

MEASURING CONSUMER INFLATION IN A DIGITAL ECONOMY

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Abstract

The effect of the possible sources of error in capturing digital products on the price index for household consumption depends in part on the weights of the affected products in the consumption basket. To calculate upper bounds for the impact on the household consumption price index of the possible sources of mismeasurement, we assume a “worst case” bias in the micro-index for each affected product category and apply weights based on an average structure of household consumption in OECD countries. The upper bound revision to the growth rate of the household consumption deflator when we adjust for cost savings from digital products that directly replace a non-digital product is about –0.1 percentage point using 2015 weights. Welfare gains from improved selection of varieties are widespread, but the impact on each individual product is small, and the revision to the overall consumption index from incorporating the variety gains is just –0.06 percentage point. Finally, the upper bound impact from completely adjusting for quality change in digital products is estimated at around –0.3 percentage point. Total “worst case” effects to the growth rate of the consumption deflator thus amount to slightly more than -0.4 percentage points, which although significant, would not have a large enough impact on real consumption growth to change the picture of low growth in real GDP seen in the macroeconomic data of many advanced economies. The assessment does not include broader welfare effects from novel and free digital products, but we argue that the inclusion of reservation prices and shadow prices in official price and volume measures that would be required to reflect such welfare effects would be problematic for practical and conceptual reasons.

1. Introduction and Key Findings

1. Whether estimates of GDP still provide good measures of growth in a digitalized economy has become a topic of debate. Economists from Silicon Valley and Wall Street have suggested that the overlooked output generated by the digital economy, including from products perceived as welfare-enhancing, could be large enough to explain the productivity slowdown that began in the mid-2000s. Several prominent academic economists, such as Martin Feldstein (2017), have argued that growth of material living standards has far outstripped growth as measured by GDP. Possible inadequacies of GDP concepts and methods for measuring the digital economy have even been a focus of articles in *The Economist*.

2. On the other side of the debate are several analyses that have found that many of the criticisms of GDP statistics are based on misunderstandings of the conceptual framework and purpose of GDP, or on

¹ Views expressed in this paper are those of the authors and should not be attributed to the IMF, its Executive Directors or its Management, or to the OECD or its Member countries.

exaggerated perceptions of the likely size of the effects. Ahmad and Schreyer (2016) considered how nominal GDP measurement is affected by digitalisation, and concluded that existing GDP concepts remain sound. Ahmad, Ribarsky, and Reinsdorf (2017) developed alternative price and welfare measures for several items and found relatively small impacts on GDP growth.

3. In this paper, we take a more comprehensive look at the possible sources of error in capturing digital products in the price and volume measures for household consumption. While all the components final demand could potentially play a role in mismeasurement of real GDP², household consumption represents the most important part of GDP in OECD countries (for instance, around 70 percent in the U.S.) and price measures of household consumption are a key gauge of inflation, with a multitude of applications. The claims that prices—and, by implication, growth—of household consumption are being mismeasured largely revolve around three potential sources of distortion. These are summarised in Table 1: (1) incomplete adjustment for quality change, i.e., the treatment of new, and typically improved, varieties of existing digital products; the treatment of new digital products that replace existing non-digital products; and improved variety selection of digital and non-digital products; (2) neglected welfare gains or cost savings from truly novel digital products when these are introduced late into price indices; (3) neglected welfare gains from free digital products when there is no imputation of shadow prices. Although digitalisation clearly poses some real measurement challenges, we argue in Section 2 that the welfare effects of truly novel products (2) and free products (3) are best addressed as part of welfare measurement “beyond GDP” rather than within an official price index. The arguments for this are both conceptual and practical.

4. We calculate upper bounds for the impact on the deflator for household consumption of the various effects that are part of (1) – quality change in existing digital products, digital replacement of non-digital products and improved variety selection – by considering each of them in turn. We then assume a “worst case” bias in the price index for each of these categories and apply an average weight calculated from detailed data sets on the weighting structure of household consumption in OECD countries. The upper bound growth rate adjustment to the household consumption deflator from cost savings from new digital products that directly replace a non-digital product is found to be about –0.2 percentage point using 2005 weights, and –0.1 percentage point using 2015 weights. The welfare growth from improved variety selection has a widespread, but small, effect, resulting in an overall impact on the adjusted consumption deflator of just –0.06 percentage points. Finally, the upper bound revision to the growth rate of the household consumption deflator from completely adjusting for quality change in digital products is around –0.3 percentage point. Although an overall effect of about -0.4 percentage point would by no means be insignificant, the scale of adjustments for the potential mismeasurement of consumer prices is not large enough to change the picture of low growth in productivity and output.

² For instance, deflators for ICT investment are identified as a source of downward bias by Byrne and Corrado (2017).

Table 1: Categorisation of sources of welfare effects

1. Quality change in existing product types	2. Appearance of truly novel products	3. Appearance and use of free products
(a) Quality change in existing digital products through evolving characteristics embodied in new varieties of digital products (e.g. computers)	e.g., smartphones	e.g., free communication services through apps
(b) Digital replacement of non-digital products (e.g., streaming services replacing CDs)		
(c) Improved variety selection among products, digital and other (e.g., clothing, books)		

2. Quality change in existing product types, truly novel products, and free products

2.1. Quality change in existing product lines

5. Price indexes for aggregates, such as household final consumption, are built from elementary price indexes that cover a single product, or product stratum that contains a narrow category of products. The elementary indexes are compiled from micro data on individual prices of different varieties and from different sellers.

6. Constructing the price index for a product would be rather straightforward if the characteristics of the varieties available for purchase never changed. However, for products with high technological content, new models embodying the latest technology often appear as replacements for older models or as new varieties. Accurate measurement of real growth when technology is changing therefore requires product-level price indexes that properly adjust for the quality change implied by changes in characteristics.

7. The basic approach used to construct elementary price indexes is to select a sample of representative varieties and sellers, and compare prices of the same varieties and sellers over time. Because like is compared with like, such a matched-model approach produces a pure measure of price change with no risk of distortion from variation in quality. However, products' characteristics tend to evolve over time, with new models appearing in the market and existing ones disappearing. Replacement of items in the sample that disappear from the market ('forced replacements') is one of the challenges faced by price statisticians.

