The Productivity Slowdown in Canada: an ICT Phenomenon?

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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 consider several models which capture channels by which ICT could affect productivity growth. Our results indicate that ICT continues to contribute to productivity growth, but that this contribution has declined and consequently accounts for part of the productivity growth slowdown. However, the productivity slowdown and the change in the contribution of ICT do not seem to have the same timing. While productivity growth slowed in the early 2000s, the ICT contribution does not appear to have fallen until around the Great Recession. This prompts the conclusion that while ICT had little to no role in the initial productivity slowdown, it has been a major determinant of the subdued productivity growth since 2007-2009.

After averaging 1.6 per cent per year from 1993 to 2003, labour productivity growth in Canada only rose 1.0 per cent from 2003 to 2014.[2] The slowdown is not unique to Canada, as it has affected most OECD countries (Syverson, 2017). This is illustrated in Chart 1 for Canada, the United States, and the G-7. Various explanations have been proposed. For instance, some have exam-

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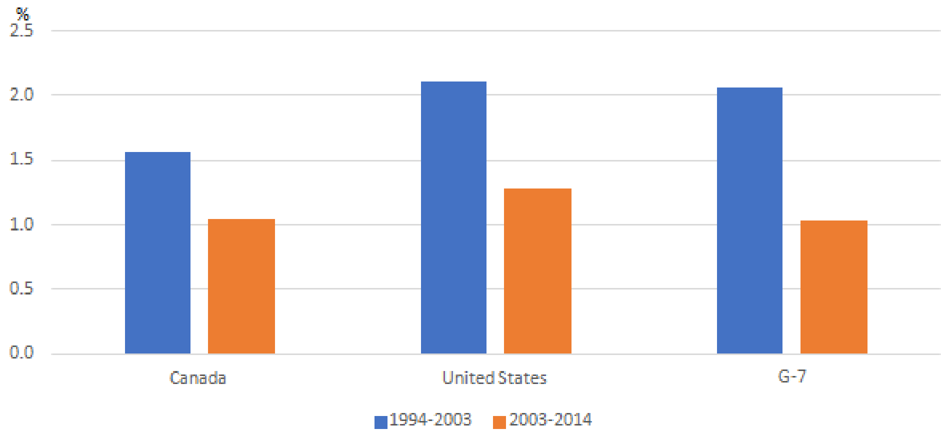
2 Lack of data availability for some of the models we study is the reason for the focus on the 1993 to 2014 period. The data up to 2016 show an even more accentuated slowdown in Canada. We calculate the slowdown from 2003 because we want two samples of reasonable length for the pre- and post-slowdown periods. We recognize that productivity in Canada began to decline after 2000, but our focus is on steady-state periods of growth, and labour productivity growth was still relatively high in 2000-2002. A further advantage of our choice of dates is that it facilitates comparison with one of the papers we build upon (Cette *et al.*, 2015). Nonetheless, the article discusses the effects of changing the dating of the weaker productivity growth period, including assuming that it started in 2000 (Sharpe and Tsang, 2018). Real GDP data are in constant dollars, not chain-weighted. All labour productivity data used in this article are in terms of output per hour worked for the total economy.

Chart 1: Labour Productivity Growth for the Total Economy in Canada, the United States and G-7 (average annual rate of change)



Source: OECD. Stat.

ined the role played by reduced business dynamism (Decker *et al.*, 2017; St-Amant and Tessier, 2018). Others have studied country-specific factors. For instance, Gu (2018) finds that in Canada the productivity slowdown can be partly explained by the higher cost of extracting natural resources and by a decline in the utilization of capital in the manufacturing sector.

Some researchers have argued that technology developments explain productivity trends. In particular, Gordon (2012) claims that the fundamental problem with productivity growth in recent years is that today's innovations do not compare in scale or impact with the breakthroughs of the 1990s, let alone the waves of earlier transformations. Some have tried to quantify the contribution of technology to the productivity slowdown. For example, using one-sector growth accounting, Cette *et al.* (2015) assess the contribution of information and communication technologies (ICT) capital deepening to labour productivity growth. They conclude that after rising significantly in the 1995-2004 period, the contribution of ICT fell after 2004 in Canada, the United States, the Euro zone, and the United Kingdom.

The Cette *et al.* model is intuitive, and represents the traditional approach applied in the literature to measure the contribution of a specific type of capital use. However, ICT capital deepening is not the only channel through which ICT can affect the growth of aggregate labour productivity. For instance, productivity growth in the ICT-producing sector (Appendix A, Chart A.2),[3] and resource reallocation to and from that sector, could affect aggregate productivity. A simple shift-share exercise (presented in Appendix A) suggests that the latter has not been a significant factor in accounting for the productivity slowdown in Canada.

