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The Productivity Slowdown in Canada: an ICT phenomenon?[1]

by

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Abstract

We ask whether a weaker contribution of information and communication technologies (ICT) to productivity growth could account for the productivity slowdown observed in Canada since the early 2000s. To answer this question, we examine several methods capturing various channels through which ICT could affect aggregate productivity growth. This includes an approach "à la Cette, Clerc and Bresson (2015)," focused on the use of ICT capital, and shift-share analyses capturing the effects of reallocation and productivity growth of the ICT-producing sector. We also examine two-sector models. An approach "à la Oulton (2012)" highlights the role of relatively weak ICT prices growth. However, Oulton's approach is based on strong assumptions about the structure of the economy, some of which are inconsistent with Canadian data. We therefore propose a different approach, based on assumptions that are less restrictive while still capturing various channels (production, capital deepening, price effects) through which ICT contributes to productivity growth. Preliminary results indicate that, while ICT contribution to aggregate labour productivity growth has remained strong, it has declined and appears to explain between 0.1 and 0.2 percentage points per year of the productivity slowdown.

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[1] The views expressed in this paper are solely those of the authors and may differ from official Bank of Canada views. No responsibility for them should be attributed to the Bank.

1. Introduction

After averaging 1.6 per cent from 1994 to 2003, labour productivity growth in Canada, as measured by Statistics Canada, only averaged 1.1 percent from 2004 to 2014. The slowdown is not unique to Canada, as it has affected most OECD countries (Syverson, 2017).[2]

Various explanations for the productivity slowdown have been proposed. For instance, Gu (2018) concludes that, in Canada (he focusses on the 2000-2014 versus 1980-2003 periods), it can be partly explained by the increased cost of extracting natural resources with declining ore grade and a decline in the utilization of capital in the manufacturing sector. Other researchers have explored the role of new technologies. For instance, Gordon (2012) claims that the fundamental problem is that today's innovations do not compare in scale or impact with the breakthroughs of the 1990s, let alone the wave of earlier transformations.

Some researchers have tried to quantify the contribution of technology to the productivity slowdown. For example, using one-sector growth accounting, Cette, Clerc, and Bresson (2015) assess the contribution of information and communication technologies (ICT) to labour productivity growth via their impact on capital deepening. They conclude that, after rising significantly in the 1994-2003 period, ICT contribution fell in Canada, the United States, the Euro zone, and the United Kingdom.

The Cette, Clerc, and Bresson model is intuitive, and is a traditional approach applied in the literature to measure the contribution of a specific type of capital use. However, capital deepening is not the only channel through which ICT can affect the growth of aggregate labour productivity. Oulton (2012) builds a two-sector (ICT and non-ICT) model that he uses to measure various channels through which ICT can contribute to productivity growth. His main contribution is to highlight the impact of relative ICT price declines, which he links with ICT total factor productivity (TFP) growth, on aggregate labour productivity growth. Specifically, Oulton argues that the relative price growth of ICT embodies the difference in TFP growth rates in the ICT sector compared to the rest of the economy. By assumption, TFP in the ICT sector

[2] The data up to 2016 suggests an even more accentuated slowdown (some of the methods we examine require data that are not available after 2014). Bergeaud, Cette and Lecat (2016) take a longer-term perspective to show that, in the United States, productivity started to slow after 1940. The spreading of ICT caused productivity to accelerate from 1980 to the early 2000s, but it slowed again thereafter. They also show that the slowdown started later in the Euro area and Japan and was less affected by ICT.

grows faster than in the non-ICT sector, so that the more ICT is used and produced, the more efficiency gains are passed on to aggregate productivity growth through the technological progress coming from ICT.

Oulton does not compare periods, but finds that ICT contribution to productivity has been strong in a group of OECD countries including Canada. Byrne and Corrado (2017) extend the Oulton (2012) model to include the contribution of intermediate business services. Focusing on the United States, they also conclude that the contribution of ICT has continued to be strong in the post-slowdown period.

In the present paper, we ask whether a weaker ICT contribution to productivity growth could account, at least in part, for the slowdown observed in Canada since the early 2000s. To answer this question, we first update the analysis of Cette, Clerc and Bresson (2015) for Canada, which informs us about the contribution of ICT capital deepening to aggregate productivity growth. We then perform simple shift-share analyses that indicate whether productivity growth in the ICT-production sector and changes in the amount of resources dedicated to that sector could account for Canadian aggregate productivity developments. We then combine these two concepts via a steady-state two-sector model.

Recognizing that declining ICT prices are a distinctive feature of technological progress that can lead to efficiency gains, we re-examine the two-sector model proposed by Oulton (2012). We apply the Oulton model to Canadian data for the periods 1994-2003 (pre-slowdown) and 2004-2014 (post-slowdown). While we find appealing the idea that relative ICT price growth contains information on the impact of ICT on aggregate labour productivity growth, we also find that the assumptions made in the model are far too restrictive for Canadian data. Specifically, we note that it supposes that the production functions of the ICT sector and the non-ICT sector are identical, except for different TFP growth rates. We therefore develop an alternative approach allowing for these differences in production functions and for distinct contributions from three different types of ICT assets: telecommunication equipment, software and computer hardware.

Our main conclusion is that, while ICT contribution to aggregate labour productivity growth has remained strong, its contribution has declined post-slowdown, which explains a portion of the productivity slowdown. However, when using a model that incorporates the relative prices of

ICT, the decline in ICT contribution is not as dramatic, indicating that relative prices may be an important channel through which ICT can affect labour productivity growth.

The paper will proceed as follows: we present our methodology in Section 2, we discuss the data in Section 3 and present our results in Section 4. We conclude in Section 5.

2. Methodology

Our goal is to determine whether ICT developments have contributed to the productivity slowdown in Canada. In answering this question, we consider various existing methodologies reflecting the main channels through which ICT developments could affect productivity.