8. There are three possibilities for handling a forced replacement. The easiest case is when a replacement for the missing item has similar characteristics and can be assumed to represent the same quality level. In this case, it is treated as a continuation of the original item. Second, the price of the replacement may be adjusted for the change in quality implied by the changes in characteristics. Last, the changes in characteristics may be too extensive to estimate the value of the quality change. In this case, a linking procedure is used. Because the linking method implicitly assumes that the entire price difference between the disappearing item and the replacement item is due to quality, true changes in quality with no

corresponding change in price are missed when linking is used.³ Whether reliance on linking for handling changes to the sample over- or understates quality change is unclear *a-priori*. If the outgoing item goes on sale at the end of its life cycle before disappearing from the sample, the implied quality adjustment may be too large because some of the ‘return to normal’ price increase is inappropriately treated as the value of quality change. Nevertheless, many authors have examined the overall treatment of variety entry and exit, typically finding an overstatement of inflation due to under-adjustment for quality change.⁴

9. Forced replacements are not the only way that new models and new products enter an elementary index. Item replacements are sometimes planned as part of sample refreshments. Sample rotations are also occasions for bringing in *new products and product varieties*, and the new products included during a sample rotation need not replace an older product. In a sample rotation, a newly selected sample is linked in, and the old sample is linked out. In other words, once the second month of price observations from the new sample has become available, the price changes in that sample begin to be used to calculate the change in the elementary index. Any quality difference between the products and varieties selected for the new sample and those in the old sample that is not fully reflected in their relative prices will not be captured, as the linking procedure assumes that the market is always in a state of perfect equilibrium in which apparent price dispersion really represents quality differences.

10. Sample rotations are also an occasion for bringing new outlets into the sample for an elementary index.⁵ Reinsdorf (1993) investigated sample rotations whose aim was to update the outlet sample to reflect current shopping patterns for food and gasoline. The outlets in the newly selected samples had systematically lower prices, but the linking procedure prevented the index from reflecting consumers’ savings from substitution to lower-priced outlets, a problem known as *outlet substitution bias*. Digitalization has again raised the question of outlet substitution bias as consumers have substituted online shopping for shopping in stores with physical locations. Nevertheless, Cavallo and Rigobon (2016, p. 158) find a high degree of similarity between online and offline price levels. Price differences are evidently not the main driver of the growth of retail e-commerce.

11. Another question in the treatment of new products that fit into an existing item stratum is the point in time in which they are brought into the elementary index. This will depend on the frequency of sample rotation. Late introduction can imply that price declines early in the life cycle are missed, a pattern that is particularly likely with digital products.

12. When (digital) replacement products are free (e.g., *WhatsUp* or *Skype* calls instead of using landlines), a case can be made for recognising the change from a positive to a zero price as part of the item substitution mentioned above. This would be a one-off effect on the price level as in subsequent periods.

13. The U.S. Boskin Commission estimated the missing quality adjustment for consumer durables in the U.S CPI in 1995 to be around 1 percent per year. Bills (2009) comes out with twice this estimate ‘My results suggest that quality growth for durables has been understated by almost 2 percent per year since 1988 (p. 673)’. Aghion *et al.* (2017) argue that imputations of price changes of continuing products for the

³ Triplett (2001, pp. 22-23) explains in detail the possibilities for splitting the price difference between the exiting item and the replacement item into a price difference and into a quality *difference*, noting that the ‘overlapping link method’ treats any price difference between the old and the replacement item as a difference in quality.

⁴ Feenstra (1994), Bills and Klenow (2001), Bills (2009), Broda and Weinstein (2010).

⁵ New outlets may also enter as forced replacements. In this case, the new outlet is linked into the index. The price observations from the new outlet are generally not treated as a continuation of the observations from the previous outlet, even if they both sell the same item.

price change of new varieties lead to an underestimation of real growth if the disappearing products are replaced by better products⁶.

14. There are also some recent studies finding evidence of overestimation of price change in official price indices for ICT and software: Byrne and Corrado (2017, Table 2) construct alternative price indices for ICT products and compare them with official price indices for the U.S. They also construct an alternative price index for ICT investment and find an annual rate of price change of -9.9 percent between 2004 and 2014, 5.8 percentage points below the official U.S. price index for ICT equipment. Byrne, Oliner, and Sichel (2015) show that microprocessor price declines are substantially understated and Byrne, Fernald and Reinsdorf (2015 p.123) “[...] infer that the BLS hedonic index may be understating the annual rate of quality improvement for PCs by 4 percentage points”. Greenstein and McDevitt (2009) assess the value of internet access as follows: “Approximately \$8.3 to \$10.6 billion was additional revenue created between 1999 and 2006. That replacement is associated with \$4.8 to \$6.7 billion in consumer surplus, which is not measured via Gross Domestic Product (GDP). An Internet-access Consumer Price Index (CPI) would have to decline by 1.6 to 2.2 percent per year for it to reflect the creation of value.”

15. Much less investigated, but not to be overlooked, is whether quality change of some digital products may actually be *overstated*. Examples of quality declines that are not captured in price measures include programmed obsolescence of certain consumer products, after-sales services that are purely machine-based, or the requirement to purchase new models of mobile phones and computers in the absence of backwards compatibility of new software with older hardware. There is also the case of digitally-enabled services where the consumer must supply a labour input as part of the transaction; for instance, self-checkout in stores. Whether these constitute quality improvements or declines is a matter of debate, but it is clear that these changes to self-service are not accounted for in official price indices.

16. To summarize, quality adjustment of replacements for existing products within a sample, and of new products coming in during sample rotations, may miss some quality change. The overlooked quality change could be in either direction, but for digital products benefitting from new technology, improvements seem more likely. One situation in which it may be possible to estimate the reduction in the cost of living from new digital products is when they accomplish the same task at a lower cost with no obvious sacrifice of convenience or other dimension of quality. By treating the new (and possibly free) digital product and the old product that serves the same function as one product, an average price paid for a to accomplish a given function could be used in the elementary price index for the item stratum. Early introduction of new products into the sample through frequent sample updates is also key.