3 All Appendices are found at www.csls.ca/ipm/ipm35/mollins_and_st_amant.pdf.

Changes in the developments of ICT prices can also be important. Oulton (2012) indeed builds a two-sector (ICT and non-ICT) model 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. Specifically, Oulton argues that the relative growth of ICT prices embodies the difference between total factor productivity (TFP) growth in the ICT and non-ICT sectors. Although Oulton does not compare periods, he finds that ICT's contribution to productivity has been strong in the 2000s in a group of OECD countries including Canada. Byrne and Corrado (2017) extend Oulton's model to include intermediate business services and make corrections for ICT prices mismeasurement. Focusing on the United States, they too conclude that the contribution of ICT has continued to be strong post-2003.

In this article, we ask whether a weaker contribution of ICT to productivity growth could account for the productivity slowdown observed in Canada since the early 2000s. To answer this question, our first approach is to update the analysis of Cette *et al.* (2015) for Canada. This informs us about the contribution of ICT capital deepening to aggregate productivity growth. In a second approach, we combine, in a two-sector steady-state model, a use effect based on ICT-capital deepening with a contribution coming from the production of ICT in Canada. We call this the simple two-sector (STS) approach.

Recognizing that declining ICT prices are a distinctive feature of technological progress, we then turn to the Oulton (2012) model with Canadian data for the periods 1993-2003 (pre-slowdown) and 2003-2014 (post-slowdown). However, this model assumes that the production functions of the ICT and non-ICT sectors are identical, except for different TFP growth rates. We show that this assumption is clearly inconsistent with Canadian data and propose an alternative approach allowing the production functions to differ in their input factor growth rates and income shares. This approach combines use, production, and price effects. We call it the Combined Use, Production and Price (CUPP) effects approach.

In our base case we compare the 1993-2003 period with the 2003-2014 period. However, we recognize that some uncertainty exists in the identification of separate steady-states, so we test the robustness of our conclusion with different starting dates for the post-slowdown period.

Our main conclusion is that while ICT is still contributing positively to labour productivity growth in Canada, this contribution has declined. Overall, we find that a reduced ICT contribution explains around 20-40 per cent of the productivity slowdown in Canada. However, the slowdown in productivity growth and in the contribution of ICT do not seem to coincide. The lower contribution seems to be stemming from developments starting around the Great Recession. ICT prices and the use of ICT consequently do not explain any of the initial slowdown in productivity growth, but instead offer insight into weak productivity growth since around 2008. Robustness checks with alternative data suggest that the contribution of ICT to the productivity slowdown could be even larger.

The article proceeds as follows: we first present our methodology, we then discuss the data, and present our results before concluding.

Methodology

Our objective is to determine whether ICT developments have contributed to the productivity slowdown in Canada. In answering this question, we consider existing methodologies identifying the main channels through which ICT affects productivity. We also propose two new approaches aimed at capturing multiple channels.

An Approach Focused on the Use of ICT

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" (UE). Cette *et al.* (2015) focus on this channel in assessing the contribution of ICT to labour productivity growth in Canada, the United States, and European countries. For each ICT component they consider (hardware, software, and communications equipment), the contribution of the use of capital to labour productivity growth for type of ICT capital j in year t (UE_t^j) can be expressed as follows:

$$\mathrm{UE}_t^j = \alpha_t^j (\dot{k}_{t-1}^j) \quad (1)$$

In equation (1), k^j is ICT capital type j divided by the total number of hours worked. The dot over a variable indicates the growth rate. The coefficient α^j corresponds to the share of type j ICT capital cost in nominal GDP.

Cette *et al.* (2015) find that after having risen significantly in 1995-2004 compared with 1974-1995, the contribution of ICT to labour productivity growth in Canada subsequently fell in the 2004-2013 period. We revisit the issue for Canada later in the article.

A Simple Two-sector (STS) Approach

We propose a two-sector approach that allows us to combine the channels by which ICT affects productivity through its use and its domestic production. Beginning with Cobb-Douglas production functions for labour productivity, the non-ICT (N) and ICT (T) sectors can be expressed as follows:

$$y_N = B_N (k_N^N)^\gamma (k_N^T)^\sigma (h_N)^{1-\gamma-\sigma}$$
$$0 < \gamma, \sigma < 1; \gamma + \sigma < 1 \quad (2)$$

$$y_T = B_T (k_T^N)^\theta (k_T^T)^\eta (h_T)^{1-\theta-\eta}$$
$$0 < \theta, \eta < 1; \theta + \eta < 1 \quad (3)$$

In equations (2) and (3), γ, σ, θ, and η are the capital income shares, 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_i^j

represent capital stock of type $j = N, T$ in per hour terms being used in sector $i = N, T$. Finally, h_i is the average level of skill (human capital) in sector i.

In the steady-state, aggregate labour productivity growth can be expressed as a weighted average of labour productivity growth in the two sectors:[4]

$$\bar{\dot{y}} = (1 - \bar{q}_T)\bar{\dot{y}}_N + \bar{q}_T\bar{\dot{y}}_T \quad (4)$$

In equation (4), q_T is the hours share of the ICT sector. Bars indicate steady-state values, calculated as period averages.

