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Joint Technological Changes in Multiple Industries

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Joint Technological Changes in Multiple Industries

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Abstract: Most neo-Ricardian studies on the "choice of technique" are based on a comparison of alternative technologies applicable to the same industrial branch. Some authors even recommend restrict analyses of the long-run technological changes to a single industry. In reality, innovations often require technological changes in several industries. In this article, it is shown that a step-by-step analysis of complex technological innovations is path-dependent and does not always lead to a result. Furthermore: The number of mathematically possible switch-points is reduced by the number of affected industries and by ambiguous price relations in the vicinity of intersection-points of wage curves. This could, without simplification of Sraffa's theory, explain why situations in which two alternative technologies generate the same prices, i.e. switch-points, are empirically extremely rare events.

Keywords: capital theory, switch-points, choice of technologies, path-dependency, embedded equations

JEL Codes: B24, C67, O14

[1] I would like to thank Dr Karin Quaas for her critical comments.

1. **Introduction**

Consider an economy consisting of n industrial branches using n different sorts of goods indexed by i and endowed with prices p_i $(i = 1,\ldots,n)$. Every industrial branch numbered by $j = 1,\ldots,n$ produces exactly one distinct sort of goods by applying a fixed-proportions technology $a_{ij} \geq 0$. There is only circulating capital consisting of those sorts of goods, and there is only one primary factor of production, namely labour, which commands a nominal wage rate w. The amount of labour applied in industrial branch j is denoted l_j. The wage rate w and interest rate r are both supposed to be common to all industrial branches; the latter are also called "sectors", "industries" or simply "branches". In the basic neo-Ricardian model, the steady-state equilibrium prices are determined by the following system of equations:

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

with a technological matrix and a vector of labour inputs

$$\mathbf{A} = \left\|a_{ij}\right\|_1^n \text{ and } \mathbf{l}^A = \left[l_1^A \quad l_2^A \quad \ldots \quad l_n^A\right]$$

that define technology A. Together with the interest (i.e. profit) rate r and the wage rate w the equations (1) generate the vector of prices:

$$\mathbf{p}^A = \left[p_1^A \quad p_2^A \quad \ldots \quad p_n^A\right]$$

Thus, according to equation system (1), prices depend on both the profit rate and the wage rate. The matrix $\mathbf{I}$ is simply the identity-matrix.[2]

In the neo-Ricardian framework, a technological alternative is reflected by a comparison of technology A with another technology C. The latter is presented by another set of parameters compiled and symbolised by the matrix $\mathbf{C}$ and the vector $\mathbf{l}^C$. Matrices $\mathbf{A}$ and $\mathbf{C}$ are assumed to be non-decomposable, although that provision can be dismissed in some special cases. Moreover, it is supposed that no column of a technological matrix can be presented as a linear combination of the other columns – that is, that the technological structure of a branch is unique. It thus follows that the respective determinants of the technological matrices are not zero and their ranks are equal to n. The vectors with the labour inputs are supposed to be positive.

2. **The so-called choice of technology**

According to Pasinetti (1978: 158), if there are multiple options to implement a technology and if a certain rate of profit is given, the technology with the higher wage rate prevails (i.e. will be chosen). Since a comprehensive analysis requires inspecting the totality of economically

[2] Row vectors are notated in brackets and column vectors in parentheses.

meaningful profit rates, wage-curves and their geometric presentations come into play. Every technology produces a function of wage rates that depends on the profit rates. Because wage curves require fixing a price benchmark, called "numéraire", the comparison of the technologies should be based on a fixed numéraire common to all technologies being compared. When comparing the wage curves of different technologies, the one will be favoured that is located furthest out to the right corner of the diagram. This curve "envelops" the curves of alternative technologies and is called "technological frontier". (Pasinetti 1978: 158)

In some case it happens that two technologies are represented by wage-curves that are crossing each other. Such an interception-point is called "switch-point" when for profit rates slightly under or above the intersection-point the more favourable technology can be unambiguously identified. Mostly based on economic arguments, Pasinetti (1978: 162) concludes that prices of the same sort of goods produced by using different techniques and technologies are identical at switch-points. A switch-point itself is neutral relative to the choice of a technology.

