Creative Capital, Information and Communication Technologies, and Economic Growth in Smart Cities

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by

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Abstract

We study aspects of economic growth in a stylized smart city with two distinct features. First, the modeled inhabitants of this city are smart because they possess skills. Using the language of Richard Florida, these inhabitants comprise the city's creative class and hence they possess creative capital. Second, the city is smart because it uses information and communication technologies (ICTs) and we model one specific kind of ICT use. In this setting, we first derive expressions for three growth related metrics. Second, we use these metrics to show that the economy of smart city A converges to a balanced growth path (BGP). Third, we compute the growth rate of output per effective creative capital unit on this BGP. Fourth, we study how heterogeneity in initial conditions affects outcomes on the BGP by introducing a second smart city B into the analysis. At time $t = 0$, two key savings rates in city A are twice as large as in city B. We compute the ratio of the BGP value of income per effective creative capital unit in city A to its value in city B. Finally, we compute the ratio of the BGP value of skills per effective creative capital unit in city A to its value in city B.

Keywords: Creative Capital, Creative Class, Economic Growth, Skills, Smart City

JEL Codes: R11, O33

1. Introduction

1.1. Objective

The purpose of this paper is to combine aspects of the existing literatures on (i) smart cities and (ii) the creative class and to then analyze some features of economic growth in a stylized smart city. Consistent with the discussion in Caragliu *et al.* (2011), the smart city we study has two distinct features. First, the modeled inhabitants of this city are smart because they possess skills. Using the language of the urbanist Richard Florida, these inhabitants comprise the city's *creative class* and hence they possess *creative capital*.[4] Having said this, we should note that instead of using the language of the creative class, some researchers such as Shapiro (2006) and Winters (2011) have conceptualized smart cities as metropolitan areas in which a large share of the adult population has a college degree.

Second, the city under study is smart because it uses information and communication technologies (ICTs) in a variety of ways. Paskaleva (2009) and Herrschel (2013) point out that some of these ways include the use of ICTs to run transportation systems, hospitals, power plants, and to conduct electronic governance. To capture this feature of smart cities in our subsequent theoretical analysis in sections 2 through 4, we model one kind of ICT use in the context of a particular production process.[5]

One can ask why the creative class can be expected to enhance the performance of smart cities. We now explain why in three parts. First, for quite some time now, students of urban

[4] The urbanist Richard Florida has successfully popularized the twin concepts of the creative class and creative capital to economists and to regional scientists. In this regard, Florida (2002, p. 68) helpfully explains that the creative class "consists of people who add economic value through their creativity." This class is composed of professionals such as doctors, lawyers, scientists, engineers, university professors, and, notably, bohemians such as artists, musicians, and sculptors. From the standpoint of the growth and development of smart cities, these people are significant because they possess creative capital which is the "intrinsically human ability to create new ideas, new technologies, new business models, new cultural forms, and whole new industries that really [matter]" (Florida, 2005, p. 32).

[5] Modeling the use of ICTs in multiple ways renders our model intractable. This is why we model the use of ICTs in one way in sections 2 through 4 below.

economic growth and development have concentrated on the role of firms in cities and particularly on the ways in which firms make location decisions and the extent to which they mass together in clusters. However, as noted by Florida (2003), such a focus is insufficient. In addition to concentrating on firms, Florida (2003, p. 3) contends that we also need to focus "on diversity and creativity as basic drivers of innovation and regional and national growth." These attributes of diversity and creativity are provided by members of the creative class and hence this class can be expected to contribute positively to the well-being of smart cities. Second, Florida (2002) has argued that cities and regions that want to prosper need to have what he calls the "3 Ts," that is, talent, technology, and tolerance. Members of the creative class have talent, they are able to create and use new technologies including ICTs, and they tend to be tolerant. This also explains why we can expect the creative class to boost the performance of smart cities. Finally, in their study of smart cities, Caragliu *et al.* (2011) and DeAngelis (2014) provide support for the two points we have just made. For instance, Caragliu *et al.* (2011, p. 65) find that "the presence of a creative class [is]…positively correlated with urban wealth."

Before proceeding any further, it is important to comprehend the difference between the concept of creative capital and the well-known concept of human capital. Observe that in empirical work, the notion of human capital is generally measured with education or with education based indicators. This notwithstanding, Marlet and Van Woerkens (2007) have rightly contended that the accumulation of creative capital does *not* always depend on the acquisition of a formal education. In other words, while the creative capital accumulated by some members of Florida's creative class (doctors, engineers, university professors) does depend on the completion of many years of formal education, the same is not always true of other members of this creative class (artists, painters, poets). Individuals in this latter group may be innately creative and hence possess creative capital despite having very little or no formal education. We agree with Marlet and Van Woerkens (2007) that there is little or no difference between the notions of human and creative capital when the accumulation of this creative capital depends on the completion of many years of formal education. In contrast, there can be a lot of difference between the notions of human and creative capital when the accumulation of this creative capital depends on things like the accumulation of professional and business experiences but *not* on the completion of a formal education. Because creative capital is of two types, it is a *more general* concept than the mainly schooling based notion of human capital and this explains why we work with creative and *not* human capital in this paper.[6] We now proceed to a brief review of the literature first on smart cities and then on the creative class.

1.2. Review of the literature

1.2.1. Smart cities

Shapiro (2006) uses a neoclassical city growth model to show that 60 percent of the employment growth effect of college graduates in a smart city is due to enhanced productivity growth. The remaining 40 percent is caused by the rise in the quality of life of the city residents. Concentrating on Boston in the United States, Fu (2007) points out that the impact of human capital depth decays rapidly beyond three miles from block centroids and hence it is appropriate to refer to the localities within cities where this limited effect occurs as "smart café cities." Sudekum (2010) studies human capital externalities in western German regions and points out that relative to other cities, "skilled cities" in western Germany grow faster. In addition, cognitive skills appear to be a key factor in urban performance.