The non-ICT sector production function can be expressed in growth rate terms as follows:

$$\dot{y}_N = \mu_N + \gamma\dot{k}_N^N + \sigma\dot{k}_N^T + (1 - \gamma - \sigma)\dot{h}_N, \quad (5)$$

where μ_N is TFP growth in the non-ICT sector and the term $\sigma\dot{k}_N^T$ captures the contribution of ICT capital to productivity in the non-ICT sector. Substituting (5) into (4) and isolating for the effect of ICT capital, we can express the steady-state total contribution of ICT to aggregate productivity growth (CO) as

$$CO_{1,T} = (1 - \bar{q}_T)\sigma\bar{\dot{k}}_N^T + \bar{q}_T\bar{\dot{y}}_T \quad (6)$$

The first term on the right-hand side of equation (6) captures the contribution of ICT capital in the non-ICT sector (use effect) and the second term captures the contribution of productivity in the ICT sector (production effect). Note that the contribution of ICT capital deepening to productivity in sector T is captured within the term $\bar{q}_T\bar{\dot{y}}_T$. This is an important difference from the one-sector model as the term $(1 - \bar{q}_T)\sigma\bar{\dot{k}}_N^T$ specifically captures ICT capital deepening in the non-ICT sector. The approach presented in this section would not capture reallocation effects (the effects on productivity of reallocating resources between sectors), but a simple shift-share decomposition, presented in Appendix A, suggests that reallocation was not a significant factor accounting for the 2003-2014 period of slower productivity growth. Also, the STS approach may not account for relative prices effects. This is discussed later in the article.

Oulton's Approach

The effects of changes in ICT prices may not be fully captured by equation (6). Oulton (2012) proposes a two-sector model that explicitly accounts for relative ICT prices when measuring the ICT contribution.[5]

He shows that, in a steady-state, ICT price changes relative to non-ICT price changes ($p = \dot{p}_T - \dot{p}_N$) equal (the negative of) the two sectors' relative TFP growth rates,[6] i.e.

4 Following Oulton (2012), we define a steady-state as a state in which the real interest rate and the depreciation rates are constant, and in which hours worked in each sector grow at the same constant rate.

5 See Appendix A in Oulton (2012) for a full presentation and derivation.

6 The intuition is that, because the production functions are identical except for TFP growth, and because nominal GDP shares of the two sectors are constant in a steady-state, differences in growth in prices have to reflect differences in TFP growth.

Table 1: **ICT and Income Shares in the Total Economy in Canada (per cent, averages)**

	1993-2003	2003-2014
ICT nominal capital income share	6.26	5.22
Non-ICT sector	5.67	4.77
ICT sector	19.12	15.52
ICT nominal capital stock growth	7.57	4.18
Non-ICT sector	7.85	5.45
ICT sector	7.21	1.06
Nominal labour income share	54.50	53.57
Non-ICT sector	53.96	52.79
ICT sector	64.81	68.60
ICT sector hours share[a]	3.79	3.89
ICT sector nominal GDP share	4.94	4.95
ICT sector real GDP share[b]	4.10	4.94

Source: Statistics Canada and author's calculations. Section 3 discusses the data in more detail.
a: Note that the non-ICT sector hours share, as well as non-ICT nominal and real GDP shares, are simply 100 minus the ICT shares shown in Table 1. *b*: Real GDP is in 2007 constant dollars.

$$\dot{p} = \mu_N + \mu_T \qquad (7)$$

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

$$CO_{2,T} = \frac{\bar{v}_{K_T}}{\bar{v}_L}(-\dot{p}) + \bar{w}_T(-\dot{p}) \qquad (8)$$

In equation (8), the first term represents a use effect, where $\bar{v}_{K_T}$ and $\bar{v}_L$ are, respectively, the shares of ICT capital and labour income in total income. The second term, where $\bar{w}_T$ denotes the relative size of the ICT production 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 four non-European countries, suggests that the main boost to growth has come from ICT use, not ICT production. For Canada, he finds that while the contribution of ICT use to labour productivity has been 0.58 percentage points per year, that of ICT production has been 0.09 percentage points per year.[7] Oulton does not compare historical episodes. In the results section of this article we present estimates based on his model for the pre- and post-slowdown periods.[8]

An important assumption made by Oulton (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 Table 1. The ICT capital income share

7 This is based, for Canada, on ICT-capital and labour shares calculated as their 2000-2004 average, and on declines of 7 per cent in relative ICT prices. These are Oulton's assumptions.

8 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 apply their model to U.S. data and find that the contribution of ICT has remained strong after 2003. Unfortunately, data limitations (data on ICT services in Canada are affected by a definitional change in 2008) prevent us from applying this model to Canadian data. Also, like Oulton (2012), these authors assume that the ICT and non-ICT sectors are identical, except for TFP growth rates. But this is inconsistent with Canadian data.

of the ICT sector has been, on average in 2003-2014, 15.5 per cent compared to 4.8 per cent for the non-ICT sector. Labour shares have also been different. Interestingly, nominal ICT capital growth has been considerably faster for the non-ICT sector in the post-slowdown period (5.5 per cent vs 1.1 per cent).