2.1 An approach focused on the use of ICT (use effect)

The contribution of ICT to aggregate labour productivity growth comes partly from the contribution of ICT investment to the economy's stock of capital. This is the "use effect." Cette, Clerc, and Bresson (2015) focus on this channel in assessing the contribution of ICT to labour productivity growth in Canada, the United States, and Europe. For each ICT component (hardware, software, and communications equipment) they consider the contribution (denoted here as UE_{jt}) of the use of capital to labour productivity growth for type of ICT capital j in year t as follows

$$UE_{jt} = \alpha_{jt}(\dot{k}_{j,t-1}). \qquad (1)$$

In equation (1), k_j is ICT capital type j divided by the total number of hours worked. The dot refers to the growth rate of the variable. The coefficient α corresponds to the share of type j ICT capital income in nominal GDP.

Cette, Clerc, and Bresson (2015) find that, after having risen significantly in 1994-2004 compared to 1974-1994, the contribution of ICT to labour productivity growth subsequently fell in the 2005-2013 period. We update their results for Canada in Section 4.

2.2 An approach focused on ICT-production and reallocation

In theory, changes to the size of the ICT-production sector could account for fluctuations in aggregate labour productivity growth. We examine this possibility by performing shift-share decompositions. Our main approach for this is the TRAD decomposition described in de Avilez (2012). This expresses the relationship between aggregate labour productivity growth ($\dot{y}$) and industry-level labour productivity growth as follows:

$$\dot{y}_t = \sum_{i=1}^{I}[WSE_{i,t} + RLE_{i,t} + RGE_{i,t}]. \qquad (2)$$

In equation (2), t is time, and the contribution of a given industry i to aggregate productivity growth is the sum of three components:

- a within-sector effect ($WSE_{i,t}$), measuring how productivity growth within industry i raised aggregate productivity growth keeping the industry share constant;
- a reallocation level effect ($RLE_{i,t}$), measuring how reallocation of labour into industry i increased aggregate productivity growth if industry i had an above-average productivity level;
- a reallocation growth effect ($RGE_{i,t}$) measuring how reallocation of labour into industry i increased aggregate productivity growth if industry i had an above-average productivity growth rate.

Reallocation of labour either away or towards the ICT-production sector will have positive (negative) effects on aggregate productivity growth if that sector has done relatively well (poorly) either in level ($RLE_{i,t}$) or in growth rate ($RGE_{i,t}$).

As a robustness check [the empirical application is forthcoming], we also used the GEAD formula, also described in de Avilez (2012). A main difference between TRAD and GEAD is that, while TRAD uses real output shares, GEAD uses nominal output shares. With TRAD, the sum of the sectors' contributions may not add up to aggregate productivity when chained index number formulas are used by the statistical agency to measure real output (as is the case in Canada).[3] With GEAD, sectoral contributions always add up to the aggregate. Another difference is that price effects might affect measures of reallocation in GEAD, but not in TRAD.[4]

2.3 An approach joining the use and production effects (joint approach)

A two-sector approach allows us to combine the concepts that ICT can affect aggregate labour productivity through the its use and its domestic production. Beginning with Cobb-Douglas

[3] As discussed below, however, GDP in constant dollars is used wherever possible which should alleviate this concern.
[4] See de Avilez (2012) for a detailed discussion.

production functions for labour productivity, the non-ICT (*N*) and ICT (*T*) sectors can be expressed as follows:

$$y_N = B_N(k_N^N)^{\gamma}(k_T^N)^{\sigma}(h_N)^{1-\gamma-\sigma}, \qquad 0 < \gamma, \sigma < 1;\ \gamma + \sigma < 1 \qquad (3)$$

$$y_T = B_T(k_N^T)^{\theta}(k_T^T)^{\eta}(h_T)^{1-\theta-\eta}. \quad 0 < \theta, \eta < 1;\ \theta + \eta < 1 \qquad (4)$$

In equations (3) and (4), y_N is labour productivity in the non-ICT sector and y_T is labour productivity in the ICT sector. B_i is total factor productivity in sector $i = N, T$. Variables k_N^N, k_T^N, k_N^T and k_T^T are the stocks of non-ICT and ICT capital in per hour terms used in sectors *N* and *T* (subscripts represent the type of capital and superscripts represents the industry of use). Finally, h_i is the average level of skill (human capital) in sector i.

In the steady state, we assume that aggregate labour productivity growth can be expressed as a weighted average of labour productivity growth in the two sectors:

$$\dot{y} = (1 - q_T)\,\dot{y}_N + q_T\dot{y}_T. \qquad (5)$$

In equation (5), q_T is the hours share of the ICT sector.

The sector N production function can be expressed in growth rate terms as follows:

$$\dot{y}_N = \mu_N + \gamma\dot{k}_N^N + \sigma\dot{k}_T^N + (1 - \gamma - \varphi)\dot{h}_N, \qquad (6)$$

where μ_N is the TFP growth in the non-ICT sector. The term $\sigma\dot{k}_T^N$ captures the contribution of ICT capital to productivity in the non-ICT sector. We can therefore express the total contribution of ICT to aggregate productivity growth as

$$CO_{1,T} = (1 - q_T)\sigma\dot{k}_T^N + q_T\dot{y}_T. \qquad (7)$$

The first term on the right-hand side of equation (7) captures the contribution of ICT capital in the N sector (use effect) and the second term captures the contribution of productivity in the T sector (production effect). Note that the contribution of ICT capital deepening to productivity in sector T is captured within the term $q_T\dot{y}_T$. It is therefore an important difference from the one-sector model that the term $(1 - q_T)\sigma\dot{k}_T^N$ only captures ICT capital deepening in the non-ICT sector.

2.4 Two-sector approaches with explicit price effects

Equations (1), (2) and (7) capture the effects of ICT on labour productivity growth coming from the use of ICT capital, the reallocation of labour to and from the ICT-producing sector, and the production of ICT goods and services. However, it may be that the impact of ICT prices is not fully captured in these approaches. Oulton (2012) proposes a two-sector model (see Appendix A of his paper for a full presentation and derivation of the model) that explicitly accounts for relative ICT prices when measuring the contribution.

