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Modeling the Diffusion of General Purpose Technologies in an Evolutionary Multi-Sector Framework

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Abstract

General Purpose Technologies (GPTs) are characterized by their pervasive use in the economy. The introduction of a new GPT (product innovation) as well as increasing productivity within a GPT-sector (as a consequence of process innovations) affect the economy in several ways. First, a new GPT offers the opportunity to produce goods by means of cheaper processes; secondly, technical progress within the GPT sector directly (by cost-advantages) and indirectly (by changing profitability of different processes) influences productivity gains in related sectors. Also social consequences such as changing wage share, technical unemployment and transitional wage inequality can be observed. Finally, in the history of economics the emergence of a GPT correlates with output decline, preceding economic growth. This paper introduces an evolutionary multi-sector framework to study these effects by combining neo-Ricardian economics and replicator-dynamics of evolutionary game theory. Empirical evidence is given by the ICT sector in Denmark and its influence on related sectors from 1966 to 2007.

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May 31, 2013

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Keywords: general prupose technologies, neo-Ricardian economics, evolutionary game theory, technical change

JEL: C6, O3, O4

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1 Introduction

General Purpose Technologies (GPTs) are basic innovations which change the productive structure of the economy via their pervasive use. The steam engine and electricity as well as the information and communication technology (ICT) in the past decades are examples of GPTs, since their emergence (as product innovations) paved the way for process innovations and hence for productivity gains. Inter-sectoral spill-over effects by the introduction of a new GPT and by technical change within a GPT-producing sector implied aggregate economic as well as distributive (and hence social) consequences: A downturn of aggregate output, transitory wage inequality, technical unemployment and changing skills are examples of effects associated with the emergence of a new GPT (Helpman, 1998).

Besides appreciative theories such as for example Mokyr‘s notion of micro- vs. macro-inventions (Mokyr, 1990), several formal economic models were set up to facilitate the understanding of economic and social consequences of a new GPT and of technical progress in the GPT sector (Helpman and Trajtenberg, 1998a,b; Aghion and Howitt, 1998; Petsas, 2003; Carlaw and Lipsey, 2006). These models are based on assumptions concerning the individual behavior of economic agents, including the rational expectations hypothesis and endogenously modeled technical progress due to R&D activities.

A neo-Ricardian multi-sector framework (Sraffa, 1960; Kurz and Salvadori, 1997) is merged with the replicator dynamic formalism of evolutionary game theory (Weibull, 1997) to model the dynamics of technical change, incorporating the following features: (1) Different sectors of the economy are related to each other by unit production input-output matrices. Technical progress in one sector can therefore induce productivity changes as well as technical progress in other sectors. Product innovations are implemented by increasing the dimension of the technology-matrices of the model. (2) Different skill levels with differing remuneration are factored in to model wage inequality. Productivity gains are reflected by rising real wages, and also the investigation of the evolution of the wage share is conducted to enable discussions concerning distributional issues. (3) The different technologies within each sector are of Leontief-type, assuming instantaneous constant returns to scale. (4) Individual behavior is not explicitly modeled, but a population view of the economy is introduced. Each process is identified as a population that grows (in terms of output) due to its reproductive fitness defined by extra profits (or losses) it can gain. As a consequence, the S-shaped pattern observed for successful economic diffusion processes (Rogers, 2003) is endogenized, including feedback effects between populations and the economic environment: Growth patterns of technologies imply changes of the cost structure, which in turn leads to altering prices and wages. These in reverse influence extra profits generated by some technology, hence affecting he population's growth potential.

Empirical evidence for the dynamics of this model is given by the development of the ICT sector in Denmark and its influence on related sectors from 1966 to 2007.[1] Denmark is chosen due to its position as a net-importer of ICT-products[2], and due to the extent of the available data. The first is important in so far as this allows to analyze the effects of ICT predominantly for the production side without needing to consider its impact on economic development via export activities. As regards the latter, Statistics Denmark provides a comprehensive data base that entails annual input-output tables in constant prices and employment data from 1966 to 2007, as well as capital flow tables spanning from 1993 to 2007 (see Strohmaier and Rainer 2013 for a detailed description of the data handling). In order to study the distributive consequences of a GPT on an empirical level, we make use of Denmark labor input data provided by the EU KLEMS database (Edition 2008). This dataset comprises the shares in total hours worked together with the shares in total labor compensation for three different qualification levels, covering a time-span of 26 years (1980–2005).

This paper proceeds as follows: In section 2 the evolutionary multi-sectoral framework is introduced. The diffusion of GPTs after some product innovation and the subsequent influence of process innovations within the GPT sector are

[1]The following industrial and service classes comprise the notion of ICT : (1) Mfr. of office machinery and computers, (2) Mfr. of radio and communications equipment etc., (3) Computer activities, Software consultancy and supply.

[2]The only exceptions are central processing units. For a detailed analysis of Denmark's position among Europe with regard to ICT activities see Koski et al. (2002).

studied in section 3. A demonstration of possible wage inequality, changing wage share and output downturn is included. In addition, empirical evidence is provided for the case of the ICT sector in Denmark from 1966 to 2007. Finally, section 4 concludes.

2 Evolutionary multi-sector model

Pervasiveness and innovative complementarity are two characteristic properties of GPTs (Helpman and Trajtenberg, 1998a). The evolutionary multi-sector model introduced in this section describes these features by making the inter-sectoral linkages explicit in a neo-Ricardian framework as introduced by Kurz and Salvadori (1997). The notational adaption to the needs of this article is provided in subsection 2.1. In subsection 2.2 this formalism is merged with evolutionary dynamics to simulate the transition path in the presence of technical change.