An Alternative Approach Combining Use, Production, and Price Effects (CUPP Approach)

An interesting feature of Oulton's (2012) approach is that it explicitly measures the impact of relative ICT prices on aggregate labour productivity. However, as we just saw, the assumption of identical production functions seems much too strong. 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 (2) and (3), where income shares and the growth rates of capital inputs are now allowed to differ. Assuming perfect competition and a simple Jorgenson user cost formula, we can develop a new expression for $\dot{y}_N$ (see Appendix B):[9]

$$\bar{\dot{y}}_N = \frac{\mu_N}{(1-\gamma-\sigma)} + \bar{\dot{h}} + \frac{\sigma}{(1-\gamma-\sigma)}(-\dot{p}) \quad (9)$$

The first two terms of equation (9) reflect the effects on labour productivity growth in the non-ICT sector from TFP growth and labour quality growth in that sector. The third term is the use effect of ICT capital in the non-ICT sector. As in Oulton, this effect says that as ICT prices fall relative to prices in the rest of the economy, and as the income share of ICT capital increases (for a given γ), labour productivity growth increases.

Lastly, we can substitute the use effect of equation (9) into (4) and obtain an expression for the contribution of ICT capital that is the sum of use and production effects:

$$CO_{3,T} = (1-\bar{q}_T)\frac{\sigma}{(1-\gamma-\sigma)}(-\dot{p}) + \bar{q}_T\bar{\dot{y}}_T \quad (10)$$

As noted earlier in equation (6), we label the second term on the right-hand side as the production effect.

Equation (10) differs from Oulton's formulation in several ways. First, the use effect is now in terms of the non-ICT sector, and is weighted by that sector's share of hours worked.[10] However,

9 See Appendix B for the derivation of a model where the production function for the ICT and non-ICT sectors differ.

10 Oulton weighs real output growth rates in the two sectors with nominal output shares because he measures real output using a Divisia (chained) index. We elect to use fixed-weighted constant GDP for our base case due to the complications that arise when summing chained GDP across sectors (in this case, the nominal weighted GDP growth rates across sectors do not add up to aggregate real GDP), and also because of some data limitations that are introduced when using chained investment (these data limitations are discussed later in the article).

in our model we do not relax the assumption, also made by Oulton, that in a steady-state the growth rate of hours worked in both sectors is the same.[11] Thus, equation (10) is constant in the steady-state. Defining labour productivity growth as the sum of the hours weighted shares of growth in the two sectors does not seem unreasonable, and allows us to solve the model for the steady-state.[12] Later in the article we perform a robustness check using chained prices for investment and GDP as well as nominal output shares.

A second key difference is that our production effect does not have a relative price term and is identical to the production effect described earlier. We make the change here because, as mentioned, this term in the Oulton model reflects the relative growth rates of TFP in the two sectors. In our model, where the production functions are different, the ICT sector's production effect includes more factors than just its relative TFP growth. For example, it 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.

In the traditional one-sector model and the STS approach presented earlier, the impact of prices is implicitly and partly captured in the capital income share through the user cost formula. Of course, the impact of prices is also captured as firms will likely invest and use more ICT capital (presumably a very efficient form of capital) as it becomes more affordable. In the CUPP approach, as ICT prices become cheaper compared with other investment goods 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.

Data

The data used to calibrate the models are either taken from publicly accessible data from Statistics Canada or received by special request from Statistics Canada. All data are for the total economy.

The ICT-production sector is defined as the aggregation 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 usual 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).

11 This assumption is necessary given that in the steady-state the hours share cannot be increasing for one sector simply because the share cannot exceed 1.

12 The ICT sector's hours share increased in the late 1990s but has not changed much in the post-slowdown period (Chart A.1 in Appendix A).

There exists a debate in the literature on the most appropriate measure of output for two-sector models. Byrne and Corrado (2017) define the output of the ICT sector by summing the consumption, investment, and net exports of specific ICT goods and services in the United States. However, 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 Statistics Canada's Productivity Accounts.

In the Oulton model, and in the CUPP model, the choice of the definition of prices is crucial. We follow Oulton and use the implicit investment price index for the price of ICT, and use the non-ICT sector GDP deflator as a proxy for the non-ICT sector prices (Table A.1 in Appendix A).[13] We obtained these data, along with capital cost and stock data, from the publicly available capital accounts, as well as by special request to Statistics Canada. Additionally, as previously mentioned, we use real capital and real investment data calculated with fixed-weighted constant 2007 dollars, instead of a Fisher chain-weighted index. This is because chain-weighted data are not disaggregated into the three ICT capital components, and we can also easily sum when using constant dollars. However, we can estimate the CUPP model with some additional assumptions using chain-weighted dollars, the results of which are shown in the next section.

Capital per hour is calculated as the capital stock divided by total hours. Ideally, capital services would be used to obtain a measure of the services derived per hour worked. However, capital input is unavailable at the granular level we require either by industry or by type of capital (i.e. computer hardware, telecommunications equipment, and software). We recognize that using capital services has become the standard practice in the literature. We also note, though, that because the CUPP is a two-sector model, capital composition differences between non-ICT capital and the different ICT capital types is accounted for in the capital income share coefficients.