Oulton (2012) shows that, in a steady state, ICT price changes relative to non-ICT price changes ($\dot{p} = \dot{p}_T - \dot{p}_N$) equal (the negative of) relative ICT TFP growth rates, i.e.,

$$\dot{p} = \mu_N - \mu_T. \quad (8)$$

In equation (8), $\dot{p}$, the relative ICT price change, is negative, reflecting the extent to which the relative growth of TFP in the ICT sector exceeds the growth of TFP elsewhere in the economy.

Oulton also shows that the model's steady-state solution for the contribution of ICT to the growth of labour productivity can be expressed as follows:

$$CO_{1,T} = \frac{\bar{v}_{K_T}}{\bar{v}_L}(-\dot{p}) + \bar{w}_T(-\dot{p}). \qquad (9)$$

In equation (9), the first term represents a use effect, where $\bar{v}_{K_T}$and $\bar{v}_L$ are the shares of ICT capital and labour in total income (bars indicate steady-state values), respectively. The second term, where $\bar{w}_t$ denotes the relative size of the ICT sector in nominal output, represents the "production effect." Oulton's main conclusion is that ICT has been an important source of productivity growth. His model, which he applies to 15 European and 4 non-European countries, implies that the main boost to growth has come from ICT use, not ICT production. For Canada, while the contribution of ICT use to labour productivity has been 0.58 percentage points per year (p.p.p.y.), that of ICT production has been 0.09 p.p.p.y. This is based, for Canada, on shares calculated as their 2000-2004 average and on declines of 7 percent in relative ICT prices. Oulton does not compare historical episodes. In Section 4 we present estimates based on his model for two periods: 1994-2003 and 2004-2014.[5]

An important assumption made by Oulton (2012) (and by Byrne and Corrado, 2017) is that the production functions of the two sectors are identical, except for the different TFP growth rates. However, this assumption is inconsistent with Canadian data, as is illustrated by Tables B.1 and B.2. Note, in particular, that the ICT capital shares of the two sectors have been very different. For instance, the ICT capital share of the ICT sector has been, on average, 15.2 percent post-slowdown. Meanwhile, the ICT capital share of the non-ICT sector was 4.6 percent. Labour shares are also quite different. Interestingly, real ICT capital growth has been faster for the non-ICT sector in the post-slowdown period (5.6 percent vs 0.7 percent).

To see whether these differences can affect conclusions concerning the role of ICT in explaining the productivity slowdown, we examine an extension of Oulton's model in which we relax the assumption that the production functions are identical. Equation (9) then changes to take the following form:

$$\frac{\bar{v}_{K_T}}{\bar{\bar{v}}_L}(-\dot{p}) + w_T\left(\left[\dot{k}_T^T - \dot{k}_T^N\right] - \dot{p}\right). \qquad (10)$$

For details about this solution, see Appendix A. Equation (10) clearly differs from the solution to the original Oulton model. This is made clear by the presence of $\left[\dot{k}_T^T - \dot{k}_T^N\right]$. While the second term of Equation (9) could plausibly reflect a production effect contributing to productivity, this is clearly not the case for Equation (10). Why would stronger ICT capital investment in the non-ICT sector, as reflected in $\dot{k}_T^N$, be negative for productivity? Additionally, w_T is no longer constant in this specification, which implies the model is not in steady-state.

In short, while some assumptions used by Oulton (2012) seem inconsistent with Canadian data, simply relaxing these assumptions does not provide a model to assess the contribution of ICT to productivity growth.

[5] Byrne and Corrado (2017) propose a model that differs from Oulton (2012) in that it incorporates the effects of ICT services (e.g. cloud services and data analytic services) as an intermediate input. They, too, assume that the production functions of the ICT and non-ICT sectors are the same, except for different TFP growth rates. They apply their model to United States data and find that the contribution of ICT has remained strong after 2003. Unfortunately, data limitations (the data on ICT services is affected by definitional change in 2008) prevent us from applying this model to Canadian data. We plan to address the data problem and examine the issue in future work.

2.5 A two-sector approach with explicit price effects and different production functions

An interesting feature of the Oulton approach in that it explicitly measures the impact of relative ICT prices on aggregate labour productivity. However, the assumption of identical production functions is much too strong, and relaxing that assumption gives an equation that likely no longer reflects the contribution of ICT in the steady-state. Therefore, we derive a different equation that retains the relative price component of the Oulton model but makes less restrictive assumptions.

We begin with production functions as expressed in equations (3) and (4) where income shares and the growth rates of the capital inputs are now allowed to differ. Assuming perfect competition and a simple Jorgenson user cost formula, we can derive a new expression for $\dot{y}_N$ (see Appendix A for full derivation):

$$\dot{y}_N = \frac{\mu_N}{(1-\theta-\eta)} + \dot{h}_N + \frac{\eta}{(1-\theta-\eta)}(-\dot{p}), \qquad (11)$$

where the third term on the right-hand side is the use effect in the non-ICT sector. Like in Oulton, this effect says that as ICT prices become cheaper relative to the rest of the economy, and as people allocate more of their income towards ICT relative to their labour costs, there will be efficiency gains that show up in labour productivity growth.

Next, we assume that in the steady-state aggregate labour productivity growth is an hours weighted share of labour productivity growth in the two sectors, i.e.

$$\dot{y} = (1 - q_T)\dot{y}_N + q_T\dot{y}_T \qquad (12)$$

As in Section 2.3., we label the second term on the right-hand side as the production effect. Lastly, we can substitute equation (11) into (12) and get an expression for the contribution of ICT capital that is the sum of an use effect and a production effect.

$$CO_{3,T} = (1 - q_T)\frac{\sigma}{1-\gamma-\sigma}(-\dot{p}) + q_T\dot{y}_T \qquad (13)$$

Equation (13) differs from Oulton's contribution term in a few key ways. The first is that the use effect is now in terms of the non-ICT sector, and is weighted by that sector's share of hours worked.

Oulton uses the share of nominal output, as this share is presumably constant in his steady state model because the difference in real output growth is equal to the relative price growth. In our specification, nominal output grows at different rates in the two sectors, and if we define the steady state as one where aggregate labour productivity growth is constant, using the nominal output shares is problematic. However, we do not relax the assumption in this model, made also by Oulton, that in a steady-state the growth rate of hours worked in both sectors is the same. Thus, equation (12) is constant in the steady state. We feel that defining labour productivity growth as the sum of the hours weighted share of growth in the two sectors is not unreasonable, and allows us to solve the model for the steady state.