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Our discussion of the two types of creative capital is not without precedent. Recently, Usman and Batabyal (2014), Batabyal and Beladi (2016a, 2016b), and Batabyal and Nijkamp (2016) have also commented on the two types of creative capital in their research.

Bakici *et al.* (2013) and Zygaris (2013) both focus on Barcelona and study the extent to which this city has become "smart" by conforming to the so called Smart City Reference Model. It is noted that being smart does not only involve greater reliance on the use of ICTs but also the use of a more general strategy that pays attention to smart districts within a city, the use of living labs, and the provision of electronic services.[7] Sounding a cautionary note, Viitanen and Kingston (2014) use evidence from Birmingham, Glasgow, and Manchester in the United Kingdom to argue that the use of a digital consumer experience to define "intelligent systems" in these smart cities has left behind parts of these same cities and their populations. Taking a different approach, Steenbruggen *et al.* (2015) argue that the use of digital data in general and mobile phone data in particular can be used to develop innovative applications for the improved management of smart cities.

1.2.2. Creative class

Marlet and Van Woerkens (2007, p. 2605) focus on urban employment growth in the Netherlands and contend that "Florida's creative class is a better standard to measure human capital than are 4 education levels." Boschma and Fritsch (2009) utilize a data set that covers more than 500 regions in seven European countries and demonstrate that there is some evidence of a positive relationship among creative class occupations, employment growth, and entrepreneurship at the regional level. McGranahan and Wojan (2007) concentrate on rural counties in the United States and point out that their measure of the creative class is strongly associated with regional development.

The statistical analysis conducted by Andersen *et al.* (2010) shows that Florida's creative class thesis is supported for larger Nordic cities but not as well for smaller Nordic cities.

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These features are closely related to the notion of "urban buzz" recently studied by Arribas-Bel *et al.* (2016).

Marrocu and Paci (2012) concentrate on 257 regions in the European Union and show that highly educated people working in creative occupations are the most relevant component in explaining production efficiency and that the so called bohemians have little impact on a region's economic performance. Finally, Kerimoglu and Karahasan (2014) focus on Spain and point out that the notion of creative capital and specifically its local spillover have a salient impact on regional income gaps in Spain once other factors such as human and physical capital accumulation have been controlled for.

Our review of the contemporary literature on smart cities and the creative class yields three conclusions. First, this literature is overwhelmingly either empirical or based on case studies. Second, this literature has paid virtually no attention to the working of smart cities from a *theoretical* standpoint. Finally, even though Caragliu *et al.* (2011) and others have pointed to a clear connection between the existence of a creative class and the success of smart cities, there are *no* theoretical studies that link the use of creative capital and ICTs to economic growth in a smart city.

Given this lacuna in the literature, in this paper, we theoretically analyze the nexuses between creative capital, ICTs, and economic growth in a stylized smart city called city A. We first delineate our dynamic model which is adapted from Mankiw *et al.* (1992) and then derive analytic expressions for three growth related metrics.[8] Second, we use these metrics to show that the economy of smart city A converges to a balanced growth path (BGP) and then we compute the growth rate of output per effective creative capital unit on this BGP.[9] Third, we calculate the

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Analyzing economic growth in smart cities is important for at least two reasons. First, a recent study---see Anonymous (2017)---found that 75% of U.S. consumers believe that smart cities will positively impact their lives. Second, as noted by Ersoy (2017), the concept of a smart city offers the promise that the unprecedented challenges faced by urban centers today can be addressed with the intelligent use of, *inter alia*, smart technologies.

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BGP values of ICT and skills per effective creative capital unit. Fourth, we study how heterogeneity in initial conditions influences outcomes on the BGP by introducing a second smart city B into the analysis. At time $t = 0$, two key savings rates in city A are assumed to be twice as large as in city B. In this setting, we compute the ratio of the BGP value of income per creative capital unit in city A to its value in city B. Finally, for the same values of the four savings rates, we calculate the ratio of the BGP value of skills per creative capital unit in city A to its value in city B.

The remainder of this paper is organized as follows. Section 2 delineates our theoretical model of smart city A in detail. Section 3.1 derives analytic expressions for three growth related metrics. Section 3.2 first uses these metrics to demonstrate that the economy of smart city A converges to a BGP and then calculates the growth rate of output per effective creative capital unit on this BGP. Section 3.3 computes the BGP values of ICT and skills per effective creative capital unit. Section 4.1 commences the study of heterogeneity in initial conditions. Specifically, this section first introduces a second smart city B into the analysis. At time $t = 0$, two salient savings rates in city A are set twice as large as in city B. In this setting, this section calculates the ratio of the BGP value of income per creative capital unit in city A to its value in city B. For the values of the four savings rates in section 4.1, section 4.2 computes the ratio of the BGP value of skills per creative capital unit in city A to its value in city B. Section 5 concludes and then discusses four ways in which the research delineated in this paper might be extended.

The sense in which we are using the term BGP in this paper is entirely consistent with the way in which this term is used in standard textbooks on economic growth. Here are two examples. Barro and Sala-i-Martin (2004, p. 34) explain that the term BGP is used "to describe the state in which all variables grow at a constant rate…" Acemoglu (2009, p. 65) points out that in models with technological change, the terms "steady state" and "BGP" can be used interchangeably. The reader should understand that although it is true that on a BGP, the relevant variables in a model grow at constant rates, there is *no* requirement that a BGP be a solution to a social planner's problem. In addition, note that for the kind of steady state analysis we conduct in this paper, there are no threshold effects to contend with. Finally, in order to get to the BGP, it is necessary that creative capital and ICTs satisfy the differential equations specified in equations (3) and (4) below. However, the reader should note that because we work with the intensive values of the key variables $q(t), \dot{c}(t)$, and $\dot{s}(t)$---see section 2 below---the existence of the steady state under study is dependent on the satisfaction of equations (12) and (16) specified in section 3.