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 level and then applied to the aggregate economy capital share. More information on constructed or custom variables is provided in Appendix C.

Results

Traditional One-Sector Model

The first method we use to examine the impact of ICT on productivity follows that employed by Cette *et al.*

13 Although Oulton uses private fixed investment, we use total fixed investment prices as we analyze the total economy.

Table 2: One-sector Model Results for the Contributions of ICT Components to Labour Productivity Growth for the Total Economy Labour Productivity in Canada, (percentage points per year)

	Computer Hardware	Telecommunications Equipment	Software	Total Contribution
1993-2003	0.19	0.06	0.22	0.47
2003-2014	0.11	0.01	0.15	0.27
2003-2016	0.09	0.00	0.13	0.22

Source: Statistics Canada and authors calculations.

(2015) and others (equation 1). The growth accounting equation enables researchers to measure the impact of the total use of ICT capital on labour productivity. Results are presented in Table 2.

Estimation of equation (1) yields results similar to those of Cette *et al.* (2015). The contribution of ICT capital use to labour productivity growth in this model declined from 0.47 percentage points per year in the pre-slowdown period to 0.27 percentage points per year in the post-slowdown period (Table 2). 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 in the post-slowdown period.

In absolute terms, the decline since 2003 comes largely from both computer hardware and software, and to a lesser extent telecommunications equipment. Most of the decline in the growth of use of these capital types came after the Great Recession. In fact, in the mid-2000s growth of real ICT capital rose to that of the late 1990s, but this growth had not recovered since it fell dramatically in 2008.[14] 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. These two sectors represented 47 per cent of the total real ICT capital stock in 2007, but had average growth rates for their ICT capital stock of -5.5 per cent and -2.7 per cent from 2009 to 2016, respectively.

Two Sector Growth Accounting

We calibrate the three two-sector approaches described earlier, namely: STS, Oulton, and CUPP. Results are shown in Table 3.

First, our baseline results in the STS approach (equation 6) suggest that the contribution of ICT to labour productivity growth was 0.49 percentage points per year in the pre-slowdown period, and then fell to 0.27 percentage points per year in the post-slowdown period. While the use effect is quantitatively much larger, about a quarter of the decline in contribution comes from the production effect. This is important be-

14 The implications of this are discussed later in the article.

Table 3: **Two-sector Model Results for the Contribution of ICT to Total Economy Labour Productivity in Canada, (percentage points per year)**

		STS	Oulton	CUPP
	Total Contribution	**0.49**	**0.62**	**0.54**
1993-2003	Use effect	0.35	0.47	0.41
	Production effect	0.13	0.15	0.13
	Total Contribution	**0.27**	**0.60**	**0.41**
2003-2014	Use effect	0.20	0.39	0.34
	Production effect	0.07	0.22	0.07
	Total Contribution	**0.21**	**0.02**	**0.13**
Differences	Use effect	0.15	0.08	0.07
	Production effect	0.06	-0.07	0.06

Source: Statistics Canada and authors calculations.

cause, as mentioned, a key difference in this methodology compared with 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. While the contribution is almost identical to the one-sector model, 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, given its large share of ICT capital income and the decline in the growth rate of ICT capital in that sector (Table 1).

Next, we estimate the Oulton approach. While we ultimately do not put much stock in this method, we want to see if the simplifying assumptions this method uses have meaningful effects on results (we drop this approach in subsequent analyses). It is interesting to find that in the world where the Oulton assumptions hold true, the contribution of ICT to productivity growth remains stable between the 1993-2003 and 2003-2014 periods. 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 of the ICT-producing sector 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 (the second term in equation 8). On the other hand, the declining ICT capital income share (Table 1) combined with a stable labour share more than compensates for declining prices within the use effect.

Lastly, we calibrate the CUPP approach. We find that the contribution to labour productivity growth was 0.54 percentage points per year in the pre-slowdown period before declining to 0.41 percentage points per year post-slowdown. This indicates that relaxing the assumption used by Oulton that the two sectors are identical (except for steady-state TFP growth) makes a difference. As can be seen in Table 3, many of the qualitative conclusions are similar to the STS approach. However, note that the contribution to productivity growth is larger in the CUPP approach for both periods. This seems to indicate that relative ICT prices contain additional information about how

Table 4: Estimation of Models with Different Years for Regime Shift of Steady States (contributions to labour productivity growth in percentage points per year)

	STS		CUPP	
	Pre-slowdown	Post-slowdown	Pre slowdown	Post slowdown
2000	0.57	0.27	0.49	0.46
2002	**0.48**	**0.28**	**0.49**	**0.45**
2004	0.49	0.24	0.60	0.35

Source: Statistics Canada and authors calculations.

Table 5: Use Effect by ICT Component for Two-sector Models with Different Steady States Periods to Total Economy Labour Productivity in Canada, (percentage points per year)

	1993-2000		**2000-2008**		**2008-2014**	
	STS	CUPP	STS	CUPP	STS	CUPP
Use effect	**0.42**	**0.34**	**0.37**	**0.67**	**0.02**	**0.10**
Computer	0.17	0.26	0.17	0.38	0.00	0.09
Telecommunications	0.10	0.03	0.08	0.18	-0.01	0.03
Software	0.16	0.05	0.13	0.15	0.03	-0.01

Notes: The use effects by asset do not add up to the total because they are multiplied by $(1 - \bar{q}_T)$ as shown in equations 6 and 10.
Source: Statistics Canada and authors calculations.

