

Quaas, Georg

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"The algebra of economic innovations.: A neo-Ricardian study"

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Working Paper, No. 185

Georg Quaas

**"The Algebra of Economic Innovations.
A neo-Ricardian study"**

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The Algebra of Economic Innovations. A neo-Ricardian study

Georg Quaas

University of Leipzig

Grimmaische Str. 12

04109 Leipzig

Germany

quaas@uni-leipzig.de

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Abstract:

The thesis that the number of mathematically possible switch points is reduced by the number of affected industries and by ambiguous price relations in the vicinity of the intersection points of wage curves must be supplemented by the condition of complete observability of the innovative technology. The rigorous proof that the number of switching points is reduced by conditions that can be regarded more realistic than the widely held theoretical view that two systems with alternative techniques differ, in general, at switch points in only one method of production could be an important step towards the empirical testing and practical application of the neo-Ricardian theory.

Keywords: capital theory, switch points, choice of technologies, embedded equations, complete observability

JEL Codes: B24, C67, O14

Introduction

The big topic of the neo-Ricardian school was and still is ‘reswitching’ – the return to a technology that had previously been used, structurally caused by a change in the distribution of the surplus product between capital and labour. (Kurz; Salvadori 2024) Re-switching requires switching to a different technology to have taken place beforehand whilst retaining the same kind of product; the theoretically estimated number of such switches differs significantly from the number of empirically observable technology switches. Since 1977 there are the following theses that have guided the discussion and analysis of technological changes:

“... if at profit rate π_1 the two alternative systems α and β ... are to yield exactly the same solution for all prices, they can, in general, differ in only one equation (except for the peculiar cases of equation systems with the rare coincidence of having identical solutions). ... The implication is that the two alternative matrices

$$\begin{bmatrix} \mathbf{A}^{(\alpha)} \\ \mathbf{a}_n^{(\alpha)} \end{bmatrix} \quad \begin{bmatrix} \mathbf{A}^{(\beta)} \\ \mathbf{a}_n^{(\beta)} \end{bmatrix}$$

differ, in general, *in only one* column (leaving aside the peculiar case just mentioned.)” (Pasinetti 1977: 163)

While at first ignoring the “peculiar case” of an exception, Pasinetti went on:

“The conclusion to be drawn is that, on the technological frontier, although the various techniques may differ in more than one method of production (and the corresponding matrices in more than one column), those techniques which are adjacent at a switch point will differ, in general, in only one method of production (and the corresponding matrices will differ in only one column). In other words, as one gradually moves along the technological frontier, the methods of production will change, in general, one at a time only one method of production will change at each switch point.” (163-164)

If this were true, the “peculiar case” of two technological matrices that differ in more than one column could be replaced by a series of two matrices that differ in one column only. This is the method for handling complex technological changes proposed by Pasinetti.

So, let us consider the case where a certain innovation affects more than one branch. In this case, the technological matrices of the two systems differed across several columns. Nevertheless, each system generates only one wage curve, so that the comparison of the technological alternatives boils down to examining exact two wage curves in terms of their points of intersection. Pasinetti, however, presents this case in a completely different light:

“There remains, of course, the exceptional case of coincidental solutions. This corresponds to the very special case in which more than two curves happen to intersect at exactly the same point (as shown in Fig VI 4) Even in this very special case, however, the various curves which intersect at exactly the same point (yielding, at this point, exactly the same price) can, in general, be so ordered as to make only one method of production change between adjacent curves. Hence

the necessary comparison can always be made between matrices which differ in only one column.” (164)

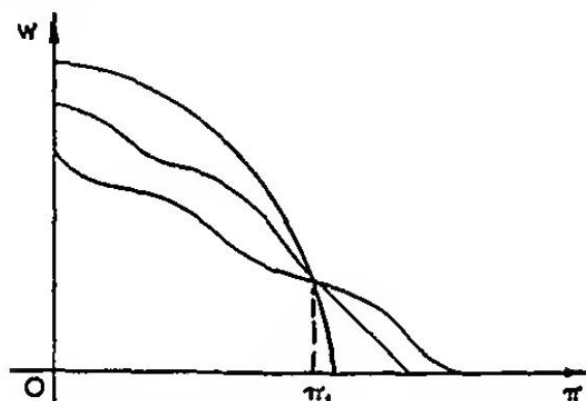


FIG VI 4 Exceptional case of 3 technical methods which are equi profitable at the same rate of profit π_1