2. The Theoretical Framework

Consider a stylized smart city that we denote by A. At any time t, this city produces a high technology or "high tech" good such as a camera, a laptop computer, or a smartphone. We denote the output of this high tech good by $Q(t)$. This high tech good is also the final consumption good whose price is normalized to unity at all points in time. To clearly model the connection between the creative class and the working of smart cities discussed in section 1, we suppose that the high tech good mentioned above is produced by creative capital units $R(t)$ working with ICTs denoted by $C(t)$. In addition, consistent with the discussion of skills in Sudekum (2010), we assume that the total amount of *skills* or *smartness* possessed by the individual creative capital units is given by $S(t)$.[10] Along with ICTs in our smart city, we suppose that there also exists a different kind of technology or *knowledge* and that this knowledge augments or makes more productive the individual creative capital units. Let us denote this creative capital augmenting knowledge by $Z(t)$ and let $Z(t)R(t)$ represent an *effective* creative capital unit.[11]

The production function for the output $Q(t)$ of the high tech good is given by the Cobb-Douglas functional form

[10] The skills or $S(t)$ we have in mind represent attributes that the individual creative capital units possess that are specific to the high tech good $Q(t)$. Therefore, the possession of these skills enables the individual creative capital units to produce this high tech good efficiently. One possible source of these skills is ongoing research and development (R&D) about the high tech good under study. Viewed in this way, even though we are not modeling R&D directly, we are accounting for an outcome of this R&D. The reader should note that these skills do *not* refer to human capital and our paper has nothing to do with human capital. In fact, as explained in detail section 1.1, there is a difference between the traditional notion of human capital and the Richard Florida inspired notion of creative capital and, in this paper, we are working with the notion of creative capital and *not* with human capital. Finally, we shall use the words "skills" and "smartness" interchangeably in the remainder of this paper.

[11] As pointed out in footnote 10 with regard to skills, one possible interpretation of this knowledge is that it arises from R&D about the high tech good under study. Also, note that because we are interested in combining aspects of the existing literatures on smart cities and the creative class and then analyzing economic growth in a stylized smart city, we have *deliberately* chosen creative capital or $R(t)$ as one particular input. In this regard, note that the possession of creative capital is the distinguishing hallmark of the members of the creative class in smart city A. In addition, given our detailed discussion of the difference between human and creative capital in section 1.1, it does *not* make sense to interpret $R(t)$ "as human capital or R&D or any type of input." If $R(t)$ can be interpreted as any type of input then it will *not* specifically represent the creative class and the use of such a generic input will contradict our basic objective stated at the beginning of section 1.1.

$$Q(t) = C(t)^{\alpha} S(t)^{\beta} \{Z(t)R(t)\}^{1-\alpha-\beta}, \tag{1}$$

where the parameters $\alpha > 0, \beta > 0$, and $\alpha + \beta < 1$. The equations of motion for the four inputs that are used to produce the high tech good are given by the differential equations

$$\dot{Z}(t) = gZ(t), \tag{2}$$

$$\dot{R}(t) = nR(t), \tag{3}$$

$$\dot{C}(t) = \sigma_C Q(t) - \delta C(t), \tag{4}$$

and

$$\dot{S}(t) = \sigma_S Q(t) - \delta S(t), \tag{5}$$

where a dot on top of a variable on the left-hand-side (LHS) of equations (2) through (5) indicates a time derivative and we have $g > 0, n > 0$, and $\delta > 0$.[12]

Of particular importance for our subsequent analysis are the coefficients $\sigma_C \in (0, 1)$ and $\sigma_S \in (0, 1)$. Specifically, σ_C (σ_S) is the *constant* fraction of the output of the final consumption good that is *saved* to create more ICTs (skills) in smart city A. The initial values of the four inputs $Z(0), C(0), R(0)$, and $S(0)$ are given exogenously and they are all positive. Finally, let the values of output, ICTs, and skills per effective creative capital unit (sometimes called the

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One can ask whether it makes sense to model production in a smart city with a "representative" production function that is "Cobb-Douglas" in nature. We now explain why we believe it does make sense to do so in four parts. First, researchers and textbooks on growth theory routinely study economies with what Acemoglu (2009, p. 27) calls "a unique final good." Clearly, this modeling strategy is not meant to suggest that real world economies of interest typically produce only a single good. However, because a theoretical growth model is an abstraction of the real world, researchers have frequently found it convenient to focus on a single (and representative) good. In this regard, it should be noted that the celebrated Solow growth model described in Acemoglu (2009, pp. 26-76) also focuses on a single good. Our analysis in the present paper simply follows this well-established tradition. Second, researchers such as Mundula and Auci (2016) have used the Cobb-Douglas functional form to model production in smart cities. Therefore, a precedent for using this functional form *already exists* in the extant literature. Third, researchers such as Batabyal and Beladi (2015), Buettner and Janeba (2016), and Porter and Batabyal (2016) have used the Cobb-Douglas functional form to study production in economies with a noteworthy presence of the creative class. So, once again, *precedents exist* for using this specific functional form in our paper. Finally, it should be noted that the *multiplicative* form of the Cobb-Douglas production function enables researchers to obtain analytic expressions for the equilibrium values of the variables they are interested in. This is why many growth models also work with the Cobb-Douglas functional form. Once we depart from this multiplicative functional form, it is very difficult---and occasionally impossible---to obtain concrete results in an economic environment of the sort studied in this paper. In the appendix to this paper we show how complicated the analysis gets and how difficult it is to obtain concrete results when the Cobb-Douglas production function is replaced with, for instance, a linear production function.

intensive values) be given by $q(t) = Q(t)/Z(t)R(t)$, $c(t) = C(t)/Z(t)R(t)$, and $s(t) = S(t)/Z(t)R(t)$.[13] This concludes the description of our stylized smart city. We now proceed to derive analytic expressions for three growth related metrics and these metrics are $q(t), \dot{c}(t)$, and $\dot{s}(t)$.

