An Alternative Decomposition Of The Fisher Index

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An Alternative Decomposition of the Fisher Index

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An Alternative Decomposition of the Fisher Index

Abstract

Aside from the aggregated information provided by price and quantity indexes, there is growing interest in index decompositions that reveal the contribution of each index component to overall index change. In this paper, we derive a “natural” decomposition of the Fisher price index that is directly implied by its linear homogeneity in price relatives. The proposed “Euler” weights not only indicate the *total* contribution of each component to total index change but also reveal which component had the highest or lowest *marginal* impact. Our results can readily be generalized to any index that satisfies the linear homogeneity property.

Keywords: Fisher index, linear homogeneity, decomposition

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1. Introduction

Price and quantity indexes play an important role in official economic statistics. Aside from the aggregated information provided by indexes, there is growing interest in additive index decompositions. These decompositions reveal the sources of the aggregate price or quantity changes by showing the contribution of each index component to overall index change. Paasche and Laspeyres indexes can easily be decomposed, but for the Fisher index (the geometric average of the Paasche and Laspeyres indexes) no unambiguous or "natural" decomposition is said to exist. Instead, starting from either an economic or an axiomatic approach, different decompositions have been derived (see Reinsdorf et al. [2002] and Balk [2004], e.g.).[1]

In this paper, we propose yet an alternative additive decomposition of the Fisher index. It is a "natural" decomposition in the sense that it is directly implied by the linear homogeneity of the Fisher price (quantity) index in next-period prices (quantities). This linear homogeneity property is an important requirement for indexes (see Balk & Diewert [2001]), and our results can be generalized to any index that satisfies this property.

This paper is organized as follows. Section 2 introduces notation, provides some definitions and summarizes the "satisfactory" decomposition as reviewed by Balk [2004]. In section 3 we derive an alternative decomposition and in section 4 we compare the derived decomposition with the satisfactory decomposition. Section 5 summarizes the paper. The Appendix contains technical details.

2. Preliminaries

We consider *N* index components (commodities, e.g.) in the base period (*t=0*) and comparison period (*t=1*), with respective prices $\left\{p_i^0, p_i^1\right\}_{i\in N}$ and quantities

[1] The *axiomatic* (or test) approach rests on desirable properties that indexes should satisfy. These properties are formalized in functional equations in which prices and quantities enter as separate variables. The *economic* approach is guided by optimization (cost minimization or revenue maximization) which implies a relation between prices and quantities.

$\left\{q_i^0, q_i^1\right\}_{i \in N}$. Throughout we assume that $\left\{p_i^t, q_i^t\right\} \in \Re_{++}^N$. The Fisher price index P_F is the geometric mean of the Laspeyres and the Paasche price indexes:

$$(1) \qquad P_F \equiv \sqrt{P_L P_P} = \left(\frac{\sum_i p_i^1 q_i^0}{\sum_i p_i^0 q_i^0} \cdot \frac{\sum_i p_i^1 q_i^1}{\sum_i p_i^0 q_i^1} \right)^{\frac{1}{2}}$$

Analogously, the Fisher quantity index Q_F is the geometric mean of the Laspeyres and the Paasche quantity indexes:

$$(2) \qquad Q_F \equiv \sqrt{Q_L Q_P} = \left(\frac{\sum_i p_i^0 q_i^1}{\sum_i p_i^0 q_i^0} \cdot \frac{\sum_i p_i^1 q_i^1}{\sum_i p_i^1 q_i^0} \right)^{\frac{1}{2}}$$

The price relative of component i (one plus the percentage change in its price) is denoted by:

$$(3) \qquad \frac{p_i^1}{p_i^0} \equiv 1 + r_i \qquad \forall i \in N$$

Additive decomposition of the Fisher price index entails specifying a set of positive weights $\{w_i\}_{i \in N}$, satisfying:

$$(4) \qquad P_F = \sum_i w_i (1 + r_i) \quad , \quad w_i \geq 0, \ \forall i \in N$$

With the additional restriction that the weights sum to unity,

$$(5) \qquad \sum_i w_i = 1 \ ,$$

the decomposition can also be written as:

$$(6) \qquad P_F - 1 = \sum_i w_i r_i$$

The additive decomposition according to (4) and (5) implies that the price index is a weighted average (convex combination) of the price relatives $\left\{p_i^1 / p_i^0\right\}_{i \in N}$.