What Pasinetti presents here (p. 164) is a comparison of *three* systems which produce the same point of intersection of the wage curves. However, this is yet another special case which has nothing to do with a comparison of *two* systems representing simultaneous changes in technology across several sectors, but not in all. Pasinetti did not deliver a strong argument for his thesis. Nevertheless, it is widely accepted. As recently as 2024, a critic of that school claimed: “As can be shown, techniques that alternate at switching points differ only in the production of a (basic) commodity...” (Helmedag 2024: 265; own English translation)

Some preliminary strictures

(i) Pasinetti’s thesis raises the question of how complex technological changes that rarely affect just a single sector alone are to be analysed. If it were true that ‘switch points’ occur one after the other on the technological front, one could depict complex technological changes as a dynamic process in which the rate of profit changes gradually. However, there is an explicit warning against such a notion that contradicts with the long-run perspective of Sraffa’s theory. Neo-Ricardian models generally depict states of equilibrium which are assumed to be reached in the long run under constant conditions. Each state of equilibrium is associated with a specific rate of profit and a specific wage rate. If we mentally shift to a different rate of profit and a different wage rate, this may well represent an entirely different economy, one that is technologically identical but whose state has emerged at some point and in some place entirely of its own accord and independently of the state previously considered. Discussions of wage curves are thus part of comparative statics: the comparison involves different equilibrium states of the economic system under analysis, each of which is established in the long run:

“There is no implication here of a process of change from one equilibrium to another. Different equilibria are to be regarded as if they were different planets with no connection between them.” (Harris 1973: 101)

(ii) There is no strong mathematical proof that analyzing complex technological changes in a stepwise manner leads to a correct result. As a matter of fact, there can be no proof because the

analysis of two matrices that differ in more than one column is excluded by Pasinetti's method. But it is precisely this analysis that is a prerequisite for a comparison with the proposed method.

(iii) It was shown in a previous study (Quaas 2024), that a step-by-step analysis of complex technological changes does not lead to a clear-cut result. It has also been shown that the alignment of price vectors is a necessary but not sufficient condition for switching points, that a distinction must be made between true and spurious switching points, and that the number of possible switching points may decrease as the number of affected industries increases. Building on this study, the question of the maximum number of switch points is revisited here. This replaces the case-analysis made in that study and the proof provided in the appendix, which was, unfortunately, inconclusive.

Theoretical Prerequisites

Within the framework of Piero Sraffa's model involving $n \geq 2$ single-product industries, it is possible to compare economic systems with different technologies even when, in the long run, they involve multiple sectors. The crux of such a comparison is the effect of technological innovations on the price system, which is captured by price vectors:

$$\mathbf{p}^A = w\mathbf{l}^A [\mathbf{I} - (1+r)\mathbf{A}]^{-1} \quad (1)$$

Prices of system C, called the *new* or *innovative system*, are given by:

$$\mathbf{p}^C = w\mathbf{l}^C [\mathbf{I} - (1+r)\mathbf{C}]^{-1} \quad (2)$$

The individual terms of system A are:

$$\mathbf{p}^A = [p_1^A \quad p_2^A \quad \dots \quad p_n^A] \text{ (vector of prices, a row vector)}$$

$$\mathbf{A} = \|a_{ij}\|_1^n \text{ (technological matrix, squared, non-negative)}$$

$$\mathbf{l}^A = [l_1^A \quad l_2^A \quad \dots \quad l_n^A] \text{ (employees per output, a row vector, strictly positive)}$$

Analog definitions apply to System C. It is additionally assumed that the matrix $\mathbf{C}$ is irreducible. The same may be true for matrix A, but this plays no role in the following argumentation.

The parameter w refers to the wage-rate, which is the same for all employees, parameter r is the rate of profit on capital.