A second key difference is that our production effect does not have a relative price term and is identical to the production effect found in Section 2.3. We make the change here because, as mentioned in Section 2.4., this term in the Oulton model reflected the relative growth rates of labour productivity, and by extension, TFP. In the world where the assumption of identical production functions is relaxed we can argue that the relative price growth perfectly embodies the relative growth of TFP. Additionally, by assumption the TFP in the ICT sector grows faster than in the non-ICT sector, so that the magnitude of that difference (weighted by the size of the ICT sector) reflects the positive contribution of ICT production to aggregate TFP growth, and thus labour productivity growth (because the production functions are the same except for TFP). In our model, ICT sector contribution includes more factors than just its relative TFP growth. For instance, the production effect now contains the contribution to labour productivity of the use of ICT capital *within* the ICT sector, because this term now differs from the use in the non-ICT sector. Therefore, a term that sums the different components of the ICT sector production function that contribute to labour productivity growth is necessary.

In the traditional one-sector model and the joint approach presented in Sections 2.1. and 2.3., the impact of prices is implicitly captured through the capital income share, although with opposing elements as the growth of prices has a negative effect on the user cost formula but the level of prices would have a positive effect. Of course, the impact of prices is also captured as firms will presumably invest and use more ICT capital as it becomes more affordable. Our model makes the effect of prices, or more accurately, relative prices explicit. While the Oulton model makes the claim that relative price growth embodies the difference in the growth of TFP between the two sectors, we prefer to claim that relative ICT price growth instead embodies the decisions of, and benefits to, the users of ICT capital. As ICT prices become cheaper compared to the rest of the investment and consumption goods, the efficiency gains are passed through to the users as they are not only able to purchase more ICT capital but other types of capital as well. Therefore, the price growth difference reflects efficiency gains that ICT users are able to incorporate into their production functions which has an effect on aggregate labour productivity growth.

In Section 4, we calibrate equations 1, 2, 7, 9 and 10 with Canadian data. We describe the data in Section 3.

3. Data

The data used to calibrate the models are either taken from CANSIM or received upon special request from Statistics Canada. All measurements are for the total economy. However, we will assess the robustness of our results using business-sector data.

The ICT-producing sector is defined as the sum of NAICS codes 51 (information and cultural services), 334 (computer and electronic product manufacturing), and 5415 (computer system design and related services). This differs somewhat from the official Statistics Canada definition, which is classified at a more granular level. Data constraints explain our choice of definition, but we also note that it is consistent with some literature (Syverson, 2017).[6]

There exists some debate in the literature as to the measure of output that is preferable for the two-sector models. In Byrne and Corrado (2017), the authors sum the consumption, investment, and net exports of specific ICT goods and services. However, because we have data on the use of ICT capital by sector, we elect to use GDP from the System of National Accounts for the three NAICS codes described above, which will be consistent with data reported in the productivity accounts.

In the Oulton model, and in our model, the choice of prices is a crucial one.[7] We follow Oulton (2012) and use the implicit investment price index for the price of ICT, and use the N sector GDP deflator as a proxy for the non-ICT sector prices (Table 1).[8] These data, along with capital cost and stock data, are taken partially from the publicly available capital accounts, as well as by special request.

[6] For ICT capital cost and stock in the ICT sector, data on NAICS 5415 was not available. However, as these variables use either ratios or growth rates, we believe that NIACS 51 and 334 are a reasonable approximation.
[7] In future work we will assess the sensitivity of our results to using the ICT price adjustments proposed by Byrne and Corrado (2017).
[8] Although Oulton uses private fixed investment, we use total fixed investment prices as we are concerned with the total economy.

Table 1. Price Growth

	Pre-slowdown	Post-slowdown
N sector GDP deflator growth	1.99	2.38
ICT capital price growth	-1.09	-2.03
Computer hardware*	-8.13	-6.25
Telecommunication equipment*	-0.53	-2.69
Software	0.85	0.93

Capital per hour terms are calculated as the capital stock divided by total hours. Ideally, capital services would be used to get a measure of the services derived per hour worked. However, capital input is unavailable at the granular level we require either at the industry level or for the type of capital (i.e. computer hardware, telecommunications equipment, and software). Additionally, for the joint model we are able to calculate ICT capital for the non-ICT sector, but are unable to break it down into the three types of capital. We therefore assume that the ratios of these capital types are the same in the non-ICT sector as they are for the total economy. We hope to refine this assumption in later versions of this paper.

Capital cost is calculated assuming constant returns to scale and thus subtracting labour compensation from nominal GDP for the total economy as well as for the two sectors. Shares of the capital cost attributed to ICT are taken from Statistics Canada's Multifactor Productivity program at the business sector and then applied to aggregate economy capital share. More information on constructed or custom variables is provided in Appendix B.

4. Results

a. *Traditional One-Sector Model*

Our first method to examine the impact of ICT on productivity relies on a method employed by Cette et al. (2015) and others. The growth accounting equation enables researchers to measure the impact of the total use of ICT capital on labour productivity.

Table 3. One-Sector Growth Accounting Results

	Computer Hardware	Telecommunication Equipment	Software	Total Contribution
1994-2003	0.20	0.05	0.17	**0.48**
2004-2014	0.13	0.01	0.12	**0.27**
2004-2016	0.10	0.00	0.12	**0.23**

Using this method, we find similar results to those of Cette et. al (2015) as shown in Table 3. The contribution of ICT capital use to labour productivity growth in this model declined from 0.48 p.p.p.y. in the pre-slowdown period to 0.27 p.p.p.y. in the post-slowdown period. One advantage of using this approach over the two-sector models is that the data requirements are less demanding, and we can therefore update the results to 2016, which decreases the contribution further post-slowdown. The decline since 2003 comes largely from both computer hardware and from software, and to a lesser extent telecommunications equipment. As can be seen in Chart B.3, most of the decline in the use of these capital types came after the great recession. In fact, in the mid-2000s the growth rates of real ICT capital rose to that of the late 1990s, but have not recovered since they fell dramatically in 2008. Unsurprisingly, much of this decline came from within the finance, insurance, real estate, rental and leasing sector, as well as from information and cultural industries, which had a combined share of 47 per cent of the real ICT capital stock in 2007, but had average growth rates of -5.5 per cent and -2.7 per cent from 2009 to 2016, respectively.

b. Shift-Share

The shift-share methodology allows one to examine both the within-industry productivity gains, as well as the effect on aggregate productivity of workers reallocating to sectors with different levels and growth rates of labour productivity. These reallocation effects are the main advantage of using a shift-share approach, especially given that the steady-state models we employ assume that there is no reallocation between sectors. However, as seen in Table 2, the reallocation effect has been negligible throughout both time periods. This is because the level of productivity in the ICT-producing sector since the mid-1990s has been quite similar to that of the total economy average.