3. One Smart City

3.1. Three growth metrics

3.1.1. An expression for q(t)

We begin by deriving an expression for output per effective creative capital unit or $q(t)$ as a function of ICTs per effective creative capital unit $c(t)$ and skills per effective creative capital unit $s(t)$. Substituting equation (1) into the definition of $q(t)$, we get

$$q(t) = \frac{C(t)^{\alpha} S(t)^{\beta} \{Z(t)R(t)\}^{1-\alpha-\beta}}{Z(t)R(t)}. \quad (6)$$

Now using the definitions of $c(t)$ and $s(t)$ given above, we can rewrite equation (6) as

$$q(t) = \frac{\{Z(t)R(t)c(t)\}^{\alpha} \{Z(t)R(t)s(t)\}^{\beta} \{Z(t)R(t)\}^{1-\alpha-\beta}}{Z(t)R(t)}. \quad (7)$$

Canceling the term $Z(t)R(t)$ from the numerator and the denominator of equation (7), we obtain the expression for $q(t)$ that we seek. Specifically, we get

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As shown in equation (1) above, the high tech good $Q(t)$ is produced in a very *particular* manner with four inputs that are *specific* and not generic. Therefore, it does *not* make sense to interpret this high tech good "as any type of consumption good." More generally, because many growth models work with a single final good (see footnote 12), if it were possible to interpret the final good "as any type of consumption good" then this point would apply to all such growth models. Finally, given our objectives in this paper (see section 1.1), it is *not* necessary to either measure or represent the quality of the high tech good $Q(t)$ under study.

$$q(t) = c(t)^{\alpha} s(t)^{\beta}. \quad (8)$$

3.1.2. *An expression for dc(t)/dt*

Differentiating both sides of the defining equation for $c(t)$ as a function of time t, we get

$$\dot{c}(t) = \frac{\dot{C}(t)Z(t)R(t) - C(t)\{\dot{Z}(t)R(t) + Z(t)\dot{R}(t)\}}{\{Z(t)R(t)\}^2}. \quad (9)$$

Using the definition $c(t) = C(t)/Z(t)R(t)$ we can simplify equation (9) to give us

$$\dot{c}(t) = \frac{\dot{C}(t)}{Z(t)R(t)} - \left\{\frac{\dot{Z}(t)}{Z(t)} + \frac{\dot{R}(t)}{R(t)}\right\} c(t). \quad (10)$$

Substituting from equations (2), (3), and (4) into equation (10) and then simplifying, we get

$$\dot{c}(t) = \sigma_C q(t) - (g + n + \delta)c(t). \quad (11)$$

Let us now substitute the value of $q(t)$ from equation (8) into equation (11). This gives us the expression for $\dot{c}(t)$ that we seek. Specifically, we get

$$\dot{c}(t) = \sigma_C c(t)^{\alpha} s(t)^{\beta} - (g + n + \delta)c(t). \quad (12)$$

3.1.3. *An expression for ds(t)/dt*

Differentiating both sides of the defining equation for skills per effective creative capital unit or $s(t)$ as a function of time t, we get

$$\dot{s}(t) = \frac{\dot{S}(t)Z(t)R(t) - S(t)\{\dot{Z}(t)R(t) + Z(t)\dot{R}(t)\}}{\{Z(t)R(t)\}^2}. \quad (13)$$

Using the definition $s(t) = S(t)/Z(t)R(t)$, equation (13) can be simplified to

$$\dot{s}(t) = \frac{\dot{S}(t)}{Z(t)R(t)} - \left\{\frac{\dot{Z}(t)}{Z(t)} + \frac{\dot{R}(t)}{R(t)}\right\} s(t). \tag{14}$$

Substituting from equations (2), (3), and (5) into equation (14) and then simplifying, we get

$$\dot{s}(t) = \sigma_S q(t) - (g + n + \delta)s(t). \tag{15}$$

Let us now substitute the value of $q(t)$ from equation (8) into equation (15). This gives us the expression for $\dot{s}(t)$ that we seek. That expression is

$$\dot{s}(t) = \sigma_S c(t)^{\alpha} s(t)^{\beta} - (g + n + \delta)s(t). \tag{16}$$

This completes the derivation of analytic expressions for $q(t), \dot{c}(t)$, and $\dot{s}(t)$. Our next task is to show that the economy of smart city A converges to a BGP and to then compute the growth rate of output per creative capital unit on the BGP.

3.2. Convergence to a BGP

To show that smart city A converges to a BGP, we must first understand the properties of the set of points in (c, s) space where $\dot{c}(t) = \dot{s}(t) = 0$. To this end, let us first work with equation (12). To obtain the $\dot{c}(t) = 0$ locus, we set the right-hand-side (RHS) of this equation equal to zero and then perform several steps of algebra to isolate $c(t)$. This gives us

$$c(t) = \{\frac{\sigma_C}{g+n+\delta}\}^{1/(1-\alpha)} s(t)^{\beta/(1-\alpha)}. \tag{17}$$

We can now use equation (17) to compute the first and the second derivatives of $c(t)$ with respect to $s(t)$. Doing this, we infer that $dc(t)/ds(t) > 0$ and that $d^2c(t)/ds(t)^2 < 0$. These last two results together tell us that the $\dot{c}(t) = 0$ locus is upward sloping and *concave* in (c, s) space.