The physical structure of the regarded economic systems is assumed to fulfil the condition of survivability, i.e., they produce a surplus, no matter how small it may be. Explained in terms of the System C, this means:

$$\mathbf{q}^C - \mathbf{z}^C = (\mathbf{I} - \mathbf{C})\mathbf{q}^C = \mathbf{s}^C \geq \mathbf{0}; \quad \mathbf{s}^C \neq \mathbf{0} \quad (3)$$

The explanations of individual terms are:

$$\mathbf{q}^C = (q_1^C \quad q_2^C \quad \dots \quad q_n^C) \text{ (positive vector of outputs, a column vector)}$$

$$\mathbf{z}^C = (z_1^C \quad z_2^C \quad \dots \quad z_n^C) \text{ (circulating capital, a column vector)}$$

$$\mathbf{s}^C = (s_1^C \quad s_2^C \quad \dots \quad s_n^C) \text{ (surplus, a column vector)}$$

Whenever possible, the convention is followed to denote a column vector by round brackets and a row vector by square brackets. Unlike scalars, vectors and matrices are written in bold.

Among other things, the following theorems will be needed:

Since $\mathbf{C}$ is nonnegative and irreducible, and $\mathbf{q}^C > \mathbf{0}$ satisfies $\mathbf{C}\mathbf{q}^C \leq \mathbf{q}^C$ with strict inequality in at least one component, the Perron–Frobenius theorem (Gantmacher II: Chapter XIII) implies that the highest characteristic value of the corresponding characteristic equation is less than one:

$$\mathbf{C}\mathbf{q}_{eig}^C = \lambda_{\max} \mathbf{q}_{eig}^C < \mathbf{q}_{eig}^C \Rightarrow \lambda_{\max} < 1 \quad (4)$$

Here, $\mathbf{q}_{eig}^C$ is the eigenvector of matrix $\mathbf{C}$ corresponding to the maximum characteristic root, which is not needed further in this context.

Applying the matrix $\mathbf{C}$ on the vector $\mathbf{I}^C$ of direct applied labour we get the vector of indirect labour $\mathbf{I}_1^C = \mathbf{I}^C \mathbf{C}$ that is needed to produce the circulating capital. Repeating this operation, leads to the vector of labour needed to produce the circulating capital for producing the circulating capital – and so on. We define the labour vector at the i -th stage of production

$$\mathbf{I}_i^C = \mathbf{I}^C \mathbf{C}^i \quad (5)$$

and consider the first $n+1$ vectors:

$$\mathbf{I}_0^C, \mathbf{I}_1^C, \dots, \mathbf{I}_n^C \quad (6)$$

According to the theory of matrix algebra, there cannot be more than n linear independent vectors among the set (6). In every given case, there are exactly p linear independent vectors with $1 \leq p \leq n$ in such a way that $\mathbf{I}_p^C$ can be depicted as a linear combination of the preceding vectors: There are exactly p linear independent vectors ($1 \leq p \leq n$) by which the $(p+1)$ -th vector can be depicted as a linear combination of the preceding vectors:

$$\mathbf{I}_p^C = \alpha_p \mathbf{I}_0^C + \alpha_{p-1} \mathbf{I}_1^C + \dots + \alpha_1 \mathbf{I}_{p-1}^C \quad (7)$$

To formulate one of the key assumptions here, the following observation matrix $\mathbf{\Omega}$ is defined with reference to (5) and (7):

$$\mathbf{\Omega}(\mathbf{I}^C, \mathbf{C}) = \begin{bmatrix} \mathbf{I}^C \\ \mathbf{I}^C \mathbf{C} \\ \vdots \\ \mathbf{I}^C \mathbf{C}^{n-1} \end{bmatrix} \quad (8)$$

System C is called *completely observable* if $\text{rank}(\mathbf{\Omega}) = n$.

Since prices depend on both the vector $\mathbf{I}^C$ and the matrix $\mathbf{C}$, there is an analogy to Kurz and Salvadori (1997: 165–168), who showed that the technological matrix $\mathbf{C}$ can be reconstructed using the price vectors, provided there are n linearly independent price vectors for n profit rates. This is the case of complete observability, which we assume as given in what follows.