2.1 A neo-Ricardian multi-sector framework

Let N be the number of different sectors in a closed economy. Within each sector m, an amount x_m of a homogeneous good is produced. This commodity can either be used as input factor of production or for final consumption y_m. The coefficient $a_{nm} \geq 0$ denotes the quantity of good m, which is *on average* necessary to produce one unit of good n. Formally there is no difference whether a_{nm} is interpreted as circulating capital necessary to produce good n, or if it is the worn-out quantity of fixed capital which has to be replaced. Let $g_n = \dot{x}_n/x_n$ denote the growth rate of sector n. Both circulating capital and the compensation of degradation of fixed capital grow by this factor. Additionally, the stock of fixed capital has to be corrected accordingly. Over and all, final consumption y_n as the net residual of gross production is given by

$$y_n = x_n - \sum_{m=1}^{N} a_{nm}x_m - \sum_{m=1}^{N} g_m a_{nm} x_m - \sum_{m=1}^{N} g_m f_{nm} x_m \tag{1}$$

with f_{nm} denoting the average quantity of fixed capital produced in sector m, necessary to produce one unit of good n. The second term in (1) is the amount of good n used for productive purposes, whereas the third term is the correcting factor due to sectoral growth. The last term incorporates the changing economy-wide stock of good n as fixed capital.

Defining the $N \times N$-matrices A and F by the technical coefficients a_{nm} and f_{nm}, respectively, the N equations stated in (1) more succinctly can be written as

$$\mathbf{y}^T = \mathbf{x}^T \left[\mathbb{I} - (\mathbb{I} + \hat{\mathbf{g}} A) - \hat{\mathbf{g}} F \right]. \tag{2}$$

$\mathbb{I}$ is the identity matrix, $\mathbf{y}, \mathbf{x}$ and $\mathbf{g}$ are the column vectors of final demand, of gross output and of the sectoral growth rates, respectively.[3] Equation (2) is the *market clearing condition*, which is assumed to hold (changing inventories are neglected).

Let l_{nk} denote the quantity of skill k necessary to produce one unit of good n. The $N \times K$-matrix L of labor input coefficients l_{nk} together with A and F characterizes the technologies of the economy. Each skill is remunerated by some real wage w_k, constituting the wage vector $\mathbf{w}$. Relative wage premia w_k/w_j are taken to be exogenously given and constant over time for all k and j. Hence it is possible to define some constant vector $\mathbf{u}$ characterizing relative wages according to $\mathbf{w} = w\mathbf{u}$ with real wage level w.

Labor is ex-post remunerated by wages, and capital is ex-ante remunerated by profits. Let r denote the *normal rate of profits* which prevails in case of free competition, then average unit production costs c_n of good n are determined by

$$c_n = (1 + r)\mathbf{p}^T \mathbf{a}_n + w\mathbf{u}^T \mathbf{l}_n \tag{3}$$

with $\mathbf{a}_n$ and $\mathbf{l}_n$ denoting the n-th row of A and L, respectively. Prices p_n are taken to equal average unit production costs, hence (3) implies the price equation

$$(1 + r)A\mathbf{p} + wL\mathbf{u} = \mathbf{p} \tag{4}$$

[3] Superscript T denotes transposition and a hat on a vector means the diagonal matrix built from this vector.

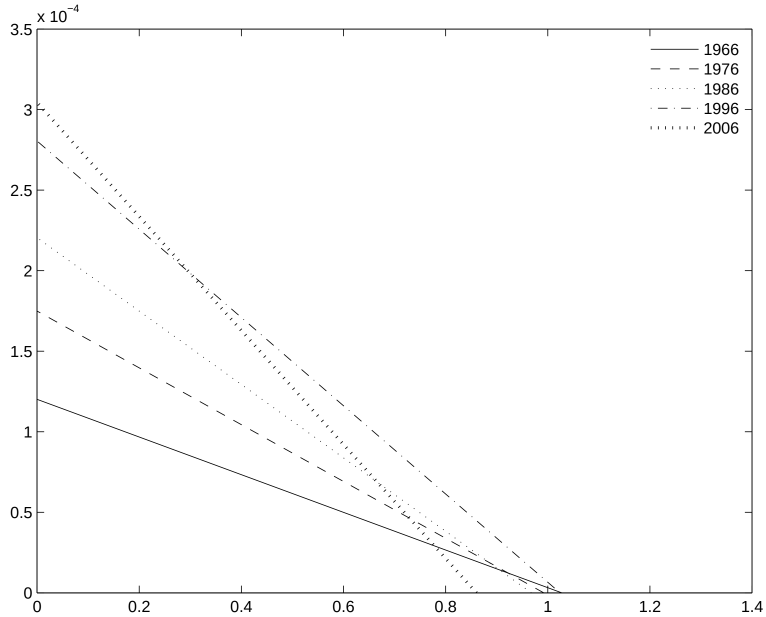

Figure 1: Wage-profit curve for Denmark from 1966 to 2006

with price vector $\mathbf{p}$. Prices are normalized with respect to some commodity bundle $\mathbf{d}$ (the *numéraire*) by $\mathbf{d}^T\mathbf{p} = 1$. Then from (4) the wage level w can be derived to

$$w = \frac{1}{\mathbf{d}^T \left[\mathbb{I} - (1+r)A\right]^{-1} L\mathbf{u}}. \tag{5}$$

The evolution of this $w - r$ relationship provides information about the kind of technical progress that takes place. Harrod-neutral or purely labor-saving technical progress is represented by a clockwise rotation of the $w - r$ curve, whereas Solow-neutral or purely capital-saving technical progress corresponds to an anti-clockwise rotation. Hicks-neutral or factor-saving technical change leads to a parallel shift outwards. Figure 1 shows the corresponding wage-profit-frontier for Denmark from 1966 to 2006. The intersections with the axes determine the maximum wage rate (for $r = 0$), and the maximum rate of profits (for $w = 0$), respectively. Until 1986 the curve rotates clockwise around a more or less stable rate of profits in the range of 0.92. Since this value is in reality unlikely to occur, one can conclude that in the 20 years between 1966 and 1986 technological change was labor-saving. For

1996 the $w - r$-relationship shows unambiguous technical progress, because both intersection points moved outwards. Since then the maximum rate of profits has decreased and the curves of 1996 and 2006 intersect at a rate of profit equal to 0.31. Nonetheless, within a realistic range of profit rates, technical progress turns out to be labor-saving and capital-using.