The within-sector effect, however, is not insignificant. Particularly in the pre-slowdown period, the ICT sector only represented 4.10 per cent of real GDP, yet contributed 0.14 p.p.p.y. to aggregate labour productivity growth. This was due to the 3.36 per cent growth of labour productivity in the ICT sector over that period. In contrast, the ICT sector actually increased in relative size in the post-slowdown period to gain a real GDP share of 4.93 per cent, but had labour productivity growth of only 1.55 per cent on average, and therefore contributed less in the post-slowdown period.

Table 2. Shift-Share Results

	Pre-slowdown	**Post-slowdown**
Labour productivity growth	1.59	1.05
ICT sector contribution	**0.14**	**0.07**
Reallocation	0.01	-0.01
Within-sector	0.14	0.08
All else	1.45	0.98

c. *Two Sector Growth Accounting*

In this section, we calibrate the three versions of the two-sector model: the joint approach, the Oulton (2012) approach, and our model. The results are summarized in Table 4.

Table 4. Two-Sector Model Results

		Joint ($CO_{1,T}$)	**Oulton ($CO_{2,T}$)**	**Our model ($CO_{3,T}$)**
Pre-slowdown	**Contribution**	**0.50**	**0.60**	**0.53**
	Use effect	0.38	0.45	0.41
	Production effect	0.12	0.15	0.12
Post-slowdown	**Contribution**	**0.29**	**0.59**	**0.40**
	Use effect	0.23	0.38	0.35
	Production effect	0.06	0.21	0.06

First, the joint approach suggests that the contribution of ICT to labour productivity growth was 0.5 p.p.p.y. in the pre-slowdown period, and then fell to 0.29 p.p.p.y. in the post-slowdown period. While the use effect is quantitatively much larger, a significant portion of the decline in contribution comes also from the production effect. This is important because, as mentioned, a key difference in this methodology compared to the one-sector approach is that the use effect is specifically for the non-ICT sector, while the one-sector model amalgamates all ICT capital use into one coefficient.[9] The two-sector model points to the fact that a large portion of the decline in the use of ICT capital is coming from the ICT sector itself.

Next, we estimate the Oulton approach. While we ultimately do not put much stock in this method, it is interesting that in the world where the Oulton assumptions hold true, the

[9] We assume here that the share attributed to each ICT capital type is the same as in the total economy, and therefore the slowdown in the use effect in this approach will have the same proportions as the one-sector model. We can, however, provide a rough estimate of the contributions from each type of capital (forthcoming).

contribution of ICT to productivity growth remains stable. Any decline that occurs comes entirely from the use effect in this model, while the production effect increases between the two periods. This is because the average nominal output share is almost identical in the pre- and post-slowdown periods, while the relative price growth of ICT is larger in absolute terms, leading to a larger production effect. On the other hand, the declining ICT capital income share (Table B.1 and B.2) combined with a stable labour share more than compensates for declining prices within the use effect.

Lastly, we calibrate our model. We find that the contribution to labour productivity growth was 0.53 p.p.p.y. in the pre-slowdown period before declining to 0.40 p.p.p.y. post-slowdown. As can be seen in Table 4, many of the qualitative conclusions are similar to the joint model. A key difference, however, is that the contribution is higher in our model for both periods. This seems to indicate that relative ICT prices contain additional information about how ICT is affecting aggregate labour productivity growth. More importantly, perhaps, is that our model indicates that the decline in the contribution is less pronounced than in the joint approach. This seems to indicate that declining ICT prices are relatively more important in the post-slowdown era as the non-ICT sector's use of ICT capital becomes relatively larger.

We can further break down the use effect into the three components as shown in Table 5. By far, the largest contributor in our model to the overall contribution is computer hardware, but it is also the only type of capital that saw its contribution decline post-slowdown. This differs from the joint approach as software was much more important when prices were not considered. However, because software prices growth was much stronger, our model shows that computer hardware, which had large prices declines in both periods, is much more important for labour productivity growth.

Table 5. Use effect for steady-state models

	Pre-slowdown			**Post-slowdown**		
	Joint	Oulton	Our model	Joint	Oulton	Our model
Use effect	**0.38**	**0.45**	**0.41**	**0.23**	**0.38**	**0.35**
Computer	0.17	0.33	0.30	0.10	0.21	0.20
Telecommunication	0.06	0.07	0.07	0.01	0.09	0.08
Software	0.16	0.05	0.06	0.13	0.07	0.07

5. Conclusions

In this paper, we asked whether a weaker contribution of information and communication technologies (ICT) to productivity growth could account for the productivity slowdown observed in Canada since the early 2000s. To answer this question, we examined several methods capturing various channels through which ICT could affect aggregate productivity.

Based on the results presented in Section 4, we draw several conclusions. The first, and the one that is most relevant to the proposed research question, is that ICT does appear to have contributed to the slowdown in labour productivity growth. This contribution, about 0.1 p.p.p.y. to 0.2 p.p.p.y., represents about a fifth to about a third of the total 0.54 pp decline in labour productivity growth. Both the ICT use effect (capital deepening) and the ICT production effect (productivity in the ICT sector) account for the slowdown. However, the lower range of the decline comes from the model we derived that incorporates declining ICT prices. We believe that this indicates that prices are an increasingly important channel through which ICT can affect labour productivity growth.