Next, we work with equation (16). To find the $\dot{s}(t) = 0$ locus, we set the RHS of this equation equal to zero and then isolate $s(t)$. We get

$$c(t) = \{\frac{g+n+\delta}{\sigma_S}\}^{1/\alpha} s(t)^{(1-\beta)/\alpha}. \quad (18)$$

Once again, we use equation (18) to ascertain the first and the second derivatives of $c(t)$ with respect to $s(t)$. Completing the necessary computations, we see that $dc(t)/ds(t) > 0$ and that $d^2c(t)/ds(t)^2 > 0$. On the basis of the signs of these two derivatives, we deduce that the $\dot{s}(t) = 0$ locus is upward sloping and *convex* in (c, s) space.

Let us now put the above information about the $\dot{c}(t) = 0$ and the $\dot{s}(t) = 0$ loci together in a phase diagram. This is shown in figure 1. This figure clearly demonstrates that the economy

Figure 1 about here

of smart city A converges to a stable BGP at the point marked E. Inspection of this figure leads to three additional results. First, if we exclude the origin where $c = s = 0$, we see that the stable BGP at point E is *unique*. Second, $c(t) = C(t)/Z(t)R(t)$ is constant on the BGP. This tells us that the ICT per creative capital unit or $C(t)/R(t) = c(t)Z(t)$ must be growing at the *same* rate as the creative capital augmenting technology or knowledge, which is g. Third, skills or smartness per effective creative capital unit or $s(t) = S(t)/Z(t)R(t)$ is also constant on the BGP. Therefore, skills per creative capital unit or $S(t)/R(t) = s(t)Z(t)$ must also be growing at the *same* rate as the creative capital enhancing technology, which is, once again, g.

Our final task in this section is to compute the growth rate of output per creative capital unit on the above described BGP. To do so, we divide both sides of the production function given in equation (1) by $R(t)$. This yields

$$\frac{Q(t)}{R(t)} = \{\frac{C(t)}{R(t)}\}^{\alpha}\{\frac{S(t)}{R(t)}\}^{\beta} Z(t)^{1-\alpha-\beta}. \tag{19}$$

We already know that the ratios $C(t)/R(t)$, $S(t)/R(t)$, and the creative capital augmenting technology $Z(t)$ all grow at rate g on the BGP. In addition, the production function in equation (1) displays constant returns to scale. These last two points together tell us that the output of the high tech good per creative capital unit in smart city A also grows at rate g on the BGP.[14] We now proceed to calculate the BGP values of ICT and skills per effective creative capital unit in terms of the savings rates σ_C, σ_S, and the other parameters of our model.

3.3. BGP values of c(t) and s(t)

Let us denote the two BGP values we seek by c^{BGP} and s^{BGP} respectively. Solving equations (17) and (18) simultaneously, we can write

$$\{s^{BGP}\}^{\frac{1-\beta}{\alpha}-\frac{\beta}{1-\alpha}} = \{\frac{\sigma_C}{g+n+\delta}\}^{\frac{1}{1-\alpha}}\{\frac{\sigma_S}{g+n+\delta}\}^{\frac{1}{\alpha}}. \tag{20}$$

Note that the exponent on s^{BGP} in equation (20) simplifies to $(1-\alpha-\beta)/\{\alpha(1-\alpha)\}$. Therefore, raising both sides of equation (20) to the reciprocal of this simplified exponent, we get our desired expression for s^{BGP} as a function of σ_C, σ_S, and the other parameters of the problem. Specifically, that expression is

$$s^{BGP} = \sigma_C^{\frac{\alpha}{1-\alpha-\beta}}\sigma_S^{\frac{1-\alpha}{1-\alpha-\beta}}\{\frac{1}{g+n+\delta}\}^{\frac{1}{1-\alpha-\beta}}. \tag{21}$$

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Note the following three points. First, the growth rate of the output of the high tech good per creative capital unit is constant and not a function of either $C(t)$ or $R(t)$. Second, as noted previously in footnote 10, our analysis in this paper has nothing to do with human capital. Finally and consistent with our observations in footnote 13, given that we are modeling the production of a high tech good in a smart city, it does *not* make sense to interpret $C(t)$ as physical capital.

To find the corresponding expression for c^{BGP}, we substitute the expression for s^{BGP} from equation (21) into equation (17). This gives us

$$c^{BGP} = \sigma_C^{\frac{1}{1-\alpha}} \{\frac{1}{g+n+\delta}\}^{\frac{1}{1-\alpha}} [\sigma_C^{\frac{\alpha}{1-\alpha-\beta}} \sigma_S^{\frac{1-\alpha}{1-\alpha-\beta}} \{\frac{1}{g+n+\delta}\}^{\frac{1}{1-\alpha-\beta}}]^{\frac{\beta}{1-\alpha}}. \quad (22)$$

After several steps of straightforward but tedious algebra, equation (22) can be simplified to

$$c^{BGP} = \sigma_C^{\frac{1-\alpha-\beta+\alpha\beta}{(1-\alpha)(1-\alpha-\beta)}} \sigma_S^{\frac{\beta}{1-\alpha-\beta}} \{\frac{1}{g+n+\delta}\}^{\frac{1-\alpha-\beta+\beta}{(1-\alpha)(1-\alpha-\beta)}}. \quad (23)$$

The exponent on σ_C in equation (23) can be simplifies because $(1-\alpha-\beta+\alpha\beta) = (1-\alpha)(1-\beta)$. Using this simplification, we get the sought after expression for c^{BGP} as a function of σ_C, $\sigma_{S,}$ and the other parameters of the problem. That expression is

$$c^{BGP} = \sigma_C^{\frac{1-\beta}{1-\alpha-\beta}} \sigma_S^{\frac{\beta}{1-\alpha-\beta}} \{\frac{1}{g+n+\delta}\}^{\frac{1}{1-\alpha-\beta}}. \quad (24)$$

Our next task is to study the impact of heterogeneity in certain initial conditions on the BGP values of some key variables.