In the following we concentrate on the Fisher price index. This is without loss of generality since all results can be transposed to the Fisher quantity index by using the price/quantity symmetry property. According to this property, switching prices and quantities transforms the Laspeyres, Paasche or Fisher price index to the corresponding quantity index, and vice versa (see Dumagan [2002]). This symmetry property also leads to the following proportionality relation:

(7) $$\frac{Q_P}{Q_L} = \frac{P_P}{P_L}$$

Balk [2004] provides an excellent review of proposed price index decompositions. For the additive decomposition, he presents the following weights, first derived by Van IJzeren [1952]:

(8) $$w_i = \frac{Q_F}{Q_F + Q_L} \cdot s_i^0 + \frac{Q_L}{Q_F + Q_L} \cdot s_i^{01} \qquad i \in N$$

with:

(9) $$s_i^0 \equiv \frac{p_i^0 q_i^0}{\sum_j p_j^0 q_j^0} \qquad \text{and} \qquad s_i^{01} \equiv \frac{p_i^0 q_i^1}{\sum_j p_j^0 q_j^1}$$

indicating the value shares of component *i* at base period prices and at base-/ comparison-period quantities. These weights are "satisfactory" since they satisfy both (4) and (5). Note that each Van IJzeren weight is in turn a convex combination of the mixed-period value shares. Hence, the Fisher index can be expressed as:

(10) $$P_F = \sum_{i=1}^{N} \left[\frac{Q_F}{Q_F + Q_L} \cdot s_i^0 + \frac{Q_L}{Q_F + Q_L} \cdot s_i^{01} \right] \cdot \frac{p_i^1}{p_i^0}$$

Balk [2004] discusses the history of this result and notes independent derivations by Reinsdorf et al. [2002] and Dumagan [2002]. In the next section, we derive an alternative decomposition.

3. An alternative decomposition of the Fisher price index

As noted by Balk & Diewert [2001], an important requirement for any price index *P* is that it is linearly homogeneous in comparison period (*t=1*) prices:

(11) $$P\left(p_i^0, q_i^0, kp_i^1, q_i^1; i \in N\right) = k\,P\left(p_i^0, q_i^0, p_i^1, q_i^1; i \in N\right) \quad , \quad k > 0$$

By Euler's theorem, it then immediately follows that (taking into account (3)):

(12) $$P = \sum_i \frac{\partial P}{\partial (1 + r_i)} (1 + r_i)$$

Comparing (12) and (4), the linear homogeneity implies that the weights are defined as partial derivatives:

(13) $$w_i = \frac{\partial P}{\partial(1+r_i)} \qquad i \in N$$

Because of this feature, we call these weights the "Euler" weights. Without specifying index *P* further, however, it cannot be determined whether (5) is also satisfied (i.e. Euler weights summing to unity).

Let us now consider the Fisher price index. From (1) it follows that:

(14) $$\frac{\partial P_F}{\partial(1+r_i)} = \frac{1}{2P_F}\left[\frac{p_i^0 q_i^0}{\sum_j p_j^0 q_j^0}\cdot\frac{\sum_j p_j^1 q_j^1}{\sum_j p_j^0 q_j^1} + \frac{p_i^0 q_i^1}{\sum_j p_j^0 q_j^1}\cdot\frac{\sum_j p_j^1 q_j^0}{\sum_j p_j^0 q_j^0}\right]$$

$$= \frac{1}{2}\left[\sqrt{\frac{P_P}{P_L}}\cdot s_i^0 + \sqrt{\frac{P_L}{P_P}}\cdot s_i^{01}\right]$$

Hence:

(15) $$P_F = \sum_{i=1}^{N}\left[\tfrac{1}{2}\sqrt{\frac{P_P}{P_L}}\cdot s_i^0 + \tfrac{1}{2}\sqrt{\frac{P_L}{P_P}}\cdot s_i^{01}\right]\cdot\frac{p_i^1}{p_i^0}$$

In section 4, we analyze these weight components in more detail.

Eq.(15) can be termed a "natural" decomposition since it is directly implied by the linear homogeneity of the Fisher index. In addition, the Euler weights not only indicate the *total* contribution of component *i* to total index change. Since the weights are partial derivatives, they at the same time indicate the effect of a *marginal* change in component *i*'s price on total index value. So given an observed change in the index, the Euler weights in (14) also reveal which component had the highest or lowest marginal impact.