ICT affects aggregate labour productivity growth. More importantly, perhaps, is that the CUPP approach indicates that the decline in the contribution is less pronounced than in the STS 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. Note that while the ICT contribution declined in absolute terms, the relative contribution actually increased slightly in the CUPP model. This perspective may suggest that ICT simply declined in proportion to the rest of the economy.

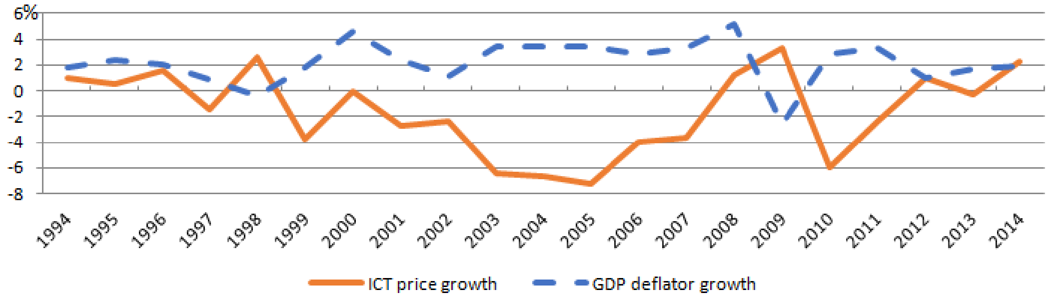
Up to this point, we have specified "pre-slowdown" as the period 1993-2003 and "post-slowdown" as 2003-2014. However, while the regime shift happened in the early 2000s, the exact timing of the beginning of the slow productivity growth period is ambiguous. While some researchers make the point that labour productivity growth slowed after 2000 (Sharpe and Thomson, 2010, and Baldwin *et al.*, 2015). Cette *et al.* (2015) chose a timing similar to ours. Of course, determining when the economy enters a new steady-state, or the date of the "regime shift," is a difficult endeavour; due to this uncertainty, we calibrate the models with varying timings for the regime shift. In Table 4, the results are summarized for the STS and CUPP models, with the date on the vertical axis representing the date at which the economy is assumed to move to a new steady-state.[15]

Table 5 indicates that in the STS approach, pushing the moment of regime shift to 2000 widens the gap between the

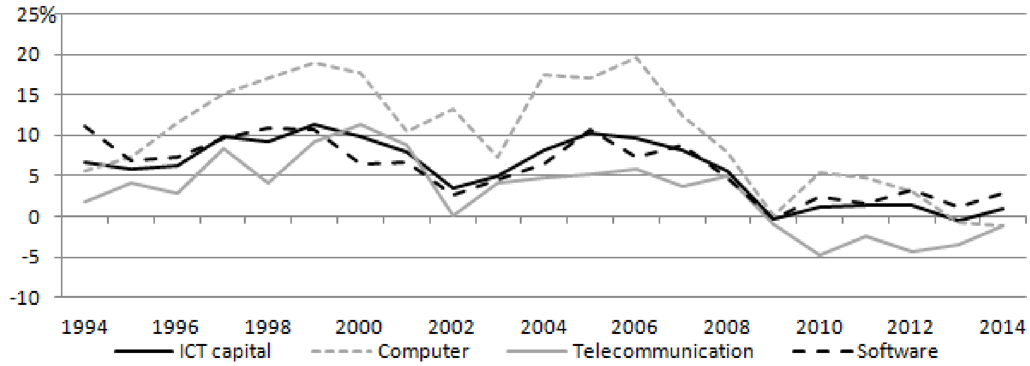
15 For example, the row for 2000 indicates that the results are for steady-states of 1993-2000 for the pre-slowdown period, and 2000-2014 for the post-slowdown period (growth rates would start in 2001 for post-slowdown).

Chart 2: GDP Deflator, ICT Prices and Real ICT Capital Growth in Canada (per cent), 1994 - 2014

Panel A. GDP Deflator and ICT Prices



Panel B. Real ICT Capital Growth



Source: Statistics Canada and author's calculations.

contributions of ICT in the two periods. This is because the STS approach captures largely the effect of capital deepening which began to decline in 1999, and ICT sector labour productivity growth was very weak in 2001. On the other hand, the CUPP approach indicates that specifying an earlier date for the regime shift practically eliminates the gap between pre- and post-slowdown ICT contributions.

