are to be done on the derived metrics. While an optimistic anticipation suggests further favorable shifts in these metrics, the possibility of stagnation cannot be dismissed. We note our data indicate there is a slowdown in the rates of decrease for the Gini Index as well as the higher-order Gini Indices.

Table 2. Definitions of lifespan inequality measures

Symbol	Description
μ	expected lifespan
G	Gini Index
GMD	Gini Mean Difference
G_2	second-order Gini Index
G_3	third-order Gini Index
Y_2	expected lifespan of the lower of two randomly selected ages at death
Y_3	expected lifespan of the lower of three randomly selected ages at death
Y_4	expected lifespan of the lower of four randomly selected ages at death
Z_3	expected lifespan of the higher of three randomly selected ages at death

Table 3. Italy

Decade	μ	G	GMD	G_2	G_3	Y_2	Y_3	Y_4	Z_3
1872-1879	26.16	0.60	31.39	0.80	0.84	10.46	5.35	4.13	52.32
1880-1889	27.00	0.60	32.30	0.79	0.84	10.85	5.54	4.29	54.27
1890-1899	30.11	0.57	34.19	0.77	0.83	13.01	6.81	5.02	58.41
1900-1909	33.57	0.53	35.73	0.75	0.82	15.70	8.56	6.07	61.77
1910-1919	35.37	0.49	34.75	0.71	0.80	18.00	10.43	6.98	62.25
1920-1929	39.43	0.46	36.55	0.68	0.78	21.16	12.59	8.66	67.03
1930-1939	44.99	0.40	36.11	0.61	0.73	26.93	17.39	12.18	71.53
1940-1949	47.65	0.36	34.76	0.57	0.69	30.28	20.68	15.00	71.95
1950-1959	59.05	0.24	28.66	0.40	0.51	44.71	35.47	28.87	77.95
1960-1969	63.98	0.19	24.41	0.32	0.41	51.78	43.73	37.68	79.98
1970-1979	68.56	0.15	20.10	0.24	0.31	58.51	51.98	47.02	82.96
1980-1989	72.10	0.12	17.04	0.19	0.25	63.58	58.22	54.22	84.36
1990-1999	74.81	0.11	16.40	0.18	0.23	66.61	61.49	57.70	86.03
2000-2009	77.92	0.10	15.12	0.16	0.20	70.36	65.72	62.30	88.83
2010-2019	80.42	0.09	13.96	0.14	0.18	73.44	69.11	65.92	90.88

Table 4. Canada

Decade	μ	G	GMD	G_2	G_3	Y_2	Y_3	Y_4	Z_3
1921-1929	40.19	0.45	36.12	0.66	0.76	22.13	13.69	9.80	67.92
1930-1939	48.05	0.36	34.28	0.55	0.67	30.91	21.43	15.78	73.52
1940-1949	53.84	0.30	31.85	0.47	0.59	37.91	28.34	22.01	76.99
1950-1959	58.36	0.25	29.44	0.41	0.52	43.64	34.32	27.78	78.20
1960-1969	62.67	0.21	26.28	0.34	0.44	49.53	41.05	34.82	80.84
1970-1979	66.05	0.17	23.11	0.29	0.37	54.50	47.21	41.83	80.58
1980-1989	69.60	0.15	20.44	0.24	0.31	59.38	53.02	48.30	84.22
1990-1999	72.48	0.13	18.88	0.21	0.27	63.03	57.16	52.81	85.53
2000-2009	74.67	0.12	18.03	0.20	0.25	65.66	60.06	55.96	86.62
2010-2019	76.31	0.12	17.81	0.19	0.24	67.41	61.93	57.96	89.28

Table 5. The United States of America

Decade	μ	G	GMD	G_2	G_3	Y_2	Y_3	Y_4	Z_3
1933-1939	52.97	0.27	29.12	0.44	0.55	38.41	29.78	23.92	72.57
1940-1949	57.18	0.24	27.09	0.38	0.49	43.63	35.27	29.34	76.62
1950-1959	61.09	0.21	25.33	0.34	0.44	48.43	40.39	34.50	78.81
1960-1969	63.99	0.18	23.65	0.30	0.39	52.16	44.62	39.01	79.35
1970-1979	66.66	0.16	21.87	0.27	0.34	55.73	48.86	43.78	80.66
1980-1989	69.50	0.15	20.76	0.24	0.31	59.12	52.63	47.82	84.10
1990-1999	71.50	0.14	20.26	0.23	0.30	61.37	55.03	50.35	85.09
2000-2009	72.89	0.14	19.96	0.22	0.28	62.91	56.70	52.17	87.47
2010-2019	73.64	0.13	19.60	0.21	0.27	63.84	57.89	53.63	86.90