2.2 An evolutionary model of technological diffusion

Technical coefficients A, F and L are defined as average inputs necessary for unit production. The dynamic evolution of these observables can be explained as follows. Let each sector n be divided into I_n different populations, defined by different processes which can be employed to produce good n. $\mathbf{a}_n^{i_n}, \mathbf{f}_n^{i_n}$ and $\mathbf{l}_n^{i_n}$ are the vectors of circulating and fixed capital and of labor, used by process i_n in sector n to produce one unit of output. If a fraction $q_n^{i_n}$ of good n is produced by process i_n, then

$$\mathbf{a}_n = \sum_{i=1}^{I_n} q_n^{i_n} \mathbf{a}_n^{i_n}, \quad \mathbf{f}_n = \sum_{i=1}^{I_n} q_n^{i_n} \mathbf{f}_n^{i_n}, \quad \mathbf{l}_n = \sum_{i=1}^{I_n} q_n^{i_n} \mathbf{l}_n^{i_n}$$

are the rows of A, F and L, respectively.

From equation (4) it then follows that prices are determined by average costs, since process i_n in sector n occasions unit costs

$$c_n^{i_n} = (1+r)\mathbf{p}^T \mathbf{a}_n^{i_n} + w\mathbf{u}^T \mathbf{l}_n^{i_n}.$$

Extra profits $\rho_n^{i_n}$ of the respective process are consequently determined by

$$(1 + r + \rho_n^{i_n})\mathbf{p}^T \mathbf{a}_n^{i_n} + w\mathbf{u}^T \mathbf{l}_n^{i_n} = p_n.$$

Positive extra profits of some process have different effects on producers: (1) firms get encouraged to invest into growth, (2) new firms get convinced to enter the sector and to use this special process, or (3) firms within the sector change their mode of production and switch to the cheaper process. Negative extra profits (losses) have the reverse effects: They make firms leave either the sector or this specific mode of production (by switching to another, more profitable process), or a firm has to shrink if it further on uses the unprofitable process.

By abstracting from the single firm, a *population* is defined by some technology. Each population is characterized by its *reproductive fitness* identified by the growth rate

$$g_n^{i_n} = \dot{x}_n^{i_n}/x_n^{i_n} = \rho_n^{i_n} + \Delta_n + g \tag{6}$$

of output $x_n^{i_n}$ produced by means of process i_n in sector n. It is influenced by three treats: (1) by extra profits $\rho_n^{i_n}$, which are idiosyncratic for the process; (2) by the overall growth rate g of the economy due to savings; and (3) by the sectoral growth rate Δ_n, which corrects sectoral output according to changes in effective demand due to varying demand for production and final consumption.

As a consequence of $x_n = \sum_{i_n=1}^{I_n} q_n^{i_n} x_n^{i_n}$, expression (6) leads to the sectoral growth rate

$$g_n = (\rho_n + \Delta_n + g) \tag{7}$$

with average fitness $\rho_n = \sum_{i_n=1}^{I_n} q_n^{i_n} \rho_n^{i_n}$ of sector n. By differentiation of $q_n^{i_n} = x_n^{i_n}/x_n$, the evolution of the system in the presence of technical change is described by the replicator dynamics

$$\dot{q}_n^{i_n} = q_n^{i_n} \left(\rho_n^{i_n} - \rho_n \right). \tag{8}$$

Different extra profits of different processes producing the same homogeneous good consequently imply changing market shares. The dynamics of $q_n^{i_n}$ depends on extra profits and therefore on the price structure $(\mathbf{p}, w)$ and on the technical coefficients $\mathbf{a}_n^{i_n}, \mathbf{f}_n^{i_n}$ and $\mathbf{l}_n^{i_n}$. Equation (8) hence describes a diffusion process, if within one sector several processes with different extra profits are in use. Introducing new innovative (cheaper) processes consequently sets off an evolutionary dynamics, possibly leading to a takeover of the sector by one of these new processes.

3 Diffusion of GPTs

In this section the modeling framework is utilized to analyze the diffusion of the influence of GPTs. In subsection 3.1 a new GPT is introduced as a second sector in a former single-sector economy, making the emergence of one or more new processes in the first sector possible. Then in subsection 3.2 technical progress in the GPT sector is allowed for, and possible consequences on the first sector are investigated.

Fixed capital is taken to be zero ($F = 0$), since this does not alter the qualitative properties of the model. This holds true because the price equation (4), which drives the diffusion process, is not affected by F. And for the quantity system (2), adding of fixed capital would lead to a retardation but not to a qualitative alteration of the diffusion process.

3.1 The diffusion of a new GPT

A new GPT is invented and introduced into the economic system at time $t = 0$. For $t < 0$ the economy is described by one aggregate sector, which reproduces itself with the net-output used up for final consumption. The production process is characterized by the technical coefficients a_{11}^1 and l_{11}^1. Gross production x_1 of this sector equals total production x_1^1 of this process. For $t \geq 0$ a second sector exists, producing a GPT, such that the old technology in sector 1 is now characterized by $\mathbf{a}_1^1 = (a_{11}^1, 0)^T$ and $\mathbf{l}_1^1 = (l_{11}^1, 0)^T$.