Since 1977 it is well known that

$$\mathbf{p}^A(r) = \mathbf{p}^C(r) \quad (9)$$

is a necessary but not sufficient condition for a so-called switch point. (Pasinetti 1977: 159) A switch point is an intersection of the wage-profit functions of system A and C which could lead to a turnover to the other technology under certain additional conditions. Because these conditions are not subject of this study we call the profit-rate r an intersection point of the wage-profit functions and not a switch point when (9) happens.

As shown in Quaas (2024), condition (9) is equivalent to the validity of the following equation:

$$-(1+r)\mathbf{I}^C [\mathbf{I} - (1+r)\mathbf{C}]^{-1} \mathbf{D} = \mathbf{I}^D \quad (10)$$

$$\text{with } \mathbf{D} = \mathbf{C} - \mathbf{A} \text{ and } \mathbf{I}^D = \mathbf{I}^C - \mathbf{I}^A \quad (11)$$

$\mathbf{D}$ is the matrix of technological innovations, and $\mathbf{I}^D$ the difference of spared or additional needed workers in system C compared to system A. Some elements of these terms can be positive, others negative, and some, but not all, are zero. A single column of $\mathbf{D}$ can be noted as a column vector:

$$\mathbf{d}_j = (d_{1j} \quad d_{2j} \quad \dots \quad d_{nj})$$

The following assumptions concerning the technological innovations and their mathematical representation are made:

The number k of non-vanishing columns vectors $\mathbf{d}_j \neq \mathbf{0}$ of matrix $\mathbf{D}$ equals to the number of industries that are affected at the same time by a complex technological change which could, at least in the long run, transform system A to system C: The number of industries can be any number between 1 and n : $k = 1, 2, \dots, n$. Without loss of generality, we assume that only the first k columns of matrix $\mathbf{D}$ are different from zero-vectors, and only the first k elements of the vector $\mathbf{I}^D$ are different from zero:

$$\mathbf{D} = \begin{bmatrix} \mathbf{d}_1 & \mathbf{d}_2 & \dots & \mathbf{d}_k & 0 & \dots & 0 \end{bmatrix}; \quad \mathbf{I}^D = \begin{bmatrix} l_1^D & l_2^D & \dots & l_k^D & 0 & \dots & 0 \end{bmatrix}$$

An important but realistic assumption is that the first k column vectors $\mathbf{d}_j$ are linearly independent: The innovations are unique in every industry.

Some properties of the inverse matrix

The inverse matrix in equation (2) can be split into a determinant and the corresponding adjoint matrix:

$$[\mathbf{I} - (1+r)\mathbf{C}]^{-1} = \lambda \frac{\mathbf{B}(\lambda)}{\Delta(\lambda)} \quad (12)$$

with $\lambda = \frac{1}{1+r}$. Equation (12) is valid for $1 \geq \lambda > \lambda_{\max}$ respective for $0 \leq r < r_{\max}$. In the following, these restrictions are called “the allowed range” of λ respective of r . $\lambda_{\max}$ is the Perron-Frobenius eigenvalue of matrix $\mathbf{C}$. Element b_{ik} of matrix $\mathbf{B}(\lambda)$ is the algebraic complement (the cofactor) of element Δ_{ki} in the determinant $\Delta(\lambda) = |\lambda\mathbf{I} - \mathbf{C}|$. Both, the determinant and its adjoint matrix $\mathbf{B}(\lambda)$ are strictly positive for parameters in the allowed range, because matrix $\mathbf{C}$ is irreducible. In this range it is also:

$$\Delta[B(\lambda)] = [\Delta(\lambda)]^{n-1} > 0 \quad (13)$$

Therefor the n column vectors of the adjoint matrix $\mathbf{B}(\lambda)$ are linearly independent.

Because the elements of $\mathbf{B}(\lambda)$ are $(n-1) \times (n-1)$ minors of $\Delta(\lambda)$, they are polynomials of degree $(n-1)$ at most. The highest degree can be found in $b_{ii}(\lambda)$ for $i = 1, \dots, n$. As λ increases, the diagonal elements grow by the highest power of $n-1$ coupled to the positive coefficient 1.