Summing the Euler weights in (14) over $i \in N$ gives:

(16) $$\sum_i \frac{\partial P_F}{\partial(1+r_i)} = \frac{1}{2}\left[\frac{P_P + P_L}{P_F}\right] \geq 1$$

since $\tfrac{1}{2}\left(P_P + P_L\right) \geq \sqrt{P_P P_L}$, with the strict equality of arithmetic and geometric mean holding only when $P_P = P_L$. Ignoring the latter trivial case, the weights do not sum to unity so they do not provide a "satisfactory" decomposition in the terminology of

Balk [2004].[2]

In the next section, we compare the decompositions (10) and (15) in more detail.

4. Comparison of decompositions

We start our analysis at the aggregate index level. As indicated by (16), the sum of the Euler weights exceeds unity – except for the trivial case where the Laspeyres and Paasche price indexes coincide.[3] When $P_L \neq P_P$, their arithmetic mean is greater than the geometric mean, and the larger the difference between the two price indexes, the larger the sum of the Euler weights. But given a difference between P_L and P_P, exactly how large is the sum of the weights? We define $d \cdot 100$ as the percentage difference between the largest and smallest index number.[4] As shown in the Appendix, this implies that the sum of the Euler weights is:

$$(17) \qquad \sum_i \frac{\partial P_F}{\partial(1+r_i)} = \frac{\frac{1}{2}\left(P_P + P_L\right)}{\sqrt{P_P P_L}} = \frac{2+d}{2\sqrt{1+d}}$$

For example, when over some time horizon P_L is 1% (or even 5%) larger than P_P, the sum of the Euler weights exceeds unity by only 0.12 basis points (or 2.98 basis points). In practice, this difference may be considered negligible. Still, if desired, the weights can be normalized:

$$(18) \qquad w_i' = \frac{\dfrac{\partial P_F}{\partial(1+r_i)}}{\sum_j \dfrac{\partial P_F}{\partial(1+r_j)}} \qquad \Rightarrow \qquad \sum_i w_i' = 1$$

---

[2] One possible solution is dividing the LHS and RHS of (15) by P_F, yielding $1 = \sum_{i=1}^{N}\left[\frac{1}{2}\frac{1}{P_L}\cdot s_i^0 + \frac{1}{2}\frac{1}{P_P}\cdot s_i^{01}\right]\cdot\frac{p_i^1}{p_i^0}$. Each term on the RHS indicates the relative contribution of component *i* to total index change. All component contributions then sum to 100%. In section 4 we revisit this issue.

[3] This is the case, for example, when quantities do not change from the base period to the comparison period.

[4] For the (likely) case that relative changes in prices and relative changes in quantities are negatively correlated, it follows that $P_P < P_L$.

The normalized Euler weights $\{w_i'\}_i$ now define P_F as a weighted average of price relatives.

As an alternative to straightforward normalization we can compute the weights that are closest (in mean-square sense) to the Euler weights but do sum to unity (i.e. satisfy (5)). To find these weights, we specify the following optimization problem:

$$(19)\qquad \min_{\{w_i\}} \sum_{i=1}^{N}\left(\frac{\partial P_F}{\partial(1+r_i)} - w_i\right)^2$$

$$\text{s.t.}\qquad \sum_i w_i(1+r_i) = P_F$$

$$\sum_i w_i = 1$$

As outlined in the Appendix, the solution is:

$$(20)\qquad \frac{\partial P_F}{\partial(1+r_i)} - w_i = \frac{1}{N}\left[\sum_j \frac{\partial P_F}{\partial(1+r_j)} - 1\right]\cdot\left[1 + \frac{m\left(m-(1+r_i)\right)}{s^2}\right] \quad , \; i\in N$$

where m and s^2 denote the mean and variance of the price relatives, respectively. The first term between square brackets is positive (see (16)). The first two terms on the RHS indicate that the excess of the summed Euler weights over 100% is allocated proportionally over the weights w_i.[5] The last term between square brackets specifies a correction factor to the proportional reallocation of the weight differences. The unweighted average of this correction factor is one. When a component's price relative is greater (smaller) than the unweighted average m of all components' price relatives, this factor is greater (smaller) than one. Hence, the last term on the RHS thus turns the unweighted average adjustment into a weighted average adjustment. The larger a component's price relative, the larger the weight adjustment, and vice versa. However, considering the fact that in practice the sum of the Euler weights will be very close to unity, we would after all suggest using the unadjusted Euler weights for the Fisher index decomposition.