While we believe that the finding that ICT has contributed to the slowdown is important to our understanding of the evolution of productivity and the role that ICT has played in that dynamic, we also wish to emphasis that our claim is not that ICT capital and production is now unimportant. Indeed, Table 4 (our method) shows that about 40 per cent of productivity growth in the post-slowdown period can be attributed to the ICT sector.

Two issues appear particularly important in assessing the robustness of our conclusions. One is the claim that ICT prices are mismeasured by statistical agencies (Byrne and Corrado, 2017; Hatzius, 2016). Byrne and Corrado (2017) develop and apply an alternative price index to United States data which indicate a much higher contribution of ICT to labour productivity growth. Given the lack of similar studies undertaken for Canada, we plan to apply the proportional difference in prices from their study to Canadian data (forthcoming), which may further alleviate the decline in the contribution of ICT in our model.

Another important issue is that, because our model is a steady state analysis, the contribution post-slowdown should be reflecting how ICT is currently affecting aggregate labour productivity growth on average. As can be seen from Charts B.3, B.4 and B.5, however, the recession may have had an impact on the ICT sector and capital use. This possible misspecification of the steady state is not lost on the authors, and sensitivity tests for different steady states are tested (forthcoming).

Various extensions to this work could be considered.

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Appendix A

In this Appendix, we examine the implications, in an approach "à la Oulton (2012)", of relaxing the assumption that the production functions of the ICT and non-ICT sectors are identical. We show that this gives expressions that do not capture the contribution of ICT to productivity growth. We also propose an alternative approach, more consistent with the contribution of ICT in a world with different production functions.

We start with the two production functions presented in Section 2.3:

$$y_N = B_N (k_N^N)^{\gamma} (k_T^N)^{\sigma} (h_N)^{1-\gamma-\sigma}, \qquad 0 < \gamma, \sigma < 1;\ \gamma + \sigma < 1 \qquad \text{(A1)}$$

and $$y_T = B_T (k_N^T)^{\theta} (k_T^T)^{\eta} (h_T)^{1-\theta-\eta}. \qquad 0 < \theta, \eta < 1;\ \theta + \eta < 1 \qquad \text{(A2)}$$

In Equations (A1) and (A2), variables are as defined in Section 2.3.

We can obtain expressions for the growth rates of equations (A1) and (A2) by taking total derivatives:

$$\dot{y}_N = \mu_N + \gamma \dot{k}_N^N + \sigma \dot{k}_T^N + (1 - \gamma - \sigma)\dot{h}_N, \quad \text{(A3)}$$

$$\dot{y}_T = \mu_T + \theta \dot{k}_N^T + \eta \dot{k}_T^T + (1 - \theta - \eta)\dot{h}_T. \quad \text{(A4)}$$

Again, in equations (A3) and (A4), the variables are as defined in Section 2.

In the non-ICT sector, the user cost can be approximated by $(r + \delta - \dot{p}_N)p_N$, where r is the real interest rate and δ is the rate of depreciation of non-ICT capital. Normalizing against non-ICT prices and setting the marginal product of labour equal to the user cost, we have

$$(r + \delta_N) = \gamma \frac{y_N}{k_N^N},$$

$$(r + \delta_T - \dot{p})p = \sigma \frac{y_N}{k_T^N}.$$

which, given that in the steady-state interest rates and depreciation rates are fixed, implies that

$$\dot{y}_N = \dot{k}_N^N = \dot{k}_T^N + \dot{p}. \quad \text{(A5)}$$

Similarly, $(r + \delta_T + \dot{p}) = \eta \frac{y_T}{k_T^T}$ implies that $\dot{y}_T = \dot{k}_T^T$.

Assuming that, in a steady-state, $\varphi \frac{y_N}{k_T^N} = \eta \frac{y_T}{k_T^T}$ implies that

$$\dot{y}_N - \dot{k}_T^N = \dot{y}_T - \dot{k}_T^T + \dot{p} \qquad \text{(A6)}$$

Rearranging, we get that

$$\dot{y}_T = \dot{y}_N + \left(\dot{k}_T^T - \dot{k}_T^N\right) - \dot{p}. \quad \text{(A7)}$$

Substituting equations (A5) into (A3) we gain an expression for labour productivity growth in the N sector

$$\dot{y}_N = \mu_N + \gamma\dot{y}_N + \ \sigma(\dot{y}_N - \dot{p}) + \dot{h}_N(1 - \gamma - \sigma). \quad \text{(A8)}$$

In the steady-state, we assume aggregate labour productivity growth can be expressed as a weighted average of the two sectors productivity growth rates, i.e.

$$\dot{y} = (1 - q_T)\dot{y}_N + q_T\dot{y}_T = \dot{y}_N + q_T(\dot{y}_T - \dot{y}_N). \qquad \text{(A9)}$$

In Oulton's original model he assumes instead that steady-state labour productivity growth is nominal output weighted sum of labour productivity growth in the two sectors. We use the hours share because when we assume different production functions, aggregate nominal output is no longer constant, but we still make the assumption that hours growth is the same in the ICT sector and the non-ICT sector.

Substituting equation (A6) into (A9)

$$\dot{y} = \dot{y}_N + q_T\left(\left[\dot{k}_T^T - \dot{k}_T^N\right] - \dot{p}\right). \qquad \text{(A10)}$$

Re-arranging Equation (A8) gives

$$\dot{y}_N = \frac{\mu_N}{(1-\theta-\vartheta)} + \dot{h}_N + \frac{\vartheta}{(1-\theta-\vartheta)}(-\dot{p}). \quad \text{(A11)}$$

Combining Equations (A10) and (A11) gives

$$\dot{y} = \frac{\mu_N}{(1-\theta-\eta)} + \dot{h}_N + \frac{\eta}{(1-\theta-\eta)}(-\dot{p}) + q_T\left(\left[\dot{k}_T^T - \dot{k}_T^N\right] - \dot{p}\right),$$

Where, if we follow Oulton's approach, the last two terms would reflect the contribution of ICT to labour productivity, as is expressed in Equation (10) of Section 2.4. But these two terms are clearly different from the solution to the original Oulton model. This is made clear by the presence of $\left[\dot{k}_{ICT}^{ICT} - \dot{k}_{ICT}^N\right]$. Why would stronger ICT capital investment in the non-ICT sector, as reflected in $\dot{k}_{ICT}^N$, be negative for productivity?