2.2. Truly novel products

17. In addition to the new products and varieties that replace existing products and varieties, truly novel products are occasionally invented. Such goods and services are recognisable by the entirely new characteristics and service flows that they offer, or by the entirely new way – and typically much more efficient way – by which service flows are generated; historical examples are the introduction of electricity, automobiles or air conditioning (‘tectonic shifts’, in the terminology of Nordhaus 1996).⁷ These

⁶ However, these results must be interpreted with much caution because they rely on strong assumptions to identify the evolution of the market share of continuing products and to translate it into changes in a cost of living index.

⁷ Nordhaus (1996) draws a basic distinction between transaction prices of the purchased products and the shadow prices of service flows derived from these purchased goods. He argues that a true cost-of-living index (COLI) should be an index of the cost of service flows, which implies regrouping products by their contribution to consumer services such as transportation or entertainment: “For revolutionary changes in technology, such as the introduction of major inventions, traditional techniques simply ignore the fact that the new good or service may be significantly more efficient [in producing flows of services]. Consider the case of automobiles. In principle, it would be possible to link automobiles with horses so as to construct a price of travel, but this has not been done in

entirely new products (or associated services) are too different from any existing product to estimate the quality adjustment needed for a comparison to an existing product. They must therefore enter as an ‘added line’ in the structure of product strata of the top-level index. This entails adjusting the weights to make room for the new elementary index, and linking the new elementary index into the top-level index as part of a general updating of the item strata definitions and weights.⁸ The delay in bringing them into the index until the next update of the basket structure and weights poses a risk of bias because, depending on the pricing strategy and market conditions, novel products may initially exhibit distinctive price change behaviour. The most common pattern is for prices of truly novel products to decline quickly at first, so the bias is upward. A key issue with entirely new products is, then, avoiding a delay in getting them into the price index.⁹

18. There is another, more basic issue with new goods. Their standard treatment in price index compilation links them into the index basket in a way that prevents any immediate effect on the index. But from a conceptual point of view, consumer welfare in the period prior to introduction of the new good is the same as if a price existed that was just high enough to drive demand for that good to zero (Hicks 1940). The difference between this unobserved ‘reservation price’ and the observed price at the moment of entry is not captured in traditional price indices. From a welfare perspective, the standard treatment misses part of the effect of new products on consumers’ living standards.¹⁰

19. There is no agreed methodology for imputing reservation prices of new goods, and, in practice, no attempts have been made to include them in official price indexes.¹¹ There is thus a question of whether the unmeasured consumer welfare effects generated by the appearance of truly new digital products are significant. The answer is likely in the affirmative, but even rather large absolute welfare effects do not automatically entail large corresponding adjustments to aggregate deflators, and aggregate real growth. The reason is the small weight that typically attaches to recently introduced products.

the price statistics for just the reasons that the true price of light was not constructed. Similar problems arise as televisions replace cinemas, air travel replaces ground travel, and modern pharmaceuticals replace snake oil.” (p. 56).

⁸ The International Consumer Price Index Manual (ILO *et al.*, 2004) provides a detailed description of the issues associated with detecting and incorporating new products.

⁹ A chained index that tracks the entire path of the new good’s price from its high starting point to its lower, long-run equilibrium, with weights reflecting the rising quantities, would closely approximate the welfare gain. A pioneering study in this area dates back some 25 years: Berndt, Griliches and Rosett (1993) found that prices of new pharmaceuticals fell relative to the prices of older pharmaceuticals, reflecting a pricing strategy by drug manufacturers that raised the prices of older brands when new generic drugs entered the market. The authors constructed an alternative price index that brought new pharmaceuticals in as soon as they became available and that showed substantively lower price change than the then official U.S. price index for pharmaceuticals. This led to a modified sampling procedure by the U.S. Bureau of Labor Statistics (Triplett 2006, p. 112).

¹⁰ For reasons of symmetry, a reservation price should also be imputed for disappearing products. In the disappearing product case, the effect on the index of the imputation would be upward.

¹¹ Indeed, there is not even a consensus on the need to do so. Although proponents of the cost-of-living-index (COLI) approach take a sympathetic view of imputing a reservation price, as called for by theory, proponents of a more traditional cost-of-goods-index (COGI) approach do not favour imputation of reservation prices. For a discussion of the COGI approach, see National Research Council (2002). Hausman (1996) is a widely-cited study of introducing a reservation price for new variants of cereals.

2.3. Free products

20. There are many empirical studies of the value of new and free products that find important gains for consumers that may be insufficiently picked up by consumption price indices. For instance, Brynjolfsson and Oh (2012) investigate welfare gains from the Internet and conclude:

Our key findings are as follows: the average incremental welfare gain from the Internet between the years 2002 and 2011 is about \$38 billion per year [for the United States]. Of that amount, we estimate that about \$25 billion accounts for the consumer surplus from the free digital services on the Internet. This corresponds to about 0.19 percent of annual GDP. In contrast, the welfare estimates are significantly lower when we estimate it in a traditional way, relying only on money-based expenditures. The best estimate of the annual incremental welfare gain is only about \$2.7 billion when we do not consider the value of time. This is about 7 percent of the estimate derived from our preferred model.

21. In addition, Varian (2006) put a \$120 billion figure on Google's search engine based on the value of time savings to average users, and Bughin (2011) estimates the consumer surplus from the Internet to be about \$64 billion based on a survey where users stated their preferences. However, multiplying the \$17,530 median willingness-to-accept to forego access to Internet search engines found by Brynjolfsson, Gannamaneni, and Eggers (2017) by the number of adult Internet users in the U.S. would imply a surplus of almost \$3.8 trillion, or 30 percent of personal consumption expenditures in the U.S. national accounts.

22. Often, the digital goods and services examined in these studies are available free of charge to consumers. This increases consumer choice and consumer welfare. The question is whether, and if so, how, free goods should be reflected in consumption price indices.