4. Two Smart Cities

4.1. Ratio of BGP value of income per effective creative capital unit in city A to city B

To study the effect of heterogeneity, we now concentrate on two smart cities. These two cities are city A---which we have been studying thus far---and a second smart city B. Smart city B is different from smart city A in two key ways. Specifically, both σ_C and σ_S are twice as large in city A as in city B. To conduct the analysis below in an analytically tractable manner, we will need to make two assumptions. As such, we first assume that apart from the differences in cities A and B that we have just mentioned, these two cities are identical in all other aspects. Second, we assume that $\alpha = 1/3$ and $\beta = 1/2$ in the remainder of this section.

Note that because the creative capital augmenting technology $Z(t)$ is the same in both the cities under study, we can compare the output of the high tech (and final consumption) good per effective creative capital unit. Using equation (8), the ratio of the output of the high tech good on the BGP in smart city A to smart city B is given by

$$\frac{q_A^{BGP}}{q_B^{BGP}} = \{\frac{c_A^{BGP}}{c_B^{BGP}}\}^{\alpha}\{\frac{s_A^{BGP}}{s_B^{BGP}}\}^{\beta}. \qquad (25)$$

We know that $\alpha = 1/3$ and that $\beta = 1/2$. Therefore, substituting these two values in equations (24) and (21), we get

$$c^{BGP} = \sigma_C^3\sigma_S^3\{\frac{1}{g+n+\delta}\}^6 \qquad (26)$$

and

$$s^{BGP} = \sigma_C^2\sigma_S^4\{\frac{1}{g+n+\delta}\}^6. \qquad (27)$$

Now, substituting equations (26) and (27) into equation (25) and then simplifying, we obtain

$$\frac{q_A^{BGP}}{q_B^{BGP}} = \left\{\frac{\sigma_{CA}\sigma_{SA}}{\sigma_{CB}\sigma_{SB}}\right\}\left\{\frac{\sigma_{CA}\sigma_{SA}^2}{\sigma_{CB}\sigma_{SB}^2}\right\}. \tag{28}$$

By assumption, we have $\sigma_{CA} = 2\sigma_{CB}$ and $\sigma_{SA} = 2\sigma_{SB}$. Except for these two key differences, the economies of smart cities A and B are identical in every other way. Therefore, substituting these assumptions about the two savings rates in equation (28), we get $q_A^{BGP}/q_B^{BGP} = 32$.

The above result clearly shows one powerful way in which initial differences in the two savings rates in the two smart cities matter. Specifically, we see that even though smart city A saves only twice the amount that smart city B does to create more ICTs and skills, this 2-fold initial difference between the two cities leads to a *32-fold* difference in the BGP output per effective creative capital unit between these same two cities. Put differently, relatively *small* initial differences in the two savings rates translate into a substantially *magnified* impact on the BGP values of output per effective creative capital unit.

One way of measuring the extent to which a city is smart is to look at skills or smartness possessed by the various creative capital units in this city. It is true that actual cities generally differ in the extent to which they are smart and that this difference can be attributed to, *inter alia*, differential skill acquisition processes. Therefore, consistent with the comparative exercise carried out in this section, we can ask how initial differences in σ_C and σ_S across the two cities A and B affect the ratio of the BGP value of skills per effective creative capital unit in these same cities. We now proceed to answer this question.

4.2. Ratio of BGP value of skills per effective creative capital unit in city A to city B

We begin by noting that we are able to compare the amount of skills per effective creative capital unit in the two smart cities because the creative capital augmenting technology

$Z(t)$ is, once again, the same in both cities. Using equation (27), the BGP ratio of skills (or smartness) in city A to those in city B is given by

$$\frac{s_A^{BGP}}{s_B^{BGP}} = \frac{\sigma_{CA}^2 \sigma_{SA}^4}{\sigma_{CB}^2 \sigma_{SB}^4}. \tag{29}$$

As in section 4.1, we suppose that $\sigma_{CA} = 2\sigma_{CB}$ and that $\sigma_{SA} = 2\sigma_{SB}$. Substituting these four values into equation (29), we get $s_A^{BGP}/s_B^{BGP} = 64$.

The above result shows a second powerful way in which initial differences in the two savings rates in the two smart cities influence BGP outcomes. Specifically, we see that even though smart city A saves only twice the amount that smart city B does to create more ICTs and skills, this 2-fold initial difference between the two cities leads to a *64-fold* difference in the BGP value of skills per effective creative capital unit between these same two cities. Consistent with the finding in section 4.1, once again we see that relatively *small* initial differences in the two savings rates translate into a substantially *magnified* effect on the BGP values of skills or smartness per effective creative capital unit. [15]

The policy implications of the comparative exercises in this and the preceding section for smart cities are threefold. First, for a given smart city, all else being equal, increasing the fraction of the output of the final consumption good that is used to generate more ICTs and skills in the

[15] One can ask whether the extent of the magnification results we have presented in this section are plausible. Our response to this query is as follows. This paper contains what we believe is the first theoretical analysis that explicitly links the use of creative capital and ICTs to economic growth in smart cities. As such, we are not aware of any studies that have attempted to quantify the magnification results obtained in this paper. Therefore, it is not possible to directly answer whether the extent of our magnification results are plausible. Having said this, we emphasize that the objective of our theoretical analysis in this section is *not* to quantify our magnification results but instead to make two specific points. First initial conditions *matter*. The work of Millar (1997) and Johnson and Takeyama (2001) provides clear support for this point. Second, small initial differences can lead to *very different* steady state results. The work of Arthur (1989) provides support for this point. Additional support is provided by Das *et al.* (2015, p. 61) who clearly state that "different initial conditions may cause economies with identical structures to come to rest at very different steady-state equilibria."