GPT as product innovation: The GPT is produced by means of capital input from sector 1. The process utilized in sector 2 is characterized by technical coefficients $\mathbf{a}_2^1 = (a_{21}^1, 0)^T$ and $\mathbf{l}_1^1 = (0, l_{22}^1)^T$. Hence the GPT is produced by high skill labor with wage premium $u > 1$. For $\mathbf{d} = (1, 0)^T$, taking the good of sector 1 as numéraire, price p of the GPT is given by

$$p = (1 + r)a_{21}^1 + wl_{22}^1 u. \tag{9}$$

An introduction of the GPT sector with the produced good not being used for final consumption ($y_2 = 0$) only pays if similarly in sector 2 a second process is introduced, which uses the GPT as factor of production. If the GPT enters as circulating capital, the innovative process can be characterized by the technical coefficients $\mathbf{a}_1^2 = (a_{11}^2, a_{12}^2)^T$ and $\mathbf{l}_1^1 = (0, l_{12}^2)^T$. Let $q_1 > 0$ denote the share of the new process in sector 1. From goods market clearing (2), which now reads

$$(y_1, 0)^T = (x_1, x_1^2 q_1 a_{12}^2)^T \left[\mathbb{I} - (\mathbb{I} + \hat{\mathbf{g}})A\right], \tag{10}$$

the growth rate g_2 of the GPT sector is given by $1 + g_2 = q_1(t)(1 + g_1)a_{12}/a_{21}$. From the first equation in (10), total output x_1 of the consumption sector exhibits a growth rate $g_1 = \rho_1 + r$ according to (7) with $g = r$. $\Delta_1 = 0$ holds because forced savings are assumed (y_1 equals net-output) and no substitution of consumption exists due to $y_2 = 0$.

Diffusion of the GPT: The evolution of the system is driven by the extra profits ρ_1^i of the two processes $i = 1, 2$ in sector 1, implicitly given by

$$\begin{array}{lclcl} (1 + r + \rho_1^1)\ a_{11}^1 & + & w l_{11}^1 & = & 1, \\ (1 + r + \rho_1^2)(a_{11}^2 + a_{12}^2 p) & + & w l_{12}^2 u & = & 1. \end{array} \tag{11}$$

From (9), p can be replaced in (11) as well as in the now prevailing price equation $(1 + r)[(1 - q_1)a_{11}^1 + q_1(a_{11}^2 + a_{12}^2 p)] + w[(1 - q_1)l_{11}^1 + q_1 l_{12}^2 u] = 1$. This problem is formally equivalent to a one-sector economy employing two processes: the first one is the same as above, characterized by technical coefficients $\tilde{a}_1 = a_{11}^1$ and $\tilde{\mathbf{l}}_1^1 = (l_{11}^1, 0)^T$; the second one is a combination of the GPT sector and the formerly defined second process, characterized by the technical coefficients $\tilde{a}_2 = a_{11}^2 + (1 + r)a_{12}^2 a_{21}^1$ and $\tilde{\mathbf{l}}_2 = (0, (1 + r)a_{12}^2 l_{22}^1 + l_{12}^2)^T$.[4] This problem is analytically solvable with solution

$$z(t)[\kappa_1 + \kappa_2 z(t)]^{\kappa_3} = \kappa_4 e^{\kappa_5 t}. \tag{12}$$

[4]Each two-sector economy with one innovative sector formally can be reduced to a 1-sector diffusion problem (Rainer, 2013).

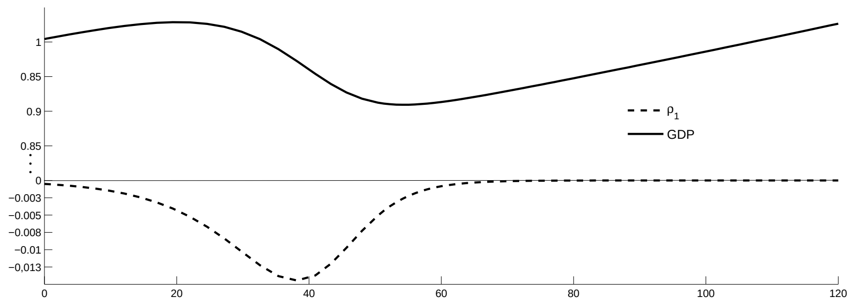

Figure 2: Negative growth and output slump.

$z = q_1/(1-q_1)$ is the relative market share of the innovative process, and $\kappa_1, \ldots, \kappa_5$ are parameters which are determined by the technical coefficients as well as by the initial condition $q_1(0)$. (Rainer, 2013)

Output slump: The evolution of total output is depicted in figure 2 for the technical coefficients $(a^1_{11}, l^1_{11}) = (0.3, 0.3)$, $(a^2_{11}, a^2_{12}, l^2_{12}) = (0.4, 0.1, 0.2)$ and $(a^1_{21}, l^1_{22}) = (0.1, 0.1)$. Since average extra profits are negative as a result of the capital using characteristic of the technical progress, real GDP exhibits a recessive tendency throughout the diffusion process Only in the long run the economic growth pattern given by $g = r = 0.01$ is restored. This result resembles the empirically found output slump after introduction of some GPT (Helpman, 1998): By the market clearing condition (2), the growth component $\rho_1 + \Delta_1$ of the sectoral growth rate $g_1 = \rho_1 + \Delta_1 + r$ is obtained by savings of workers. Since $\Delta_1 = 0$, $\rho_1 < 0$ implies forced savings. Consumers therefore accept lower final consumption due to changing circumstances. They are passive observers of the process of *creative destruction* (Schumpeter, 1954), which in this framework is caused by declining output of the old process. This downturn cannot be compensated by the rising output of the innovative process and therefore leads to a regression of available goods for final consumption.