We therefore take a different approach. Substituting Equation (A11) in Equation (A9) gives

$$\dot{y} = q_T \dot{y}_T + (1 - q_T) \frac{\eta}{(1-\theta-\eta)} (-\dot{p}) + (1 - q_T) \left[\frac{\mu_N}{(1-\theta-\eta)} + \dot{h}_N \right] \qquad \text{(A12)}$$

The first two terms on the right-hand side of Equation (A12) measure the contribution of ICT to aggregate labour productivity as expressed in Equation (13) and discussed in Section 2.5.

Appendix B

In this appendix, we expand on Section 3 to discuss several data issues that we experience when estimating the models used in this paper with Canadian data.

B.1. Gross Domestic Product

As mentioned in Section 3, we use three NAICS codes to approximate the ICT sector: NAICS 334, 51, and 5415.

Whenever real GDP is required, we use 2007 constant dollars, as opposed to a Divisia index, in order to allow for the summation of real goods and services across sectors.

The ICT GDP series that is created concatenates data from three different CANSIM tables. GDP for NAICS 5415 is unavailable pre-1997, and so from 1994-1996 we backcast under the assumption that the growth rate of this sector's output is equal to that of NAICS 54.

B.2. Capital, Capital Cost, and the Labour Share

ICT capital is defined as computer hardware, telecommunication equipment, and software. We received the disaggregation from Statistics Canada for telecommunication and computer hardware for the total economy, as well as for the NAICS codes 51 and 334. Computer system design and related services, however, did not have capital data as it was aggregated at the two-digit level. Therefore, to construct a series for ICT capital stock and ICT capital cost we first assume that, like the rest of the economy, this sector has constant returns to scale. Given this assumption and that data exists for nominal GDP and labour compensation, we are able to obtain total capital cost for the sector. Next, using data acquired from Statistics Canada on the MFP program, we are able to breakdown the share of the cost of capital services that is ICT up until

2008, which we extend to 2014 using the shares from the other two sectors.[10] To get the real ICT capital in the sector, we calculate a ICT user cost by dividing the ICT capital cost in the total economy by real capital, and then applying that to NAICS 5415 to get an estimate of the real ICT capital in the sector.

ICT capital cost can be calculated using a simple Jorgenson user cost as shown in Appendix A. To calculate the capital cost for the total economy however, we decide to use the capital cost series from Statistics Canada's MFP program for the business sector, and apply the ratio of ICT capital cost out of total capital cost to the aggregate economy after assuming constant returns to scale. We then disaggregate the ICT capital cost by type of capital by using the shares calculated using the Jorgenson formulas.

The constant returns to scale is an important assumption as much of the data we use will depend upon the labour share. We calculate the labour share simply as the labour compensation divided by nominal GDP at basic prices. This gives a slightly lower labour share than is sometimes calculated, for example in Statistics Canada's Productivity Accounts. Sensitivity tests are forthcoming, but because the change in the labour share between the two periods likely will remain very similar, our qualitative results should hold.

B.3. Intermediate ICT Business Services

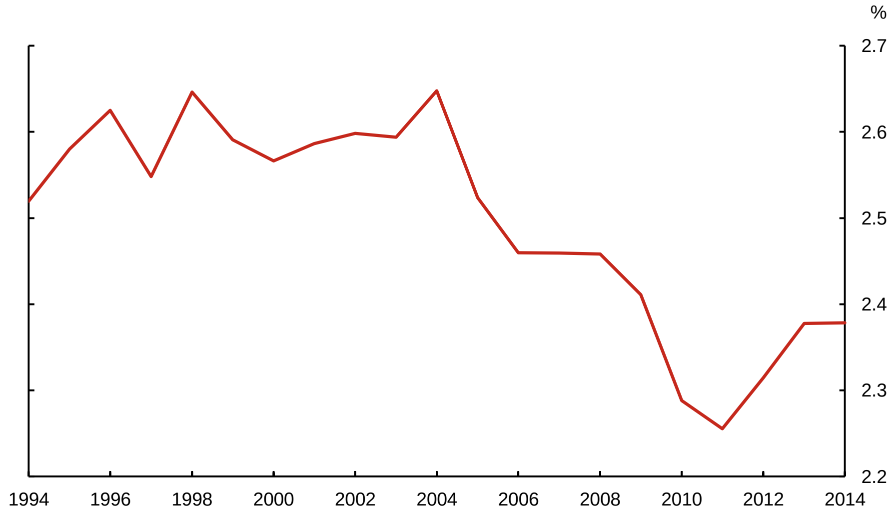
Byrne and Corrado also use intermediate ICT business services in their production functions. We attempt to calculate a similar measure using data from Statistics Canada input-output and supply-use tables (Chart B.2). While we are told that there are currently efforts to create a continuous time series, as of the time of writing there are several breaks in the detailed data. Therefore, to construct the series, inputs were manually chosen from three different series and ICT sector own-use was subtracted from the total. There exists a fairly large break in the data in 2008, when the input-output tables are discontinued. However, it is not entirely obvious how much of this break is due to the appendment of the series versus the role of the Great Recession. We still find it to be interesting that these services did not experience a large increase in use in the so-called

[10] We also test using the average share of ICT from 2004-2008, which yields the same qualitative conclusion. We plan to some more sensitivity tests on this variable, however, because the labour share is so high in this sector, the capital cost and level of real ICT capital is not large. It thus does not have a large impact on the results.

"digital era" of the late 2000s to present day. Ultimately, however, the authors believe that there is likely a small downward bias in the constructed series post-2008 and therefore do not include this measure in the research above.