creative capital units *now* will yield greatly magnified benefits in terms of increased output and skills per effective creative capital unit *later*. Second, consider a smart city that is lagging behind another smart city in terms of output and skills per effective creative capital unit. For such a city to get ahead, it will need to *increase* the two constant fractions or, equivalently, the two savings rates denoted by σ_C and σ_S. Finally, the size of the magnification effect on output and skills that we have been discussing thus far can be easily computed by a policymaker in a smart city for the general case of a *m-fold initial* difference between the relevant savings rates in any two smart cities. To this end, suppose that we have $\sigma_{CA} = m\sigma_{CB}$ and $\sigma_{SA} = m\sigma_{SB}$ where m is any arbitrary positive integer that is greater than two. In this case, straightforward computations show that $q_A^{BGP}/q_B^{BGP} = m^5$ and that $s_A^{BGP}/s_B^{BGP} = m^6$. This completes our discussion of the connections between creative capital, ICTs, and economic growth in smart cities.

5. Conclusions

In this paper, we examined the nexuses between creative capital, ICTs, and economic growth in a stylized smart city A. We first delineated our model and then derived closed-form expressions for three growth related metrics. Second, we used these metrics to show that the economy of smart city A converged to a BGP and then we computed the growth rate of output per effective creative capital unit on this BGP. Third, we computed the BGP values of ICT and skills per effective creative capital unit. Fourth, we studied how heterogeneity in initial conditions influenced outcomes on the BGP by introducing a second smart city B into the analysis. At time $t = 0$, two key savings rates in city A were twice as large as in city B. In this setting, we calculated the ratio of the BGP value of income per effective creative capital unit in city A to its value in city B. Finally, for the same values of the four savings rates, we computed the ratio of the BGP value of skills per effective creative capital unit in city A to its value in city B.

The analysis in this paper can be extended in a number of different directions. In what follows, we suggest four possible extensions. First, we have not studied the functioning of a smart city during an economic crisis. Therefore, it would be useful to determine how the quality of life of the inhabitants of a smart city might be improved so that they participate meaningfully in a smart city's cultural and political life during a crisis and more generally as well. Second, it would be instructive to examine the ways in which financing can be used to provide services to citizens efficiently so that, in the long run, we create smart cities that are dynamic, livable, and sustainable. Third, it would be helpful to think not only about alternate sources of capital but also about how this capital can be used to tackle the fiscal challenges of today while building smart cities with sustainable financial systems for the future. Finally, one could examine how to bring about improvements in the governance of and the institutions in smart cities so that such cities attempt to meet the twin goals of environmental and financial sustainability. Studies that analyze these aspects of the underlying problem in smart cities will provide additional insights into the nexuses between alternate spatial, fiscal, and institutional factors on the one hand and sustainable economic growth on the other.

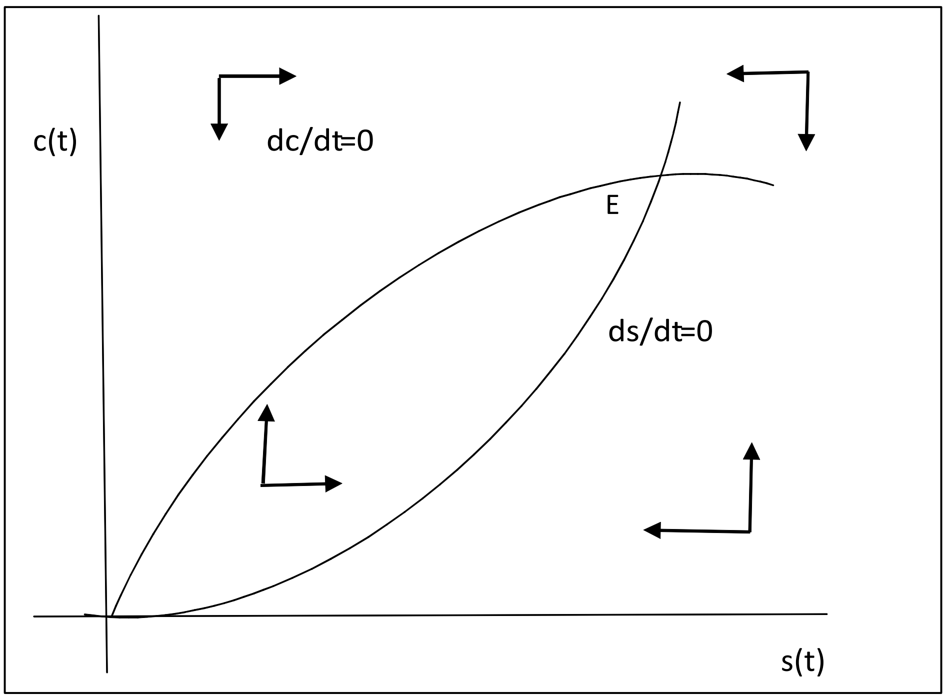

Figure 1: Economy of smart city *A* converges to a BGP

Appendix

The purpose of this appendix is to show how complicated the analysis in this paper gets and how difficult it is to obtain analytical results of the sort obtained in the body of the paper when the *multiplicative* form of the Cobb-Douglas production function in equation (1) is replaced with a *non-multiplicative* functional form such as the linear functional form. Consider the constant elasticity of substitution (CES) production function given by $Q(t) = [C(t)^r + S(t)^r + \{Z(t)R(t)\}^r]^{1/r}$, where r is the parameter. Without making further assumptions, it is *not* possible to make additional progress with the above functional form in a way that leads to tractable mathematical results. Therefore, we specialize the subsequent discussion in this appendix to the case where $r = 1$ so that the above CES production function simplifies to the linear production function that is now the analog of the production function given in equation (1).[16] Specifically, we get

$$Q(t) = C(t) + S(t) + Z(t)R(t). \tag{A1}$$

Standard computations of the sort carried out in section 3.1.1 give us an expression for $q(t)$ and the analog of equation (8). We get