To provide empirical evidence, figure 3 represents the evolution of real GDP in Denmark between 1966 and 2007. The solid line shows the long-term trend

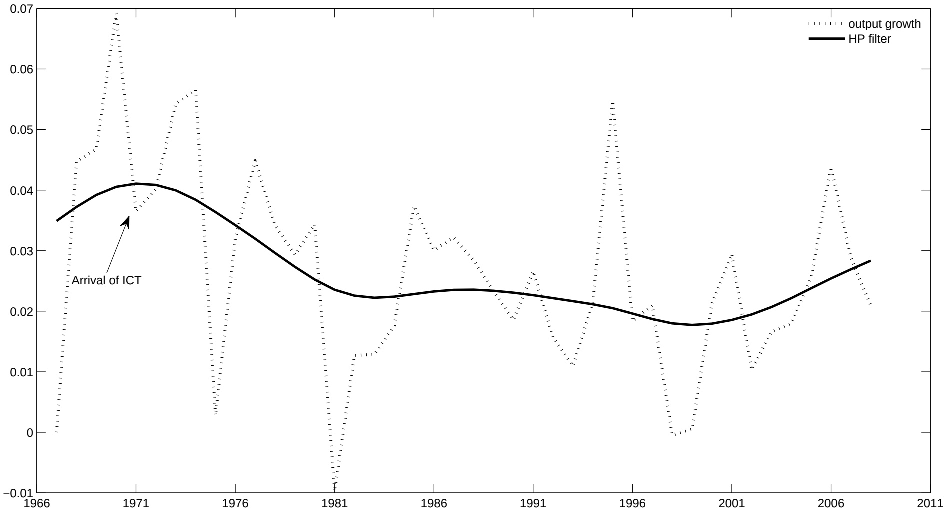

Figure 3: Growth of real GDP

as obtained by the Hodrick-Prescott (HP) filter. Jovanovic and Rousseau (2005) suggest to date the arrival of ICT with the invention of Intel's 4004 processor, or alternatively at the point in time when ICT equipment represents 1% of the capital stock[5] of the median sector. In both cases, the ICT-era in Denmark would start out in 1971. While output growth shows a falling tendency throughout the whole period under study, figure 3 suggests that the emergence of ICT has even amplified the slump.

Wage inequality: Different skills which are differently remunerated imply wage inequality within the class of laborers. For two different skills, as assumed in this example, wage inequality can be estimated by the GINI index[6]

$$GINI = q_h(1-q_h)\frac{u-1}{1+(u-1)q_h}. \tag{13}$$

[5]The corresponding data was retrieved from the EU-Klems database.

[6]The derivation of the GINI index for the case of K skills is conducted in Rainer (2013).

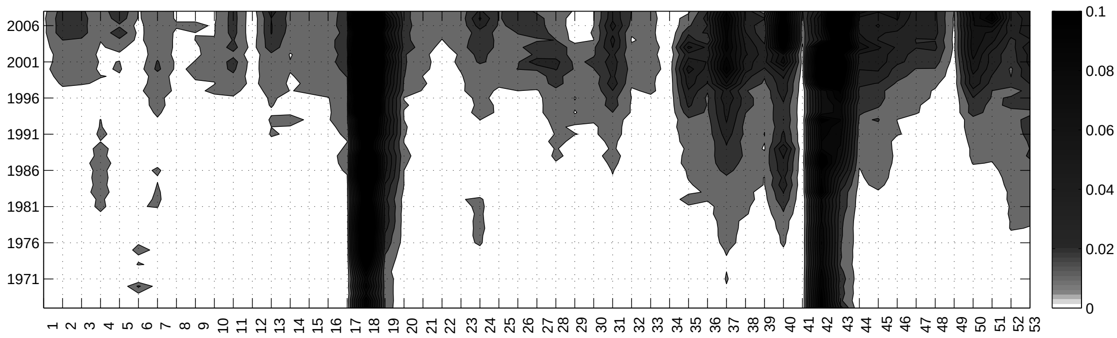

Figure 4: The diffusion of ICT products across sectors

The share q_h of high skill labor is remunerated by some wage premium $u > 1$ relative to the employed low skilled labor. It is given by

$$q_h = \frac{x_1^2 l_{12}^2 + x_2^1 l_{22}^1}{x_1^1 l_{11}^1 + x_1^2 l_{12}^2 + x_2^1 l_{22}^1} = \left[1 + \frac{1-q_1}{q_1} \frac{l_{11}^1}{l_{12}^2 + a_{12}^2 l_{22}^1}\right]^{-1}. \tag{14}$$

The last term in equation (14) accrues from $x_2 = x_1^2 q_1 a_{12}^2$ and by acknowledging $x_1^i = q_1^i x_1$ for $i = 1, 2$. In this case, the GINI index is independent of sectoral growth patterns, since growth of the GPT sector is coupled to the demand from sector 1.

From an empirical perspective, the following evidence is provided for the diffusion process described by (12) and for the resulting transitional wage inequality calculated by (13). The compound direct requirements matrix, which includes not only domestic and imported flows of intermediate products, but also of capital, is used in the following to derive the diffusion pattern of ICT.[7] An input coefficient for ICT manufacturing and service products above 0.01 was arbitrarily chosen as an indicator that the respective sector has adopted this technology in its produc-

[7] By including investment flows, the input matrix cannot be interpreted as a matrix of technical coefficients, since it now contains an element of expectation (see e.g. Verspagen, 2004).

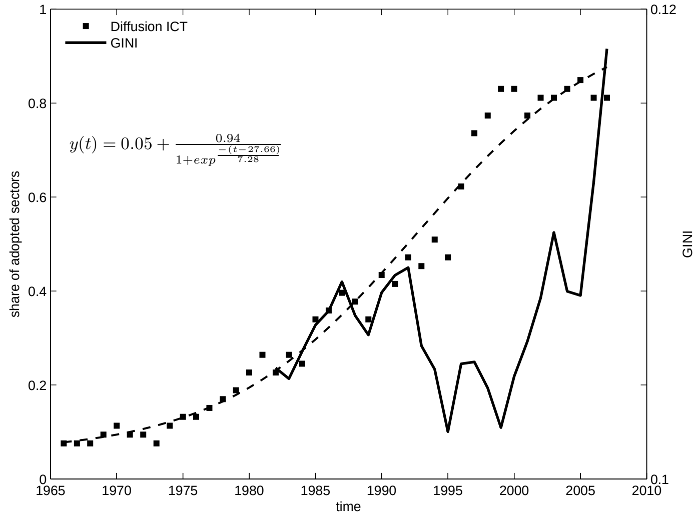

Figure 5: The diffusion of ICT products across sectors (left ordinate) and the GINI-coefficient for low and high-skilled labor (right ordinate).