Weaker ICT Contribution and the Recession

Based on the results above, both the STS and CUPP approaches seem to indicate that a declining contribution of ICT can explain part of the slower productivity growth after the early 2000s. Furthermore, particularly in the CUPP model, the more recent the date used for the regime shift, the more of the total decline in productivity growth that ICT seems to explain. This is likely because the timing of slower productivity growth and a declining contribution of ICT do not coincide. Panel A in Chart 2 shows that the relative price of ICT actually declined in the early 2000s, and only converged to GDP deflator growth during the recession. Similarly, Panel B indicates that while the growth of ICT capital in Canada declined in the early 2000s, it began to recover very shortly afterwards only to fall and remain subdued after 2009. Tables 3 and 4 point to a declining growth of productivity in the ICT sector and a less important ICT use effect. However, these parameters seem to be reacting to the adverse pres-

Table 6: ICT Contribution to Total Economy Labour Productivity Growth in Canada across Different Steady States with Constant and Chained Prices

	STS (percentage points)			CUPP (percentage points)			Labour Productivity (%)
Panel A: Using Constant Prices							
	Use effect	Production effect	Total contribution	Use effect	Production effect	Total contribution	
1993-2000	0.42	0.15	0.57	0.34	0.15	0.49	1.89
2000-2008	0.37	0.10	0.47	0.67	0.10	0.77	0.86
2008-2014	0.02	0.04	0.07	0.10	0.04	0.14	1.19
Panel B: Using Chained Prices							
1993-2000	0.39	0.22	0.60	0.70	0.22	0.92	1.85
2000-2008	0.37	0.14	0.51	0.69	0.14	0.84	0.89
2008-2014	0.03	0.07	0.10	0.08	0.07	0.15	1.23

Source: Statistics Canada and authors calculations.

sure on ICT coming from the recession.[16] In other words, while productivity in Canada appears to have entered a state of slow growth in the early 2000s, this may not have been initially caused by a lower contribution of ICT.

To determine whether the declines in the ICT contribution and in labour productivity growth coincide, we propose that the contribution of ICT be broken into three periods: 1993-2000, 2000-2008, and 2008-2014. Of course, because these models are derived from a Cobb-Douglas equation of the total economy, this analysis must assume that there are, in fact, three separate steady states over the 20-year period in question. This is a bold claim; however, we believe the illustrative nature of this exercise justifies the flexibility.

Panel A of Table 6 shows that it is only in the 2008-2014 period that we see evidence of a significant decline in the contribution of ICT to labour productivity growth. In fact, in the CUPP model, the ICT contribution increases after 2000. While the production effect seems to show a gradual decline across the three periods, the use effect is the main determinant of a dramatic decline in contribution in the most recent period.

We can further break down the use effect from Panel A of Table 6 into the three components as shown in Table 5. One of the major differences between the use effects in the STS and the CUPP approaches is the relative impact of software. In the STS approach, the use of software contributes strongly to productivity growth, and in the 2008-2014 period is the only positive contributor. In the CUPP approach, though, it is relatively small, and is negative following the recession. This is because the price growth of software is positive (it is negative for the other assets in most periods, particularly computer hardware), so that the relative price term in the CUPP model subdues the positive im-

16 The convergence in the rate of increase in ICT prices relative to that of the GDP deflator seems to begin before the recession, and therefore it could be argued that the flow of causation is ambiguous.

pact of the incorporation of software into production in most periods.

The spike in the use effect in the CUPP approach in the 2000-2008 period points to the fact that the gap between ICT price growth and prices in the rest of the economy was wide in the early 2000s but began to close around 2008.[17] In the CUPP approach, the relative price growth is largely (although not exactly) an indicator of efficiency in the use and production of ICT assets.

This may suggest that innovation was still occurring in the ICT sector even as productivity growth was slowing in the rest of the economy in the early 2000s. Perhaps the weaker ICT productivity gains observed since around 2008 are linked to the 2008-09 recession. These weaker gains could have partly caused it if, for instance, they contributed to weaker expectations about future productivity growth, with immediate effects on spending.[18] The recession may also be responsible for price convergence if the weaker investment growth and spending on innovation that the recession triggered contributed to smaller declines in ICT prices. Our approaches cannot really shed light on these issues. However, it is interesting to note that ICT prices started to converge before the recession, which may suggest that slower ICT innovation was a cause of the recession.

Ultimately, splitting the two-sector models into three periods suggests that the decline in ICT's contribution to labour productivity growth did not coincide with the overall productivity slowdown, and therefore was not a factor in the initiation of the slow productivity growth period. However, it seems obvious that ICT has been a significant factor in the continuation of subdued productivity growth since around the recession.

Chained versus Constant Prices

The above analyses expresses all real variables in constant 2007 dollars. This is done because of the complications that arise from summations across sectors as well as data limitations.[19] However, it is possible to obtain an approximation of the CUPP approach using chained investment and GDP.[20] While this relies on some additional assumptions, we believe this robustness check is necessary given that there seems to exist a significant difference in prices in the 1993-2000 period (Charts A.3 and A.4 in Appendix A). We summarize the results of the two-sector models using chained indices in

17 Although when using chained prices, the period 1993-2000 also had very weak relative ICT price growth.

18 Blanchard *et al.*, 2017, discuss the channels by which changes in expectations about future growth could cause large short-term declines in GDP growth

19 Computer hardware and telecommunications equipment do not have separate chained dollar investment data, and splitting them is therefore difficult especially given the fact that we require the data for estimates of price growth.