Introducing equation (12) into equation (10) delivers:

$$\mathbf{I}^C \mathbf{B}(\lambda) \mathbf{D} + \Delta(\lambda) \mathbf{I}^D = 0 \quad (14)$$

Equation (14) was called the “embedded system of equations” (Quaas 2024) – embedded in the primary equations (1) and (2) and equivalent to equation (9).

Analysis of single terms

The elements of the row vector $\mathbf{I}^C \mathbf{B}(\lambda)$ are linear combinations of polynomials with the highest degree of $n-1$:

$$\mathbf{I}^C \mathbf{B}(\lambda) = \left\| \sum_{i=1}^n l_i^C b_{i1}(\lambda) \quad \sum_{i=1}^n l_i^C b_{i2}(\lambda) \quad \dots \quad \sum_{i=1}^n l_i^C b_{in}(\lambda) \right\| \quad (15)$$

All elements of this vector are positive because $l_i > 0$ and $b_{ik} > 0$. The coefficient of λ^{n-1} is just $\mathbf{I}^C$. Multiplication from the right with the matrix of innovations $\mathbf{D}$ produces a row vector with elements that are kind of weighted sums of the elements of vector (15):

$$\mathbf{I}^C \mathbf{B}(\lambda) \mathbf{D} = \left\| \sum_{i,j=1}^n l_i^C b_{ij}(\lambda) d_{j1} \quad \sum_{i,j=1}^n l_i^C b_{ij}(\lambda) d_{j2} \quad \dots \quad \sum_{i,j=1}^n l_i^C b_{ij}(\lambda) d_{jk} \quad 0 \quad \dots \quad 0 \right\| \quad (16)$$

The determinant $\Delta(\lambda)$ is a polynomial of degree n . The highest power has a coefficient of 1. Within the allowed range of λ the determinant is positive and can be written as follows:

$$\Delta(\lambda) = \lambda^n - s_1 \lambda^{n-1} - \dots - s_n$$

The coefficient s_i is the sum of diagonal elements of the matrix $\mathbf{C}^i$ (Gantmacher I: 87). Adding $\Delta(\lambda) \mathbf{I}^D$ to vector (16) produces a row vector $\mathbf{g}$ of which the elements are polynomials with the highest degree of n :

$$\mathbf{g} = \left\| \gamma_1(\lambda) \quad \gamma_2(\lambda) \quad \dots \quad \gamma_k(\lambda) \quad 0 \quad \dots \quad 0 \right\|$$

The h -th individual element of this vector is:

$$\gamma_h(\lambda) = \sum_{i,j=1}^n l_i^C b_{ij}(\lambda) d_{jh} + l_h^D \Delta(\lambda) \text{ with } h = 1, \dots, k.$$

Separating the algebraic components

Polynomials can be ordered by powers of λ . We define a row-vector

$$\mathbf{\Lambda} = \begin{bmatrix} \lambda^n & \lambda^{n-1} & \lambda^{n-2} & \dots & \lambda & 1 \end{bmatrix}$$

and start with the reconstruction of the term $\mathbf{I}^C \mathbf{B}(\lambda)$. A $(n+1, n)$ -matrix $\mathbf{M}$

$$\mathbf{M} = \begin{pmatrix} 0 & 0 & \cdots & 0 \\ l_1^C & l_2^C & \cdots & l_n^C \\ m_{21} & m_{22} & \cdots & m_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nn} \end{pmatrix}$$

with coefficients m_{ij} ($i = 2, 3, \dots, n$; $j = 1, 2, \dots, n$) can be constructed in such a way that the following relationship holds:

$$\mathbf{l}^C \mathbf{B}(\lambda) = \Lambda \mathbf{M} \quad (17)$$

Multiplying by matrix $\mathbf{D}$ from the right produces k different sums of the elements depicted in (15), i.e., a row vector with k more or less different polynomials whose highest degree is $n-1$:

$$\mathbf{l}^C \mathbf{B}(\lambda) \mathbf{D} = \Lambda \mathbf{M} \mathbf{D} \quad (18)$$