tion. Figure 4 depicts the diffusion of ICT throughout the Danish economy from 1966 until 2007 (the industry classification is listed in the appendix). The contour plot shows that ICT goods (produced by Sector 18) and ICT services (Sector 43) initially spread over the neighboring industries, such as Mfr. of machinery and equipment n.e.c. (17), Mfr. of other electrical, medical and optical equipment (19), as well as Real estate activities (41) and Renting of machinery and equipment (incl. office computers) n.e.c. (42). In the mid 70ies Post and telecommunications (37) and the Financial markets (40) started to utilize ICT. Almost a decade later, one can see the beginning of online sale (31) and online auctioning (45), and the entry of ICT in Research & development (44). Afterwards, the technology spreads over most sectors in manufacturing and services, with the primary industries as the last sector to adopt it.

Figure 5 links the diffusion of ICT to the evolution of wages of low and high skilled labor in Denmark. The left ordinate presents the share of sectors already using ICT, and the right ordinate gives the GINI coefficient as a measure of the dispersion of wages of low and high-skilled labor in the ICT-using industries. Figure 5 shows that the diffusion path approaches the typical sigmoid curve with the

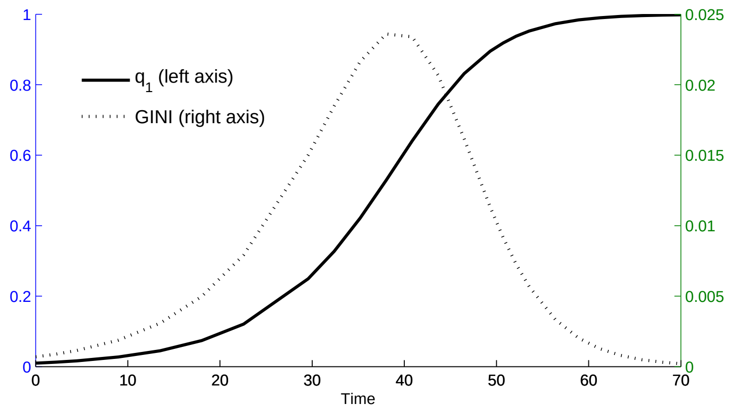

Figure 6: The diffusion of an innovative process and the resulting wage inequality.

adoption rate increasing around 1985 and again after 1995. After the dot.com-crash in 2000 the speed of diffusion slowed down significantly. With regard to the evolution of wage differentials, the GINI as an indicator of wage dispersion peaked for the first time when the rate of adoption of ICT was about taking off in the 1990s.

That these empirically found diffusion patterns can be reconstructed by the model can be seen in figure 6 which, on the basis of (12), reveals a similar behavior of the share q_1 of the innovative process as suggested by figure 5. What gets apparent is the slow start of the diffusion of the innovative process due to the growth process based on the replicator dynamics, which is followed by a *take off* at $t \approx 25$. The respective course of the GINI index, also depicted in figure 6 for $u = 1.1$, can be explained as follows: At the beginning of the diffusion process almost all workers perform low skill labor with wage w, whereas near the end of the process almost all workers are high skilled with wage $wu > w$. Therefore the GINI index approaches zero at the beginning and towards the end of the process, whereas there is *transitional wage inequality* in between when high and low skill labor is concurrently employed.

Wage share: Another measure touching on inequality and distribution is the wage share $\omega = W/(W+P)$ comprising total wages $W = w\mathbf{x}^T L\mathbf{u} = \mathbf{x}^T \left[\mathbb{I} - (1+r)A\right] \mathbf{p}$

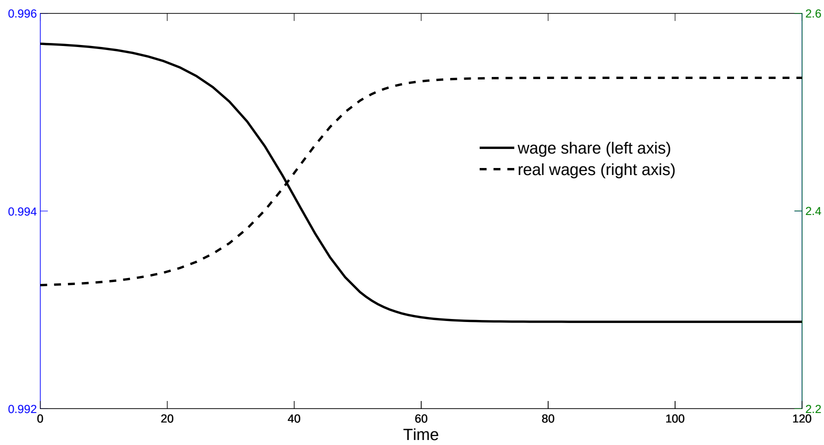

Figure 7: Changing real wages and wage share

and total profits $P = r\mathbf{x}^T A\mathbf{p}$. The changing wage share in the present example is depicted in figure 7. It is decreasing as a consequence of the capital using and labor saving nature of the technical progress. Increasing wages are a general property of this model, indicating the tendency of the system towards higher labor productivity (Rainer, 2013). This, as a result of rising labor productivity, including the decline of the wage share, indicates *technical unemployment* or increasing leisure time.