23. Under a cost-of-living perspective, with all observed prices unchanged but more free digital services becoming available, the price index should decline to reflect the rise in living standards. This would occur by introducing free products into the price index and assigning shadow prices to them. To fix ideas, consider a situation where households' utility depends on a vector of products $q = [q_1, q_2, \dots, q_N]$ with a positive price $p = [p_1, p_2, \dots, p_N]$ and a set of 'environmental variables' $z = [z_1, z_2, \dots, z_M]$ for which there is no market price. This could be environmental variables in the sense of the term such as clean air or free digital products. Consumer utility is then given by $u = f(q, z)$ ¹² and the corresponding *variable or conditional cost function* (McFadden 1978) is:

$$C(u, p, z) = \min_q (p \cdot q : f(q, z) \geq u). \quad (1)$$

24. $C(u, p, z)$ thus indicates the minimum expenditure consumers incur on market products q given p and z . It can be shown that C is linearly homogenous and non-decreasing in p and non-increasing in z . A cost of living price index (Konüs 1939) conditioned on environmental variables z is then given by:

$$P(u, p^1, p^0, z) = C(u, p^1, z) / C(u, p^0, z). \quad (2)$$

25. By holding z constant, equation (2) reflects the basis for the current practice of considering only priced goods in constructing price indexes that estimate the COLI. To compute a price index that estimates equation (2) from just market prices and quantities, an assumption about the 'free' goods z is necessary. One possibility is to take z as remaining unchanged.¹³ This is, however, a strong assumption in an environment of rapidly emerging free products. Another possibility is to follow Diewert (2000), who

¹² The utility function $u(q, z)$ is continuous and quasi-concave, and increasing in q and z .

¹³ The more formal assumption that allows z to be ignored is separability of the cost function $c(u, p, z) = f(u)h(p)g(z)$.

shows that as long as the price index number formula is superlative¹⁴, and the effects of z on the consumption basket are monotonic, changes in z can be accommodated in the sense that the measured cost of living corresponds to some average level of z available between the periods of comparison.

26. While the latter assumption is a less stringent requirement, it is still the case that the COLI is *conditional on environmental variables*, including free products, and therefore does not reflect cost-of-living decreases due to the introduction of free products. What would a price index that makes explicit allowance for such free products look like? We can directly follow Diewert and Fox (2016) who demonstrate that the inclusion of free products into the consumers' cost minimisation leads to a cost function of the form $C(u,p,w)$ where w represent shadow prices for each environmental variable. Under cost minimisation, it holds that $w \equiv -\nabla_z c(u,p,z)$, i.e., shadow prices correspond to the marginal change in total costs to consumers due to the use of one additional unit of a free product. As Diewert and Fox (2016, p.11) point out: '[these are]...the appropriate prices to use when valuing the services of free goods in order to construct cost of living indexes or measures of money metric utility change'. Given shadow prices and quantities of free products, these would be introduced into the price index number formula just like any market product.

27. Unfortunately, there are two issues here. First, where would shadow prices come from? Another, more fundamental question is whether shadow prices should be introduced in a consumption price index in the first place. We consider these questions in turn.

28. Concerning the measurement of shadow prices, one option is assessing the consumer's willingness to accept a payment to give up free products via surveys or indirect measurement tools.¹⁵ One such indirect tool has been tried. Brynjolfsson, Eggers and Gannamaneni (2017) designed a sequence of discrete choice experiments to elicit U.S. consumers' willingness-to-accept to forego access to various kinds of free Internet services. The results imply large valuations for some of these free services, as high as \$17,530 to forego all search engines for a year.

29. Another option is to expand the model of consumer behaviour to include the consumer's time budget as a second constraint along with the normal monetary budget constraint. The opportunity cost of the time involved would then act to limit the consumption of free products. After all, the value of consumers' time constitutes the main impediment to increasing marginal use of free Internet and smartphone app products. The prices of the ICT equipment and communications services required to access the free products are, of course, a relevant for the decision of whether to consume the package of services, but once those prices have been paid, the only constraint on marginal consumption of more services comes from the time budget.

30. A third consideration is that many 'free' digital products are not in fact free, but involve an implicit payment through the consumer's acceptance of advertisements while using the free product (an app, for instance), or her acceptance to share personal data with the provider of free product.¹⁶ However, neither the valuation of time, nor the valuation of implicit contracts in exchange for viewing the free product, is straightforward in practice, and these approaches also raise theoretical issues.¹⁷ While extremely

¹⁴ Diewert (1976) defined a price index (quantity index) to be superlative if it is exact for a unit cost function capable of providing a second-order differential approximation to an arbitrary twice-differentiable linearly homogeneous function. The Fisher index number formula used in the U.S. national accounts is an example of a superlative form.

¹⁵ For a formal elaboration see for instance Diewert and Fox (2016).

¹⁶ See Ahmad and Schreyer (2016) for a discussion of the national accounting implications.

¹⁷ See for example Nakamura and Soloveichik (2015) for valuing free media or Diewert, Fox and Schreyer (2017) for a discussion of the conceptual and econometric issues in valuing consumer time for non-market activities and

valuable as a research project, the implementation of shadow prices in an official price index may raise questions of transparency, reproducibility, and, ultimately, credibility of the price index.

31. Concerning the more basic question of whether free products should be part of the COLI in the first place, much depends on the purpose of measurement. It is difficult to justify the inclusion of ‘free’ digital products into a COLI while at the same time excluding other non-market products that also command a shadow price in terms of the value of time: child care, care of the elderly, or gardening, to name just a few examples. This is even more so as these types of activity are clearly acts of production, in contrast to the time spent using free digital products, which may fall under leisure, not production. Another example is the environmental variable ‘life expectancy’ that has been steadily rising over the past decades in large parts of the world, thus raising consumer welfare for a given market consumption bundle.¹⁸ Rising life expectancy has a massive welfare effect that adds to the consumption of market products. Thus, full inclusion of non-market products and environmental variables would fundamentally change the character of the consumption deflator.

32. The answer to the question ‘Would the CPI be a better tool for policymaking if welfare from free goods or services were included?’ thus depends on the type of policy question under consideration.¹⁹ For example, for purposes of macro-economic management or monetary policy, a consumer deflator excluding free products is likely to be the right choice²⁰. On the other hand, measuring shadow prices of free products, the associated full income and extensive COLI is an important step towards broader measures of consumer welfare.