Table 6. The Netherlands

Decade	μ	G	GMD	G_2	G_3	Y_2	Y_3	Y_4	Z_3
1850-1859	28.96	0.56	32.52	0.76	0.82	12.70	6.92	5.35	55.60
1860-1869	27.79	0.58	32.11	0.77	0.81	11.72	6.33	5.17	54.75
1870-1879	28.12	0.58	32.84	0.77	0.80	11.70	6.42	5.63	55.40
1880-1889	29.47	0.57	33.85	0.77	0.80	12.54	6.89	5.90	57.17
1890-1899	32.76	0.54	35.26	0.74	0.79	15.13	8.53	6.86	61.59
1900-1909	35.94	0.51	36.43	0.72	0.78	17.72	10.24	7.77	65.05
1910-1919	40.39	0.45	36.43	0.67	0.77	22.17	13.50	9.42	67.86
1920-1929	47.51	0.37	35.01	0.57	0.69	30.01	20.35	14.70	73.12
1930-1939	55.06	0.28	30.60	0.45	0.57	39.77	30.32	23.86	76.53
1940-1949	54.49	0.28	31.03	0.46	0.58	38.97	29.48	23.05	75.20
1950-1959	63.77	0.19	24.59	0.32	0.42	51.47	43.32	37.18	79.71
1960-1969	67.24	0.16	21.42	0.26	0.34	56.53	49.50	44.14	82.03
1970-1979	70.00	0.14	18.96	0.22	0.29	60.52	54.45	49.87	84.00
1980-1989	72.63	0.12	17.46	0.20	0.25	63.90	58.42	54.33	84.25
1990-1999	74.49	0.11	16.89	0.18	0.24	66.04	60.78	56.88	85.67
2000-2009	75.88	0.11	16.29	0.17	0.22	67.73	62.69	58.99	88.02
2010-2019	77.86	0.10	15.40	0.16	0.20	70.16	65.46	62.06	88.76

Table 7. Japan

Decade	μ	G	GMD	G_2	G_3	Y_2	Y_3	Y_4	Z_3
1947-1949	38.46	0.44	33.85	0.65	0.76	21.53	13.41	9.29	64.23
1950-1959	49.97	0.32	32.09	0.51	0.63	33.93	24.53	18.46	72.46
1960-1969	61.08	0.20	24.89	0.33	0.43	48.63	40.65	34.79	78.49
1970-1979	65.69	0.16	21.59	0.27	0.35	54.89	47.95	42.75	79.49
1980-1989	70.25	0.13	18.64	0.22	0.28	60.93	55.06	50.72	82.19
1990-1999	73.52	0.12	17.11	0.19	0.24	64.97	59.73	55.93	86.02
2000-2009	76.69	0.10	16.02	0.17	0.21	68.68	63.87	60.40	86.66
2010-2019	80.46	0.09	14.40	0.14	0.18	73.26	68.90	65.72	90.92

Table 8. Poland

Decade	μ	G	GMD	G_2	G_3	Y_2	Y_3	Y_4	Z_3
1958-1959	48.19	0.36	34.50	0.55	0.66	30.94	21.48	16.27	73.73
1960-1969	57.39	0.25	28.22	0.40	0.51	43.28	34.37	28.07	77.48
1970-1979	62.94	0.19	23.82	0.31	0.40	51.02	43.27	37.47	79.30
1980-1989	66.04	0.17	21.81	0.27	0.35	55.13	48.10	42.85	81.89
1990-1999	68.50	0.14	19.62	0.23	0.29	58.69	52.68	48.30	81.52
2000-2009	70.65	0.13	17.96	0.20	0.26	61.67	56.32	52.51	84.07
2010-2019	73.37	0.12	17.07	0.19	0.23	64.84	59.79	56.24	85.84

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