Chart B.2: Intermediate ICT business services

Annual data



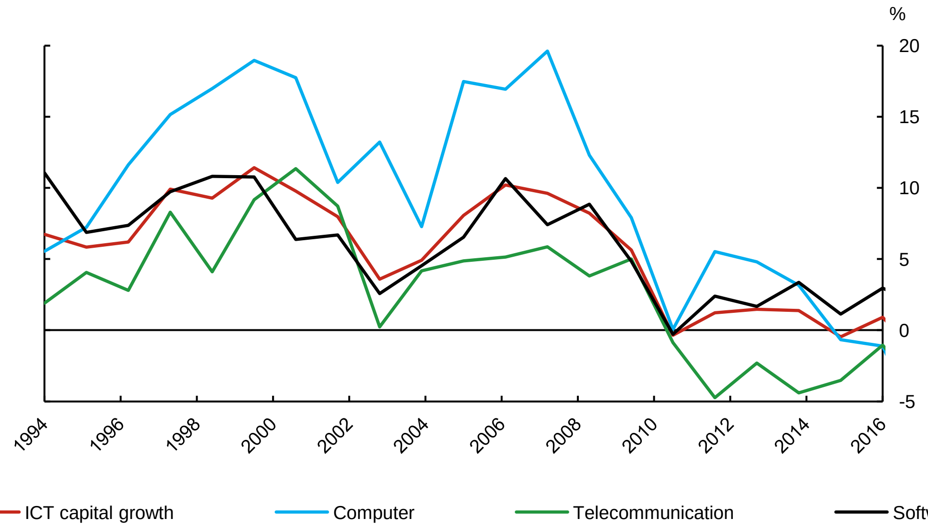
Sources: Bank of Canada and authors' calculations

Last observation: 2014

B.4. Supplementary Data and Charts

Chart B.3: ICT capital growth

Annual data

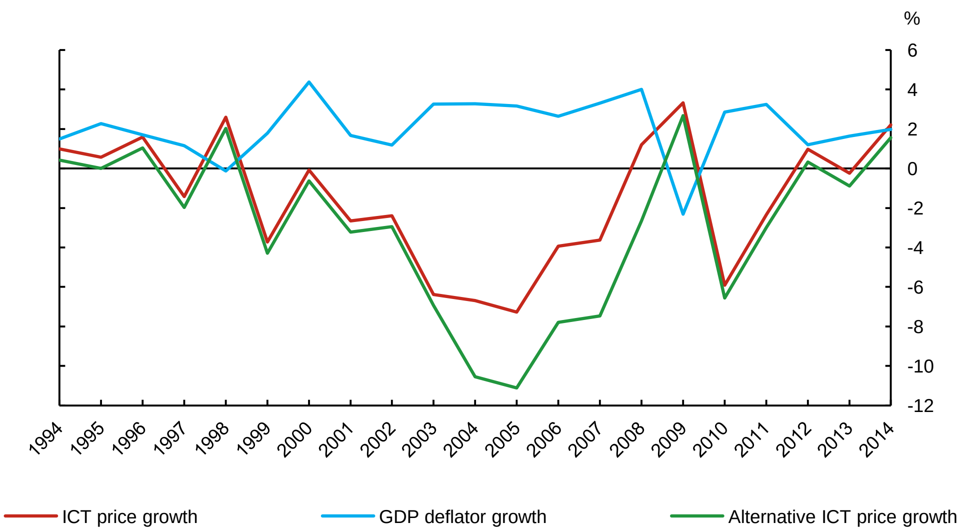


Sources: Statistics Canada and authors's calculations

Last observation: 2016

Chart B.4: GDP deflator, ICT prices, and alternative ICT prices (growth rates)

Annual data

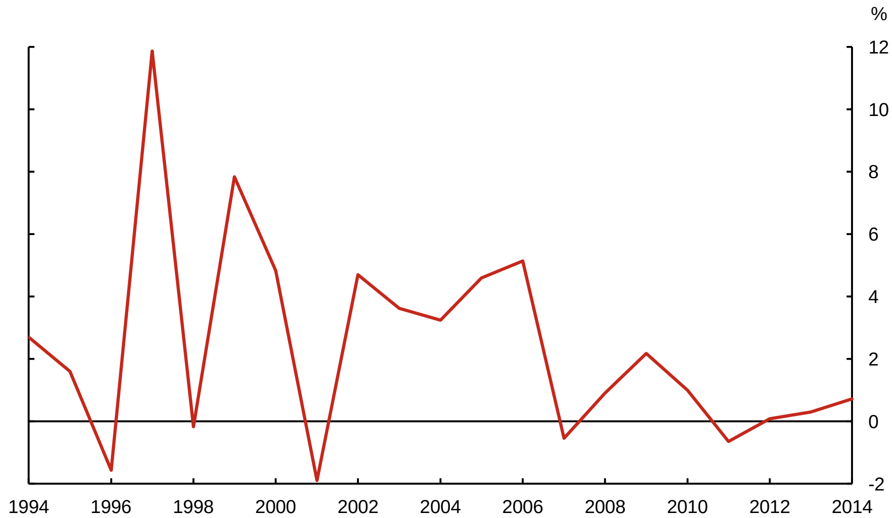


Sources: Statistics Canada and author's calculations

Last observation: 2014

Chart B.5: ICT-producing sector labour productivity growth

Annual data



Sources: Statistics Canada and authors's calculations

Last observation: 1994

Table B.1. ICT capital income shares by type of capital

		Pre-slowdown	Post-slowdown
Computer	Aggregate	1.78	1.33
	Non-ICT sector	1.62	1.22
	ICT sector	5.45	3.87
Telecommunication	Aggregate	1.58	0.92
	Non-ICT sector	1.43	0.84
	ICT sector	4.84	2.67
Software	Aggregate	2.89	2.97
	Non-ICT sector	2.62	2.73
	ICT sector	8.84	8.66

Table B.2. ICT shares in the total economy

	Pre-slowdown	Post-slowdown
ICT capital income share	6.26	5.22
Non-ICT sector	5.67	4.79

ICT sector	19.12	15.20
Labour income share	54.50	53.57
Non-ICT sector	53.96	52.79
ICT sector	64.81	68.60
Hours share	3.61	3.74
Nominal GDP share	4.94	4.95
Real GDP share	4.10	4.93