33. In summary, quality change of existing products, the emergence of new products, and free goods are not new issues, but the digital economy, with its fast pace of innovation, has brought them to the fore. Rapid change in available products and in product characteristic has increased the potential for price measurement shortcomings. Indeed, there is evidence of understatement of some price indices due to insufficient quality adjustment, and long lags in bringing new products into the index may also be a source of bias. The failure of the official price and volume indices to capture the welfare gains at the moment entry of truly novel new products, and the welfare effects of free products is well noted but practical and, to some extent, conceptual considerations support these omissions. Nevertheless, broader welfare effects are important to measure. This can be done as part of statistics “Beyond GDP”, as will be discussed below in Section 4.

3. What’s the potential impact?

34. The next task is assessing the potential bias in consumption deflators that may arise in conjunction with digital products. The discussion in Section 2 has identified some reasons why current

leisure. A simpler version with cross-country comparisons of full consumption (monetary consumption expenditure plus value of time) and the derivation of an associated consumer price index can be found in Schreyer and Diewert (2014).

¹⁸ Deaton (2013).

¹⁹ A 2006 U.S. National Academy of Sciences panel was unable to agree on whether welfare from new goods like cell phones and Viagra would be conceptually desirable to include, even if it could be measured.

²⁰ Note also that even if shadow prices of free products are not a standard element of a consumption price index, the effects of free digital replacements (Section 2.1) should and can be captured under standard price index methodology: At the point of entry, the zero price of the replacement product is compared with the positive price of the old product. Weights will be positive and reflect the base period if a Laspeyres index is used, or an average of base period and comparison period if a Fisher index is used.

price index compilation practices may not reflect the welfare effects from quality change and from novel and free products:

- a) Less-than-complete quality adjustment when new varieties of existing products and new products with similar functions to an existing product enter the sample, and lags in bringing in them into the index;
- b) Lags in bringing truly novel new products into the price index, and no imputation of a reservation price;
- c) No imputation of shadow prices for free products.

35. Section 2 also argued that some of the omitted welfare effects are not appropriate to include in official indexes of consumption prices, in particular when their main purpose is macro-economic management or monetary policy. In what follows, we shall therefore focus on issue a), because there is a consensus that quality change should be reflected in price index practice; indeed, this is recommended in international guidelines for price and volume measures. No quantification will be provided for the absence of reservation prices for truly novel products and for shadow prices of free services or more generally for effects of environmental variables. These are good candidates for broader welfare measures, but they are out of scope for the CPI and the deflator for household consumption from a macro-policy perspective.

Quality adjustment

36. It is sometimes forgotten that even significant biases in individual product categories only affect the aggregate picture in proportion to their weight. This oversight leads to what could be called ‘anecdotal fallacy’, whereby the bias in the price change of one particular product is extrapolated to the index as a whole. To avoid this fallacy, we consider the question: If prices of the affected products were corrected for the bias that could potentially be present, what would be the implications for the aggregate price index?

37. Our approach to quantifying the potential inadequacies in quality adjustment techniques proceeds by examining ‘pessimistic’ scenarios that assume that the official procedures largely overlook the quality changes in digital products. (Some of the relevant evidence has been summarized in Section 2). The main tool for our analysis is a detailed set of 145 private consumption expenditure weights from 34 OECD countries for the years 2005 and 2015 from the OECD Purchasing Power Parities database. Expenditure weights are not affected by any price measurement bias, but they provide the link to translate measurement errors in price changes of individual products to the aggregate price index. Our illustration of the plausible upper bound of the effects will be based on averages of the weights for each OECD member as of 2005.

38. We proceed in two steps. First, we classify all expenditure items into three groups based on the degree to which the price measures are likely to be affected by difficulties in measuring digital products:

- 1) ***Affected products***: products that clearly fall under the label of ‘digital’ and whose price measures are most prone to difficulties due to digitalisation, such as information and communication technology goods or communication services;
- 2) ***Unaffected products***: products whose prices are very unlikely to suffer from a measurement problem associated with the digital economy, such as food, tobacco or housing;
- 3) ***Possibly affected products***: products that are in between, such as cars or other consumer durables where digital features may have gone unnoticed in price measurement;

39. The second step is to further break down the categories 1) *Affected* and 3) *Possibly Affected* by type of effect. This breakdown is judgemental, but it is fit-for-use for the problem of determining an upper

bound of the plausible range for the impact on the measurement of the deflator for household consumption. Three kinds of effects may be distinguished:

- a) ***Quality adjustments in deflators of existing digital products***: for digital products where ***advances in technology*** are causing rapid quality improvement, it is plausible that official price indexes under-adjust for quality change. Affected products include telephone equipment, telephone services, and computers and software. Based on the growth rate gaps reported in Byrne and Corrado (2017b), we assume a ***5 percentage point per year over-estimation of the price change*** in the affected categories (which are shown in the top four rows of Table A-1 in Annex A. Bearing in mind that most countries have procedures in place to capture at least some of the quality change, this figure can be taken as an upper bound based on the available studies on selected products. In addition, we assume a ***2 percentage point per year over-estimation of the price change*** in the possibly-affected categories (next four rows of Table A-1). This is, again, an upper bound for the potential size of the bias. Motor vehicles are the largest of possibly-affected categories, and for them the existing procedures appear likely to capture most of the quality change. The composition of the other possibly-affected categories gives a relatively low weight to digital items with quality changes.
- b) ***Digital replacements***: Some digital products provide a free or cheaper replacement for a more expensive item that used to be the only alternative. For example, in some places Uber services are cheaper than a taxi. Or digital cameras made photo processing services unnecessary and, only to become unnecessary themselves as smartphones replaced a separate digital camera. Official price indexes only partially capture the cost-of-living declines from lower-cost or free digital replacements. For the item categories that have been extensively replaced by digital alternatives (shown in the top five rows of Table A-2), we assume that the cost of living index declines by ***5 percent per year*** relative to a conventional price index over the ten years from 2005 to 2015. Other digital replacements require some increases in spending elsewhere—one must first purchase a smartphone, or at least a computer and internet access services to benefit from the replacement. Also, there is an upper limit to this kind of bias, because once everyone has switched to the digital replacement, there are no further gains to be made. For categories in the possibly-affected group (in which items not replaced by a digital alternative predominate) we assume a ***1 percentage point decline in the cost of living***.
- c) ***Access and information enabling better selection of varieties***: E-commerce has expanded consumers' access to varieties, and online sources of information have reduced search costs for finding the best match for one's individual needs and tastes. Brynjolfsson, Hu and Smith (2003) provide some evidence on the welfare gains from increased access to variety for the case of books, finding that "obscure" titles accessible only through online bookstores accounted for 2.35 percent of online book sales. With a plausible value of 4 for the elasticity of substitution, the Feenstra (1994) formula for the effect of new varieties on a cost of living index implies a decline of about 0.8 percentage points from newly accessible books (Byrne, Fernald and Reinsdorf, 2017). If the expansion in the selection of books available online took four years, the average annual impact would be 0.2 percentage points. Second, better information that allows better selection of varieties affects almost any kind of differentiated product consumed by households. These welfare gains are a major part of Hulten and Nakamura's (2017) concept of "output-saving technological change".²¹ Table A-3 identifies the product categories that are relevant for the effects of online information or for both effects, and finds that they had a budget share of almost 17 percent in 2005. In absence of