3.2 Consequences of technical progress in the GPT sector

The model economy of the preceding subsection can be extended to the case of two different processes, which enter the first sector as a consequence of the occurrence of the new GPT in sector 2. Process 3 is characterized by the input coefficients $(a_{11}^3, a_{12}^3) = (0.405, 0.085)$ and therefore uses less of the GPT as input (labor input is the same for processes 2 and 3 to keep matters simple). As depicted in figure 8 for $t < 70$, this leads to an extinction of the old process and an advantage for the third process, which uses less GPT as input in comparison with the second process. Without further incidents, for $t > 70$ the market share of process 3 would increase and finally take over the market due to its cost advantage compared to process 2.

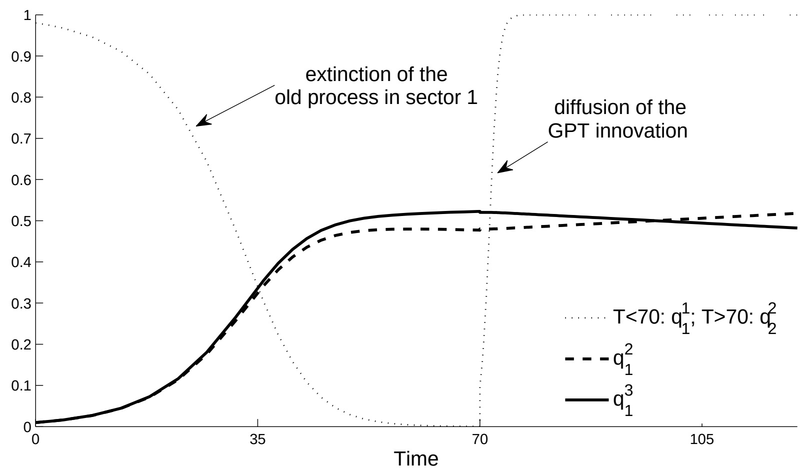

Figure 8: Two innovative processes

This scenario occasionally changes if technical progress in the GPT sector reduces its unit costs, possibly (not necessarily) leading to a switch of profitability in sector 1 as indicated in figure 8 for $t > 70$: In sector 1 only the new processes 2 and 3 are depicted, and the new process in sector 2 is characterized by pure labor saving technical progress with $l_{22}^2 = 0.05$. The emergence of technical change in the GPT sector therefore changes the long-run behavior of sector 1, where now process 2 is on the way to dominate process 3.

What also can be observed is increasing labor productivity, indicated by rising real wages which always prevail if at least one commodity which positively enters the numéraire basket **d** is directly or indirectly related to some sector in which technical progress takes place (Rainer, 2013). This is all the more the case for a GPT-sector, since a general purpose technology is inter alia characterized by its scope of improvement during its lifetime. After its arrival, the crude technology may take decades to mature and show its full potential. The relation between technical progress in a GPT-producing sector and rising labor productivity in the application sectors is empirically studied by means of a structural decomposition analysis (SDA). Labor productivity growth is thereby measured as the relative change in the maximum wage rate as defined in equation (5). In this case the SDA resembles growth accounting because the change in one growth variable – labor productivity – is broken down to its underlying sources.[8]

Technical change in the ICT-producing sector as measured from an input-output perspective is a developable indicator for improvements of the technology itself; especially since it does not consider capital goods which embody the bulk of technological progress in ICT. However, input-output data are capable of showing process innovations on a meso-economic level. In this regard, figure 9 shows the contribution of technical change *within* the ICT-sector to labor productivity growth of all other industries from 1966 onwards. To underpin this analyis, the gray shades of the surface represent the degree of (local) innovation activity as given by the share of ICT patents in total patent applications.[9] As concerns the time-path, technical change in the ICT-producing industries manifests itself in labor productivity growth not earlier than from the mid 1990s onwards.

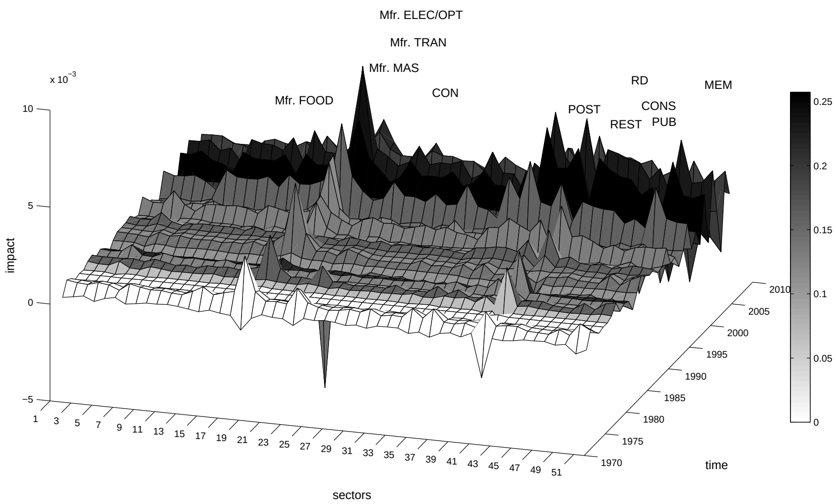

Figure 9: The contribution of technical change in the ICT manufacturing sector to sectoral labor productivity growth.
Mfr.=Manufacturing of; FOOD=Food, beverages and tobacco; MAS=Machinery and equipment n.e.c.; OPT=Optical and medical equipment; TRAN=Transport equipment; CON=Construction; POST=Post and telecommunications; REST=Real estate activities; RD=Research and development; CONS=Consultancy etc.; PUB=Public administration; MEM=Activities of membership organizations n.e.c.

[8] A detailed description of the SDA can be found in Strohmaier and Rainer (2013).

[9] ...filed by Danish applicants under PCT between 1977 and 2007. Data source: OECD.Stat.