Let us know compare the weights at the individual component level. Using (1), we can rewrite the Van IJzeren weights in (8) as:

[5] This comes as no surprise since we minimize the *unweighted* sum of squared differences in (19).

$$(21) \qquad w_i = \frac{\sqrt{Q_P}}{\sqrt{Q_P}+\sqrt{Q_L}} \cdot s_i^0 + \frac{\sqrt{Q_L}}{\sqrt{Q_P}+\sqrt{Q_L}} \cdot s_i^{01}$$

$$= \tfrac{1}{2}\sqrt{\frac{P_P}{P_L}} \cdot \left[\frac{2}{1+\sqrt{\frac{P_P}{P_L}}}\right] \cdot s_i^0 + \tfrac{1}{2}\sqrt{\frac{P_L}{P_P}} \cdot \left[\frac{2}{1+\sqrt{\frac{P_L}{P_P}}}\right] \cdot s_i^{01} \qquad i \in N$$

where the last equality follows from applying the symmetry property (7). The terms in square brackets are the differences with the Euler weights in (14). Multiplying numerator and denominator of the second term in square brackets with $\sqrt{P_P / P_L}$ yields:

$$(22) \qquad w_i = \sqrt{\frac{P_P}{P_L}} \cdot \left[\frac{1}{1+\sqrt{\frac{P_P}{P_L}}}\right] \cdot s_i^0 + \sqrt{\frac{P_L}{P_P}} \cdot \left[\frac{\sqrt{\frac{P_P}{P_L}}}{1+\sqrt{\frac{P_P}{P_L}}}\right] \cdot s_i^{01}$$

For the Euler weights, the terms in square brackets all equal ½. In (22) these terms (also) sum to unity, but depending on the degree of difference between P_L and P_P, they are larger or smaller than ½. To get a feeling for the order of magnitude involved, suppose that P_L is 1% (or 5%) larger than P_P (so *d*=1% and 5%, respectively). The two terms between square brackets in (22) are then (50.12%; 49.88%) and (50.61%; 49.39%), respectively. Depending on the relative magnitude of the value shares s_i^0 and s_i^{01} for component *i*, this implies that there can exist substantial differences between its Van IJzeren weight and its Euler weight.

5. Conclusions

The Van IJzeren [1952] decomposition of the Fisher price index allows writing the index as a weighted average of price relatives. Each weight multiplied with the corresponding price relative indicates the total contribution of the index component to the total change in the index. In this paper, we derived an alternative additive decomposition of the Fisher index. It is a “natural” decomposition in the sense that it is directly implied by the linear homogeneity of the Fisher price index in next-period prices. The weight for each index component is given by the partial derivative of the index with respect to the component's price relative. Because of this feature, the weights are termed "Euler" weights.

Euler weights not only indicate the *total* contribution of each component to total index change. Since the weights are partial derivatives, they also indicate the effect of a *marginal* change in a component's price relative on total index value. So given an observed change in the index, the Euler weights reveal which component had the highest or lowest marginal impact.

The Euler weights, however, do not sum to unity. We investigated the relation between the Van IJzeren weights and the Euler weights in detail, both on the individual component level as on the aggregate index level. On the latter level, we showed how the sum of the Euler weights can easily be computed from the difference between the Laspeyres and Paasche price indexes. Even for a large discrepancy of 5% between the Laspeyres and Paasche indexes, the sum of the Euler weights is only 3 basis points above unity. On the individual weight level, we also derived normalized Euler weights: these weights approximate the Euler weights in mean-square sense and sum to unity. However, considering the fact that in practice the sum of the Euler weights will be very close to unity, we would after all suggest using the unadjusted Euler weights for the Fisher index decomposition.

Finally, we note that our results can be generalized to any index that satisfies the linear homogeneity property.

Appendix

This appendix derives the sum of the Euler weights and the definition of the normalized Euler weights.

Inferring the sum of the Euler weights

Consider two numbers X and Y. Let $a \cdot 100$ be the percentage difference between their arithmetic and geometric mean:

$$(23) \qquad \frac{\frac{1}{2}(X+Y)}{\sqrt{XY}} = 1+a$$

By definition, $a \geq 0$, with the strict equality holding only when $X = Y$.
Let $d \cdot 100$ be the percentage difference between the largest and smallest number, where without loss of generality we assume that $Y \geq X$:

$$(24) \qquad Y = (1+d)X \quad , \quad d \geq 0$$

Plugging (24) in (23) yields:

$$(25) \qquad 1+a = \frac{2+d}{2\sqrt{1+d}}$$

So given an observed relative difference d between the Laspeyres and Paasche price indexes, the sum of the Euler weights $1+a$ easily follows.