²¹ Note that GDP measures output, so the label "output-saving" implies that the gains do not belong in GDP.

much direct evidence, we will assume *0.3 percentage point per year* over-estimation of the relevant prices as the upper bound for the variety effects. At least for recent years, this is probably too high. The gains from variety access and better information are concentrated in the early days of the Internet: once the variety set was already large, adding an additional variety would have had little marginal impact on welfare, and information is also subject to decreasing returns.

40. Table 2 shows the corrections to a household consumption price index whose purpose is assumed to be to estimate a broad cost-of-living index that accounts for welfare gains from quality change, digital replacements, and expanded and improved selection of varieties. The first observation here is that the categories of *affected* and *potentially affected* products account for 31.5 percent of consumer expenditure in 2015 (unweighted average across 34 OECD countries). In other words, over *two-thirds* of private consumption expenditure is unlikely to be subject to a measurement bias linked to the digital economy. The second observation is for each kind of effect (quality adjustment, digital replacement, better choice of varieties) the expenditure share has declined between 2005 and 2015. This may reflect declining relative prices of the products (or transition to free products), possibly coupled with an elasticity of substitution below unity. Whatever the precise cause, the consequence is that the sensitivity of aggregate inflation to measurement errors in prices of digital products has declined.

41. In terms of the simulated effects of possible measurement errors, the upper bound correction to the index's growth rate for overlooked quality change is about -0.3 percentage point, and the upper bound correction for improved variety selection is about -0.06 percentage point. The cost savings from digital replacements decline from about 0.2 percent of total consumption expenditures based on the 2005 weights to about 0.1 percent based on the 2015 weights. Combining all the effects, the upper bound for the potential bias from mismeasurement of digital products is just -0.56 percentage points in 2005 and just -0.44 percentage point in 2015. A correction on the order of half a percentage point to annual real consumption growth would not be insignificant, but it would moderate only a small fraction of the productivity slowdown,²² and it would not change the conclusion that we have entered a period of slow growth.

²² And if the question is the role of mismeasurement in the productivity slowdown, the quality change effect should be set aside, as quality change was similarly underestimated before the slowdown began.

Table 2: Corrections to Growth Rate of the Consumption Deflator if the Goal is to Estimate a Broad Cost-of-Living Index

	Assumed Measurement Error in Growth Rate of Prices (% points per year)	2005 Weight (unweighted average across 34 OECD countries) (%)	2015 Weight (unweighted average across 34 OECD countries) (%)	Correction to Growth Rate of the Consumption Deflator, 2005 Weights (% points)	Correction to Growth Rate of the Consumption Deflator, 2015 Weights (% points)
Significant potential for under adjustment for quality change (<i>'affected products'</i>)	5	3.50	3.10	-0.18	-0.16
Some potential for under adjustment for quality change (<i>'potentially affected products'</i>)	2	7.38	6.15	-0.15	-0.12
Potential effect on aggregate deflator of under adjustment for quality change				-0.32	-0.28
Significant replacement by alternative product from the digital economy (<i>'affected products'</i>)	5	2.36	0.99	-0.12	-0.05
Some replacement by alternative product from the digital economy (<i>'potentially affected products'</i>)	1	5.81	5.72	-0.06	-0.06
Potential effect on aggregate deflator of digital replacement				-0.18	-0.11
Significant potential for improved variety selection (<i>'affected and potentially affected products'</i>)	0.3	16.83	15.55	-0.06	-0.06
All potential effects on aggregate deflator		35.9	31.5	-0.56	-0.44

4. Two unorthodox points and *Beyond GDP*

4.1. *Hulten Paradox*

42. Hulten (1996) — in a discussion of the estimates of the price of light and potential measurement biases in long-term real income in Nordhaus' (1996) — concluded that our ancestors would have suffered from an implausibly low standard of living had there been a long-term upward bias in price measures of the magnitude suggested by Nordhaus. Here, we transpose Hulten's thought experiment to a shorter and more recent time period, but its basic spirit is unchanged.

43. The private consumption deflator in the US national accounts rose by 3.3 percent per year between 1959 and 2016. As shown in Table 2, in 1959, median household income was 5400 dollars at then-current prices. In today's prices, and given the 3.3 percent annual price increase, this 1959 income translates into 34 636 dollars/household. Compared with today's income of 59 039 dollars at current 2016 prices, there has thus been a 70 percent rise of real income over the past six decades.

44. Now assume that the private consumption deflator was biased upwards by 1 percentage point per year, so that 'true' inflation was only 2.3 percent per year. This yields a 1959 income of 19,588 dollars in 2016 prices, implying a tripling of material living standards over the six decades. And the 1959 median income, expressed in 2016 prices, would only be 11,077 dollars if a 2 percentage points upward bias is assumed, implying a *four-fold* rise in living standards in less than a lifetime ($59039/11077=4.33$). This seems high.