$$q(t) = c(t) + s(t) + 1. \tag{A2}$$

Next, we need an expression for $\dot{c}(t)$. Performing computations of the sort shown in section 3.1.2, we get the following analog of equation (12)

$$\dot{c}(t) = \sigma_C\{c(t) + s(t) + 1\} - (g + n + \delta)c(t). \tag{A3}$$

Finally, calculations of the sort shown in section 3.1.3 give us an expression for $\dot{s}(t)$ that is the analog of equation (16). We get

$$\dot{s}(t) = \sigma_S\{c(t) + s(t) + 1\} - (g + n + \delta)s(t). \tag{A4}$$

16

Two other special cases are of some interest. When r approaches zero in the limit we get the Cobb-Douglas production function. Finally, when r approaches negative infinity in the limit we get the Leontief or perfect complements production function.

To show that smart city A converges to a BGP when the high tech good is produced in accordance with the linear production function in equation (A1), we have to comprehend the nature of the set of points in (c, s) space where $\dot{c}(t) = \dot{s}(t) = 0$. We begin with equation (A3). Setting $\dot{c}(t) = 0$ and then simplifying, gives us the analog of equation (17). We get

$$c(t) = \frac{\sigma_C}{g+n+\delta-\sigma_C} + \left\{\frac{\sigma_C}{g+n+\delta-\sigma_C}\right\} s(t). \tag{A5}$$

Inspecting equation (A5), it is clear that the $\dot{c}(t) = 0$ locus is an upward sloping straight line in (c, s) space with intercept and slope given by $\sigma_C/(g + n + \delta - \sigma_C)$ and we assume that $g + n + \delta > \sigma_C$. Similarly, setting $\dot{s}(t) = 0$ and then simplifying yields an equation that is the analog of equation (18). The equation of interest now is

$$c(t) = -1 + \left\{\frac{g+n+\delta-\sigma_S}{\sigma_S}\right\} s(t). \tag{A6}$$

Inspecting equation (A6), we see that the $\dot{s}(t) = 0$ locus is also an upward sloping straight line in (c, s) space with intercept -1 and slope $(g + n + \delta - \sigma_S)/\sigma_S$ and we assume, once again, that $g + n + \delta > \sigma_S$.

Since the two functions of interest in equations (A5) and (A6) are linear, as an alternative to drawing a phase diagram, we solve these two equations simultaneously. Doing so demonstrates that analogous to point E in figure 1, once again, we have a unique BGP equilibrium in which

$$s^{BGP} = \frac{(g+n+\delta)\sigma_S}{(g+n+\delta-\sigma_C)(g+n+\delta-\sigma_S)-\sigma_C\sigma_S} \tag{A7}$$

and

$$c^{BGP} = \frac{(g+n+\delta)\sigma_C\sigma_S}{(g+n+\delta-\sigma_C)(g+n+\delta-\sigma_S)\sigma_S-\sigma_C\sigma_S^2}. \tag{A8}$$

Equations (A7) and (A8) are the analogs of equations (21) and (24) in the body of the paper.

We now proceed to briefly discuss economic growth in two smart cities when the high tech good in both cities is produced with a linear production function of the sort specified in equation (A1). Now, the ratio of output of the high tech good on the BGP in smart city A to that in smart city B or the analog of equation (25) is given by

$$\frac{q_A^{BGP}}{q_B^{BGP}} = \frac{c_A^{BGP}+s_A^{BGP}+1}{c_B^{BGP}+s_B^{BGP}+1}. \tag{A9}$$

Using equations (A7) and (A8), equation (A9) can be simplified. This simplification---which involves straightforward but very tedious algebra---gives us

$$\frac{q_A^{BGP}}{q_B^{BGP}} = \frac{\frac{(g+n+\delta)\sigma_{SA}\Delta_{1A}+\sigma_{SA}\sigma_{CA}(g+n+\delta)\Delta_{2A}+\Delta_{1A}\Delta_{2A}}{\Delta_{1A}\Delta_{2A}}}{\frac{(g+n+\delta)\sigma_{SB}\Delta_{1B}+\sigma_{SB}\sigma_{CB}(g+n+\delta)\Delta_{2B}+\Delta_{1B}\Delta_{2B}}{\Delta_{1B}\Delta_{2B}}}, \tag{A10}$$

where $\Delta_{1i} = (g+n+\delta-\sigma_{Ci})(g+n+\delta-\sigma_{Si})\sigma_{Si}-\sigma_{Ci}\sigma_{Si}^2$ for $i = A, B,$ and $\Delta_{2j} = \left(g+n+d-\sigma_{Cj}\right)\left(g+n+\delta-\sigma_{Sj}\right)-\sigma_{Cj}\sigma_{Sj}$ for $j = A, B$.

By assumption, we have $\sigma_{CA} = 2\sigma_{CB}$ and $\sigma_{SA} = 2\sigma_{SB}$. However, even with these two assumptions and the fact that there are no production function exponents α and β to contend with, unlike the case studied in section 4.1, it is *not* possible to simplify the RHS of equation (A10) without making *many more* assumptions. A similar line of reasoning applies to the corresponding expression for the relative skills ratio s_A^{BGP}/s_B^{BGP}. Therefore, we now conclude our discussion in this appendix with two key observations. First, of the various types of production functions discussed in Griffin *et al.* (1987), it is possible to obtain concrete results for *some* functional forms such as the Cobb-Douglas and the linear forms but *not* for other forms such as the generalized CES form. Second and as noted in footnote 12, when we engage in a comparative exercise of two heterogeneous smart cities, once we depart from the *multiplicative* functional form present in the Cobb-Douglas production function, it is *not* possible to obtain concrete results without making many more assumptions about the numerical values of the parameters of the model.

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