Only the first k elements of the row vector $\mathbf{l}^D \Delta(\lambda)$ are different from zero. These elements are polynomials with the highest degree of n . We define a column vector

$$\mathbf{s} = (1 \quad -s_1 \quad -s_2 \quad \cdots \quad -s_n)$$

and get for the second term in (14):

$$\mathbf{l}^D \Delta(\lambda) = \Lambda \mathbf{s} \mathbf{l}^D \quad (19)$$

Substituting the equations (18) and (19) into equation (14) gives:

$$\Lambda (\mathbf{M} \mathbf{D} + \mathbf{s} \mathbf{l}^D) = 0 \quad (20)$$

The mere algebraic part can be defined as a $(n+1, n)$ -Matrix $\mathbf{G}$:

$$\mathbf{G} = \mathbf{M} \mathbf{D} + \mathbf{s} \mathbf{l}^D$$

With this transformation one gets a very short version of the embedded equation:

$$\Lambda \mathbf{G} = \mathbf{g} = \mathbf{0} \quad (21)$$

We are interested in how many roots λ_i this equation has under which conditions. For this purpose, we analyse the rank of matrix $\mathbf{G}$. There are only k non-vanishing columns in $\mathbf{G}$ therefore we know already that $\text{rank}(\mathbf{G}) \leq k$.

Hypothetical roots

The coefficients of row vector $\mathbf{g}$ are polynomials with the highest degree of n . In the literature, it was often remarked that there could be n different roots solving the polynomials in (21). To be precise, this argument must be applied to the specific case in which only a single industrial sector is affected. However, when $k > 1$ the roots that fulfill (21) need to be common to all k polynomials. Let us assume that there are exactly m ($0 \leq m \leq n$) different roots that are common for all non-vanishing elements of $\mathbf{g}$. With these roots we can construe m different row vectors

$$\Lambda(\lambda_i) = [\lambda_i^n \quad \lambda_i^{n-1} \quad \lambda_i^{n-2} \quad \dots \quad \lambda_i \quad 1] \quad j = 1, 2, \dots, m \quad (22)$$

that are linearly independent from each other (because the roots are different) and fulfill all the following equation:

$$\Lambda(\lambda_i) \mathbf{G} = \mathbf{0} \quad (23)$$

It means that matrix $\mathbf{G}$ has at least a defect of m . We say “at least” because there can be more than one vector which belongs to any root λ_i and which are linearly independent from the ones we have counted. Because the rank of a matrix $\mathbf{G}$ is the difference between the dimension of the room in which $\mathbf{G}$ operates and its defect $d(\mathbf{G})$, it follows:

$$\text{rank}(\mathbf{G}) = n + 1 - d(\mathbf{G}) \leq n + 1 - m \quad (24)$$

From this inequality, we can determine the maximal number of roots of the embedded equation if the rank of matrix $\mathbf{G}$ is known.

The rank of the embedded equation

We assume provisional that the k columns of matrix $\mathbf{G}$ are linearly dependent. In this case a column-vector exists:

$$\mathbf{x} = (x_1 \quad x_2 \quad \dots \quad x_k \quad 0 \quad \dots \quad 0) \neq \mathbf{0}$$

that fulfils the following equation:

$$\mathbf{G}\mathbf{x} = (\mathbf{MD} + \mathbf{s}\mathbf{l}^D)\mathbf{x} = \mathbf{0} \quad (25)$$

On the other hand, we have proposed that the first k columns of matrix $\mathbf{D}$ are linearly independent. Therefor it follows necessarily that

$$\mathbf{D}\mathbf{x} = \mathbf{y} \neq \mathbf{0} \quad (26)$$

With this vector, equation (25) can be rewritten:

$$\mathbf{M}\mathbf{y} + \mathbf{s}\mathbf{h} = \mathbf{0} \text{ with } \mathbf{h} = \mathbf{I}^D \mathbf{x} \quad (27)$$

After multiplying from the left by $\Delta(\lambda)$ we get:

$$\mathbf{I}^C \mathbf{B}(\lambda) \mathbf{y} + \Delta(\lambda) \mathbf{h} = \mathbf{0} \quad (28)$$