45. There is another telling comparison: By today's poverty threshold, the 1959 *median* income expressed in 2016 prices would lie just above the poverty line (1 percent bias scenario), or markedly below it in the 2 percent bias scenario. To be sure, none of this is hard evidence, and the Hulten Paradox rests on a hypothetical scenario. Nevertheless, it puts some plausibility limits on any *persistent and significant* bias in overall inflation measurement.²³

²³ A persistent bias may be less probable than a bias for shorter periods of time, as statisticians usually take measures to address known issues. For instance, hedonic quality adjustment methods for computers were introduced in the U.S. as early as 1986, and their use spread to other countries following the Boskin Commission.

Table 3: Median Income Per Household Under Alternative Inflation Assumptions (United States)

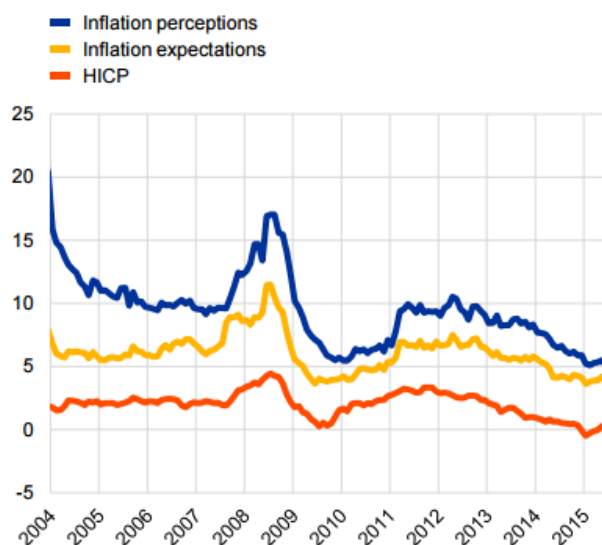
Year	Price basis	USD
2016	2016	59039
1959	1959	5400
1959	2016 with official PCE deflator	34636
1959	2016 prices with assumed bias 1%	19588
1960	2016 prices with assumed bias 2%	11077
Poverty threshold		
2016	2016, for HH size 2	15,569
2016	2016, for HH size 3	19,105
Source: US Bureau of Economic Analysis and US Census Bureau		
Real income change 2016/1959		
		70.5%
Real income change 2016/1959, 1% bias		
		201.4%
Real income change 2016/1959, 2% bias		
		433.0%

4.2. Perceived inflation

46. Central Banks, the European Commission, and other institutions have systematically monitored peoples' perceptions and expectations about consumer inflation. Expected inflation is obviously an important piece of information for central banks, given the role of expectations as a transmission channel of monetary policy. Yet, for the question at hand — whether there is a systematic upward bias in aggregate consumer inflation due to mismeasured prices of digital products — it is less the expectation of inflation than the gap between perceived inflation and measured inflation that is of interest. We take the European data, recently analysed by Arioli *et al.* (2017) as representative of a finding that seems to hold broadly: Despite differences between countries and over time, the level of perceived inflation is nearly always above the level of inflation as measured by consumer price indices.

47. There are explanations for such a discrepancy: incorrect weighting of price changes by consumers (small, frequently purchased items tend to get disproportionate weight in perceptions), other psychological reasons (price rises are better remembered than price drops) and, often-quoted, the fact that consumers do not account for quality change, whereas statisticians do. Thus, the 500-dollar cost of a new laptop today is registered as no price change over the 500-dollar laptop purchased three years ago, even if the new model offers vastly improved performance and weighs less than the old model. Another factor that may play out here is inequality. Households at different points of the income distribution may face different inflation rates and the survey results may summarise the experience of individual households differently from the aggregate consumer price index.

Figure 1. EU consumers' quantitative estimates of inflation perceptions and expectations



Source: Chart 4a in Arioli et al (2017); Note: HICP = harmonised consumer price index in the European Union.

48. The implications of these observations for the question at hand are of a qualitative nature. First, we simply note that consumers tend to believe that their own cost of living has risen by **more** than is shown by aggregate official price indices. Thus, if the official deflator is upward biased because it overlooks the welfare gains from digital products, correcting for such a bias will widen the gap between perceived and measured inflation. Perceived, rather than official, inflation is what drives many elements of consumer behaviour, so a wider gap may pose some issues both from a policy perspective and from a perspective of credibility of statistics.

49. Second, an observation of a more philosophical nature is that our theory of quality adjustment of consumer prices is firmly rooted in the picture of a utility-maximising, well-informed representative consumer. The measurement of welfare gains that come with new products, free products and digitally-enabled products relies on the same consumer theory. However, as the discussion of perceived inflation shows, consumers do not appear to make rational and well-informed judgements on the rate of inflation. Are consumers increasingly well off even if this is contrary to their own judgement? Or are consumers indeed rational but equipped with a more elaborate intuitive perception of their net welfare gains than the economic models underlying price measurement? For instance, people might intuitively factor in certain disadvantages that come with digital products (24/7 connectedness, extended working hours, loss of privacy, cybersecurity incidents, etc.). Or consumers might attribute less of a quality improvement to their new computer than statisticians because the higher-performing computer is simply necessary to accommodate more-demanding software that essentially performs the same tasks.

50. Any answer to this question is beyond the scope of the present paper, but a potentially wide gap between perceived and measured inflation is an issue that cannot be ignored as a matter of credibility and perceived quality of official statistics.

4.3. 'Beyond GDP'

51. The welfare gains from digital products are, undoubtedly, large. But from a statistical perspective, the question is, how many of these welfare effects should be packed into our core macro-

economic measures – consumption, real income, and GDP? Or should these welfare effects instead be identified in data designed to gauge quality of life *Beyond GDP*? One consideration is whether the macroeconomic measures would remain fit for key macro-economic policymaking purposes. While a consensus on this criterion will likely remain elusive, it can at least help with drawing the boundaries. For instance, a consumer price index that partly depends on shadow prices is unlikely to pass the criterion of fit-for-policy. Reproducibility of results, objectivity, and transparency of methods are additional criteria, along with purely practical considerations. For example, even if we set aside the conceptual problems, developing an estimate of a reservation price for a truly novel product is a major research project that would be impossible to conduct within the normal timeliness and resource constraints of statistical offices. At the same time, there are good reasons to go further in incorporating quality adjustments to the greatest extent possible, and in capturing new products early in their life cycle.