Most of the important innovations in ICT, which aim at facilitating its widespread use, were developed between 1975 and 1990. Dating the arrival of this GPT to the beginning of the 70ies it thus took more than two decades for ICT to become a major source of productivity growth. It is interesting to note that *local* innovation activity was highest between 1998 and 2003, at a late stage of the diffusion process. This indicates the long time span necessary for a GPT to reach maturity and for the economic system to adapt to the new technology, something which is resembled by the model results. Breaking down its effects on the sectoral level, ICT had its strongest impact on labor productivity growth in the following manufacturing industries: Machinery and equipment, Electrical, optical and medical instruments and Transport equipment. It also significantly affected the construction sector. As regards the service sector, a high impact on Post and telecommunications, Real estate activities, Other business activities, Research & development, Public administration and Services of membership organizations can be observed.

4 Conclusion

From growth patterns of technologies related to their cost structure the following observations – related to the diffusion of GPTs and to the spread of productivity gains due to technical progress within the GPT sector – are reconstructed: (1) The emergence of a new GPT sector (by a product innovation) or technical progress in a GPT sector (by process innovations) induce technical progress as well as productivity changes in related sectors. Spill-over effects of new GPTs or of changing productivity within the GPT sector are studied. This includes negative output growth after the emergence of a new GPT, which precedes subsequent economic growth. (2) Transitional wage inequality is demonstrated by assuming a higher skill level used for technologies which are related to the GPT sector. Technical unemployment and higher per-capita income can be shown to emerge by demonstrating a decline of the wage share despite higher wages and wage premia. (3) The S-shaped diffusion pattern, which prevails for successful innovations, is endogenized, and feedback effects between output growth and the economic environment (prices and wages) are considered.

The economic dynamics which is triggered off by the arrival of a GPT, studied on a theoretical level, is augmented by empirical evidence from data of the ICT sector in Denmark from 1966 to 2007. The main purpose of the empirical part was to show that ICT was not only a sectoral revolution; it transformed processes throughout the whole economy. Since it took several decades for this technology to pervade the production system, its impact could only be observed recently. As regards the consequences of ICT for the labor market, the diffusion of this technology can be associated with transitional wage dispersion in the ICT-using industries.

The analysis of the role of ICT for labor productivity change in the rest of the economy also reveals industry clusters: The ICT sector had its strongest impact on technology-intensive manufacturing industries, such as Machinery and equipment or Transport equipment as well as on neighboring service sectors such as Post and telecommunications, Real estate and Other business activities. This supports the hypothesis that new technologies are first applied in similar industries, before they spread over more divergent sectors.

A Industry classification

Table 1: Aggregation of Danish industries. Note: The numbers in the second column indicate the assignment of the respective sector to the Danish 130-industry-classification, the third column to ICT-producing, ICT-using and Non-ICT industries.

Code	Industry	Aggregation	ICT-classification
1	Agriculture	1	Non-ICT
2	Horticulture, orchards etc.	2	Non-ICT
3	Agricultural services; landscape gardeners etc.	3	Non-ICT
4	Forestry	4	Non-ICT
5	Fishing	5	Non-ICT
6	Extr. of crude petroleum, natural gas etc.	6	Non-ICT
7	Extr. of gravel, clay, stone and salt etc.	7	Non-ICT
8	Mfr. of food, beverages and tobacco	8-18	Non-ICT

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Table 1 – continued from previous page

Code	Industry	Aggregation	ICT-classification
9	Mfr. of textiles, wearing apparel, leather	19-21	Non-ICT
10	Mfr. of wood and wood products	22	Non-ICT
11	Mfr. of paper prod.; printing and publish.	23-26	Non-ICT
12	Mfr. of refined petroleum products etc.	27	Non-ICT
13	Mfr. of chemicals and man-made fibres etc.	28-35	Non-ICT
14	Mfr. of rubber and plastic products	36-38	Non-ICT
15	Mfr. of other non-metallic mineral products	39-41	Non-ICT
16	Mfr. and processing of basic metals	42-47	Non-ICT
17	Mfr. of machinery and equipment n.e.c.	48-52	ICT-using
18	Mfr. of ICT equipment	53,55	ICT-producing
19	Mfr. of electrical mach n.e.c, & optical and medical equipment	56	ICT-using
20	Mfr. of transport equipment	57-59	ICT-using
21	Mfr. of furniture; manufacturing n.e.c.	60-62	Non-ICT
22	Electricity supply	63	Non-ICT
23	Gas and water supply	64-66	Non-ICT
24	Construction	67-70	Non-ICT
25	Sale and repair of motor vehicles etc.	71-73	ICT-using
26	Ws. and commis. trade, exc. of m. vehicles	74	ICT-using
27	Retail trade of food etc.	75	ICT-using
28	Department stores	76	ICT-using
29	Re. sale of phar. goods, cosmetic art. etc.	77	ICT-using
30	Re. sale of clothing, footwear etc.	78	ICT-using
31	Other retail sale, repair work	79	ICT-using
32	Hotels and restaurants	80-81	Non-ICT
33	Land transport; transport via pipelines	82-85	Non-ICT
34	Water transport	86	Non-ICT
35	Air transport	87	Non-ICT
36	Support. trans. activities; travel agencies	88-89	Non-ICT
37	Post and telecommunications	90	ICT-using
38	Financial intermediation	91-92	ICT-using
39	Insurance and pension funding	93-94	ICT-using
40	Activities auxiliary to finan. intermediat.	95	ICT-using
41	Real estate activities	96-98	ICT-using
42	Renting of machinery and equipment etc.	99	ICT-using
43	Computer and related activities	100-101	ICT-producing
44	Research and development	102-103	ICT-using
45	Other business activities	104-109	ICT-using
46	Public administration etc.	110-113	Non-ICT
47	Education	114-118	Non-ICT
48	Health care services	119-120	Non-ICT
49	Social institutions	121-122	Non-ICT
50	Sewage and refuse disp. and similar act.	123-125	Non-ICT
51	Activities of membership organiza. n.e.c.	126	ICT-using
52	Recreational, cultural, sporting activities	127-128	Non-ICT

Continued on next page

Table 1 – continued from previous page

Code	Industry	Aggregation	ICT-classification
53	Other service activities	129-130	ICT-using

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