20 It is considerably more difficult to obtain an estimate of the STS approach with chained prices given that the data requirements are at the sectoral level, and chained capital does not exist at this level of granularity.

Panel B of Table 6.[21]

The larger contribution in the 1993-2000 period using chained dollars is coming from both the use and production effects as prices are declining more rapidly in the 1993-2000 period and labour productivity growth in the ICT-producing sector is higher compared with constant-dollar data. Here, we assume that chained GDP growth is a nominal output weighted sum of the growth rates in each sector (the most appropriate weighting when using chained dollars). We also split the chained investment series between computer hardware and telecommunications using the ratio of investment in constant dollars for the two capital types. While these assumptions are cumbersome, results indicate that when using chained dollars, ICT is still heavily responsible for slow growth following the recession. The narrative here is that because fixed-weighted (i.e. constant dollar) investment assumes the same quantity mix throughout the entire 1993-2014 series (it assumes the basket is the same as in 2007, while chained investment would update the quantity mix each year), it may be that the investment goods that had rapid price declines in the late 1990s were not as heavily represented in 2007 when the quantity index was constructed.[22]

Nevertheless, the conclusions remain similar whether using chained or constant dollars. While the ICT contribution is higher in both models for each period, particularly in 1993-2000 in the CUPP model, it still remains true that it was not until after 2008 that the contribution seems to have fallen significantly for ICT.

Conclusion

In this article, we asked whether a weaker contribution of ICT to productivity growth could account for the labour productivity slowdown observed in Canada since the early 2000s. To answer this question, we examined several models which capture various channels through which ICT could affect aggregate productivity.

Our main conclusion is that while ICT is still contributing positively to productivity growth, this contribution has declined, explaining part of the slower aggregate productivity growth. In our base case, we calculate that about 0.1 to 0.2 percentage points per year of the productivity slowdown (around 20-40 per cent of the total 0.58 percentage point slowdown) is explained by the weaker ICT contribution. ICT-use (ICT-capital deepening and price effects) and ICT-production (productivity in the ICT sector) both account for the ICT contribution. Results using chained dollars indi-

21 For a more complete discussion on the differences between using chained-aggregated and fixed-weighted data see, Whelan (2002).

22 Note, however, that we split the chained investment series for computer hardware and telecommunications according to the constant index due to data limitations. It is thus not clear that the price growth is applied correctly to each type of capital. Both capital types have much slower growth with chained prices in the 1993-2000 period, but applying the ratio from investment in constant dollars may be incorporating an additional bias into the model.

cate that a weaker contribution of ICT may be explaining even more of the aggregate productivity slowdown.

However, the slowdown in productivity growth and in the contribution of ICT do not seem to have the same timing. While productivity growth slowed in the early 2000s, ICT's contribution does not appear to fall until around the Great Recession. The fall in contribution is caused mostly by the convergence of ICT prices with non-ICT prices (a direct input into the use effect of the CUPP model), and the lower adoption rates of ICT assets. This prompts the conclusion that while ICT had little to no role in the initial productivity slowdown, it has been a major determinant of the subdued productivity growth in the period since 2008-2009.

A limitation of our analysis is that it is performed at an aggregate level and may overlook some important nuances. It may be that lower use effects hide the concentration of ICT capital in certain industries (not unlike the superstar firm hypothesis proposed by Autor *et al.* (2017) and others). This limitation highlights the need for further analysis at a more disaggregated level.

Another limitation is that while the convergence of ICT and non-ICT prices seems to indicate that efficiency improvements in the production of ICT products has slowed in recent years, it may also be subject to price mismeasurement issues raised by some researchers (e.g. Byrne and Corrado, 2017). Note, however, that mismeasurement issues would need to have worsened, when compared with the pre-slowdown period, to account for the productivity slowdown.[23] Unfortunately, we have little information regarding price mismeasurement for Canada and therefore leave it to future research to examine this issue in Canada.

Another issue is that the nature of technology has changed. ICT services (e.g. cloud computing) may act more like investment and capital in an increasingly digitalized economy, but they may not be categorized as such in Canadian data.[24] Nevertheless, if produced in Canada, they would be captured through the production effect in our two-sector models. However, if these services are imported from another country, they may not be captured in our models.[25] Also, it may be that the intangible capital needed to properly utilize ICT and digital technology (some of which is not captured in national accounts data), has taken the place of much of the resources previously devoted to ICT capital. We also leave the investigation of these fac-

23 Byrne *et al.* (2016) examine the issue in U.S. data and conclude that measurement issues do not explain the U.S. productivity slowdown.

24 Kim (2018) discusses the issue

25 According to Rostami (2018), the imports of ICT services are somewhere between 5 per cent and 8.5 per cent of our estimates of real ICT capital. However, much of this is likely already an intermediate input into the ICT-producing sector, which would be captured by our model. Note also that adding services imports as a capital asset would be a level effect, and it would only impact the ICT capital income share (and a smaller effect on the capital deepening component, which is in growth terms).

tors to future research.

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