The procedure can also be reversed: given a maximum admissible deviation of the summed Euler weights from unity, we can compute the maximum admissible relative difference between the Laspeyres and Paasche price indexes. Squaring the LHS and RHS of (25) and collecting terms we get the following quadratic equation:

$$(26) \qquad \tfrac{1}{4}d^2 + \left[1-(1+a)^2\right]d + \left[1-(1+a)^2\right] = 0$$

Solving for d we get:

$$(27) \qquad d = 2\left[a(2+a) \pm (1+a)\sqrt{a(2+a)}\right]$$

For the plus (minus) sign between the square brackets, d is positive (negative). Because of our definition (24), only the positive value of d is relevant. However, because percentage differences are almost symmetric (i.e. $(1+d)^{-1} \approx 1-d$), (27) implies that the term $a(2+a)$ must be immaterial when compared to $(1+a)\sqrt{a(2+a)}$. Indeed, this is the case. Hence, we can approximate d quite accurately by the simpler expression:

(28) $$d \approx 2(1+a)\sqrt{a(2+a)}$$

Deriving normalized Euler weights

We want to compute the weights that are closest (in mean-square sense) to the Euler weights but sum to unity (i.e. satisfy (5)). These weights are implied by the following optimization problem:

(19) $$\min_{\{w_i\}} \sum_{i=1}^{N} \left(\frac{\partial P_F}{\partial (1+r_i)} - w_i \right)^2$$

subject to:

(29) $$\sum_i w_i (1+r_i) = P_F$$

and

(30) $$\sum_i w_i = 1$$

Forming the Lagrangian with respective parameters l and g, the first order optimality conditions are:

(31) $$w_i - \frac{\partial P_F}{\partial (1+r_i)} - l(1+r_i) - g = 0 \ , \qquad i \in N$$

together with the original restrictions (29) and (30).

Multiplying (31) with $(1+r_i)$, summing over $i \in N$ and solving for g yields:

(32) $$g = -l \, \frac{\sum_i (1+r_i)^2}{\sum_i (1+r_i)}$$

(where we have used (29) and (12)). Plugging this result in (31) gives:

(33) $$\frac{\partial P_F}{\partial (1+r_i)} - w_i = l \left[\frac{\sum_j \left(1+r_j\right)^2}{\sum_j \left(1+r_j\right)} - (1+r_i) \right]$$

Summing over $i \in N$ and solving for l gives:

(34) $$l = \left[\sum_j \frac{\partial P_F}{\partial \left(1+r_j\right)} - 1 \right] \frac{1}{N \frac{\sum_j \left(1+r_j\right)^2}{\sum_j \left(1+r_j\right)} - \sum_j \left(1+r_j\right)}$$

Plugging this back in (33) gives:

(35) $$\frac{\partial P_F}{\partial(1+r_i)} - w_i = \frac{1}{N}\left[\sum_j \frac{\partial P_F}{\partial\left(1+r_j\right)} - 1\right] \frac{\dfrac{\frac{1}{N}\sum_j\left(1+r_j\right)^2}{\frac{1}{N}\sum_j\left(1+r_j\right)} - (1+r_i)}{\dfrac{\frac{1}{N}\sum_j\left(1+r_j\right)^2}{\frac{1}{N}\sum_j\left(1+r_j\right)} - \frac{1}{N}\sum_j\left(1+r_j\right)} \quad , \; i \in N$$

where we have added the averaging factors $\frac{1}{N}$ in order to obtain average price relatives and mean sum of squared price relatives. Defining the average of price relatives:

(36) $$m \equiv \tfrac{1}{N}\sum_j\left(1+r_j\right)$$

and their variance:

(37) $$s^2 \equiv \tfrac{1}{N}\sum_j\left(1+r_j\right)^2 - \left[\tfrac{1}{N}\sum_j\left(1+r_j\right)\right]^2$$

we can rewrite (35) as:

(38) $$\frac{\partial P_F}{\partial(1+r_i)} - w_i = \frac{1}{N}\left[\sum_j \frac{\partial P_F}{\partial\left(1+r_j\right)} - 1\right] \cdot \left[1 + \frac{m\left(m-(1+r_i)\right)}{s^2}\right] \quad , \; i \in N$$

The first term between square brackets is positive (see (16)). The first two terms on the RHS indicate that the excess of the summed Euler weights over 100% is allocated proportionally over the weights w_i. The last term between square brackets specifies a correction factor to the proportional reallocation of the weight differences. The unweighted average of the correction factors is unity. When a component's price relative is greater (smaller) than the average m of all components' price relatives, the correction factor is greater (smaller) than one. The correction term thus turns the unweighted average adjustment into a weighted average adjustment. The larger a component's price relative, the larger the weight adjustment, and vice versa.

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