52. Another promising avenue is to attempt to systematically capture important dimensions of welfare and well-being in data sets that complement macro-economic aggregates. On the one hand, some elements of this work are conceptually tied to the *System of National Accounts* and provide additional depth to existing data, such as introducing distributional information into measures of household consumption or real income (Jorgenson and Schreyer 2017, Zwijsenburger, Bournot and Giovannelli 2017). In the area of price statistics, an analogous complement would be an investigation of whether the implied price changes from new goods disproportionately affect certain income groups. This sort of analysis could also be relevant for free services from digital platforms, and platform-enabled services and rentals.

53. On the other hand, the ‘Beyond GDP’ agenda clearly requires indicators on well-being and welfare that cover broader dimensions of life, economic and otherwise. The agenda has been set by Stiglitz, Sen and Fitoussi (2009) and work been put in place nationally and internationally (for instance OECD 2013, 2015, 2017). Current, and more specific research in the context of the OECD’s *Going Digital*²⁴ Strategy concerns the link between digitalisation and well-being. It aims at assessing the effects of digitalisation across major dimensions of the quality of life. These are highly relevant welfare effects, but none of them will be reflected in consumer price indexes, nor should they be.

5. Conclusion

54. The potential sources of distortion in the price index for household consumption can be divided into three categories: (1) neglected welfare gains from new and free goods, and from improved matching of variety characteristics and consumer tastes; (2) the cost savings from new free or low-cost products in the digital economy that directly replace existing products; and (3) incomplete adjustment for changes in the quality of products embodying digital technology. We argue that some of the more abstract welfare effects of new and free goods are relevant for a complementary welfare account but less relevant for the measurement in official GDP and consumer price statistics. With the help of detailed data on the weighting structure of household consumption in OECD countries, we calibrate upper bounds for the impact on the deflator for household consumption of incorporating the remaining welfare gains (though their inclusion in GDP is also debatable), the cost savings, and complete adjustments for quality change. The upper bound adjustment to the index’s growth rate for omitted welfare gains is about –0.2 percentage point using 2005 weights, and –0.1 percentage points using 2015 weights. The upper bound adjustment for the welfare gains from better matching of variety characteristics and consumer tastes is –0.06 percentage points. The upper bound adjustment for possible under adjustment for quality change in digital products such as computers, and telecommunication equipment and service is around –0.3 percentage point. Although an overall effect of almost –0.5 percentage point is by no means insignificant, the scale of the adjustment for the potential mismeasurement of the digital economy is not large enough to change the picture of low growth in productivity and output.

²⁴ <http://www.oecd.org/going-digital/>

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ANNEX A. WEIGHTS IN HOUSEHOLD CONSUMPTION BASKET OF PRODUCT CATEGORIES POTENTIALLY AFFECTED BY MEASUREMENT ERRORS IN DEFLATORS

Table A-1. Weights in Household Consumption of Products with Potentially Overlooked Quality Improvements
Unweighted averages across 34 OECD countries

Product Category	Potential Source of Measurement Error	2005 Weight (per mil)	2015 Weight (per mil)
Telecommunication equipment	Overlooked quality change	2.1	4.1
Telecommunication services	Overlooked quality change and replacement by digital alternatives	27.1	23.8
Information processing equipment and software	Overlooked quality change	4.5	4.9
Photographic/cinematographic equipment	Overlooked quality change and replacement by the smartphone	1.3	0.9
Major and small HH appliances	Possibly/partially affected by overlooked quality change	11.2	9.5
Equipment for the reception and recording of sound and vision	Possibly/partially affected by overlooked quality change and replacement by online services	7.0	5.3
Motor vehicles and parts	Possibly/partially affected by overlooked quality change	50.8	42.6
Games, toys and hobbies	Possibly/partially affected by overlooked quality change	4.8	4.2
Total		108.8	95.3

Table A-2. Weights in Household Final Consumption of Products subject to Replacement by Digital Alternatives¹
Unweighted averages across 34 OECD countries

Product Category	Digital Alternative providing Replacement	2005 Weight (per mil)	2015 Weight (per mil)
Passenger transport, taxi or hired car with driver	Platform-enabled ridesharing	3.1	3.0
Pre-recorded recording media	Digital media, downloads and streaming	2.2	1.2
Unrecorded recording media	Digital downloads and streaming	1.1	0.4
Newspapers and periodicals	Online media	6.8	4.5
Category containing film developing and printing	Digital cameras and storage media	10.4	0.7
Books ²	e-books and used books bought online	4.7	3.3
Passenger transport by air ²	Internet enables households to be their own travel agent	6.8	8.9
Package holidays ²	Digital replacement for travel agents	8.1	9.3
Accommodation services ²	Sharing economy replacement for hotels	14.1	15.6
Services for maintenance and repair of dwelling ²	YouTube enables do-it-yourself repairs	4.6	4.1
Postal services ²	Online billing paying (and quality improvement from online tracking of packages)	1.1	0.9
Jewellery, clocks and watches ²	Smartphone replaces watches and clocks	4.3	3.9
FISIM ²	Better rates of online banks and peer-to-peer lenders	14.2	14.6
Total		81.5	70.4

1. The adjustment for quality change in photographic instruments and equipment for reception and recording of sound and vision is assumed to include effect of digital replacements, so they are omitted here.
2. Replacement by digital alternative limited in scope.

Table A-3. Weights in Consumption of Products where Digitalisation may have Enabled Improved Variety Selection
Unweighted averages across 34 OECD countries

Product Category	2005 Weight (per mil)	2015 Weight (per mil)
Cloth and clothing	51.6	44.5
Furniture, floor coverings, HH textiles, and repairs thereof	25.0	19.8
Games, toys and hobbies	4.8	4.2
Newspapers and periodicals	6.8	4.5
Books	4.7	3.3
Other durable and nondurable HH goods	18.3	16.9
Restaurants, cafes and dancing establishments	38.4	42.6
Accommodation services	14.1	15.6
Services for maintenance and repair of dwelling	4.6	4.1
Total	168.3	155.5