This is a polynomial identity which consists of two parts:

$$\mathbf{I}^C \mathbf{B}(\lambda) \mathbf{y} = \lambda^{n-1} \mathbf{I}^C \mathbf{y} + \lambda^{n-2} \mathbf{I}^C \mathbf{B}_{n-2} \mathbf{y} + \dots + \mathbf{I}^C \mathbf{B}_0 \mathbf{y} \quad (29a)$$

$$\Delta(\lambda) \mathbf{h} = \lambda^n \mathbf{h} - s_1 \lambda^{n-1} \mathbf{h} - \dots - s_n \mathbf{h} \quad (29b)$$

If we compare the two polynomials while taking their powers into account, we find that for λ^n it must be the case that

$$\mathbf{h} = \mathbf{0} \quad (30)$$

With (30) the equation (28) reduces to:

$$\mathbf{I}^C \mathbf{B}(\lambda) \mathbf{y} = \mathbf{0} \quad (31)$$

Because $\Delta(\lambda) > 0$ in the allowed range, we can divide (31) by the determinant and get:

$$\mathbf{I}^C (\lambda \mathbf{I} - \mathbf{C})^{-1} \mathbf{y} = \mathbf{0} \quad (32)$$

We expand the inverse matrix into an infinite series:

$$\mathbf{I}^C (\lambda \mathbf{I} - \mathbf{C})^{-1} \mathbf{y} = \frac{1}{\lambda} \mathbf{I}^C \left(\mathbf{I} + \frac{\mathbf{C}}{\lambda} + \frac{\mathbf{C}^2}{\lambda^2} + \dots + \frac{\mathbf{C}^{p-1}}{\lambda^{p-1}} + \dots + \frac{\mathbf{C}^{n-1}}{\lambda^{n-1}} + \dots \right) \mathbf{y} = \mathbf{0} \quad (33)$$

The equation (33) is an identity in λ that is valid for all $\lambda > \lambda_{\max}$. Since the left-hand side is identically zero, all coefficients of this Laurent expansion must vanish. In particular:

$$\mathbf{I}^C \mathbf{y} = \mathbf{I}^C \mathbf{C} \mathbf{y} = \dots = \mathbf{I}^C \mathbf{C}^{n-1} \mathbf{y} = \mathbf{0} \quad (34)$$

By the help of the observability¹ matrix equation (34) can be written as:

$$\Omega(\mathbf{I}^c, \mathbf{C})\mathbf{y} = 0 \quad (35)$$

In the special case that the $\text{rank}(\Omega) = n$, it follows that

$$\mathbf{y} = 0 \quad (36)$$

Because the relevant columns in matrix $\mathbf{D}$ are linearly independent, it also follows that under complete observability it must be:

$$\mathbf{x} = 0 \quad (37)$$

That means: The first k columns of $\mathbf{G}$ can never be linearly dependent if $p = n$ (p is the number of linear independent labour-vectors). Under this condition we can determine the rank of matrix $\mathbf{G}$ in an exact manner:

$$\text{rank}(\mathbf{G}) = k \quad (38)$$

Taking equation (24) into account, the consequence is that the maximum number of solutions of the embedded equation is restricted in the case of complete observability:

$$m \leq n + 1 - k \quad (39)$$

Therefore, the following conclusion needs to be drawn: It is not the number of affected industries per se, but rather the number of algebraically independent technological changes and the observability of the new technology that determines the extent to which the number m of different, but common rates of profit is limited at which the two wage-profit curves of the old and the new system intersect. It was already shown (Quaas 2024) that the number of mathematically possible switch-points is restricted by the number of intersection points and may often be less because of ambiguous price relations in the vicinity of intersection-points.

Note on the use of artificial intelligence tools

There were the following tools of artificial intelligence used: E-Views for the detailed and extensive calculations, MathType for the presentation of formulas, DeepL for controlling the British English, and ChatGPT for controlling the logical structure of the mathematical arguments. The responsibility for all aspects of the final version of the manuscript lies entirely with the author.

¹ The use of the observability matrix for solving Equation (33) was proposed by ChatGPT.

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