Pasinetti's criteria for identifying the best technology in the vicinity of a switch-point are valid if the analysis of technological changes is restricted to one sector only with n–1 sectors remaining unchanged. (Pasinetti 1978: 158) If that condition is accepted, a complex technological change involving multiple sectors has theoretically to split into a sequence of single-sector changes. Even in a small economic system with only a few industries there may be different ways to reconstruct a complex change in technology. Therefore, among other problems, the analysis poses the question of path dependency. With this in mind, it will be at first shown that Pasinetti's criterion, when applied to complex technological changes, is insufficient for identifying switch-points. To show a sufficient condition, a thesis articulated by Kurz and Gehrke (1991: 102) and reiterated by Kurz (1995: 725) will be modified and applied – claiming that the choice of a numéraire cannot alter the mathematical properties of the underlying economic system.

3. **Spurious switch-points**

Let matrices $\left(\mathbf{A},\mathbf{l}^A\right)$ and $\left(\mathbf{C},\mathbf{l}^C\right)$ represent two economic systems applying technology A and C respectively. Both systems produce the same sorts of goods, although perhaps in different quantities. At least one branch of system C shall apply a different technology compared to the corresponding branch of system A. That means, at least one column of matrix $\mathbf{C}$ or of vector $\mathbf{l}^C$ differs from the corresponding column of matrix $\mathbf{A}$ or of vector $\mathbf{l}^A$. The maximum number of branches with different technologies is n. To be on the safe side, let us suppose that $\mathbf{A}$ and $\mathbf{C}$ are non-negative, indecomposable and of order n. Both vector $\mathbf{l}^A$ and $\mathbf{l}^C$ are positive but different. In that case, there are two completely different systems of prices: along with prices $\mathbf{p}^A$ of equation (1) there are the prices $\mathbf{p}^C$ that are, in general, different even if profit rate r and wage rate w are the same:

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

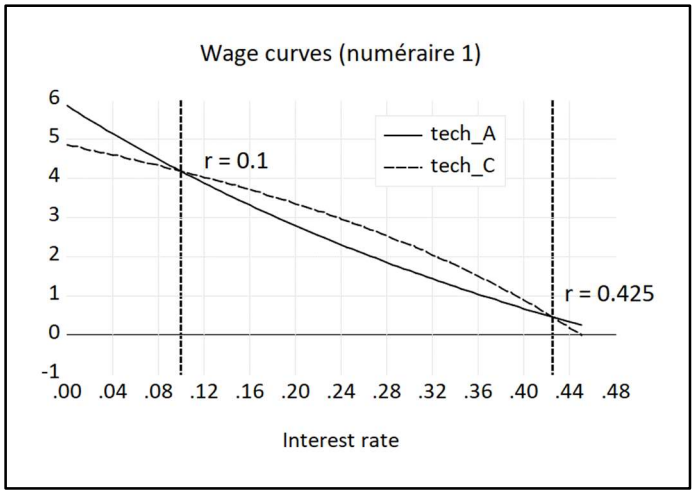
As an example, we compare the wage curves of the following matrix representation of technology A and a completely different technology C:[3]

$$\mathbf{A} = \begin{Vmatrix} 186/450 & 54/21 & 30/60 \\ 12/450 & 6/21 & 3/60 \\ 9/450 & 6/21 & 15/60 \end{Vmatrix} \qquad \mathbf{C} = \begin{Vmatrix} 64/450 & 24/21 & 20/60 \\ 6/450 & 11/21 & 3/60 \\ 9/450 & 8/21 & 30/60 \end{Vmatrix}$$

$$\mathbf{l}^A = \begin{bmatrix} 1/125 & 4/5 & 9/10 \end{bmatrix} \qquad \mathbf{l}^C = \begin{bmatrix} 55/450 & 5/21 & 30/60 \end{bmatrix}$$

As can be seen, the technologies of all sectors, reflected by the values in the columns, differ from each other. With good 1 as the numéraire of prices, two wage-curves with two points of intersection are obtained (Fig. 1).

Figure 1



Applying the described criterion of the choice of technology to the curves in the area of interest rates between 0 and 0.1, technology A is evaluated to be the better one because of the higher wage rate. For the same reason, technology C prevails when the interest rate exceeds 0.1. (Let us postpone the discussion what happens at the second intersection-point. A hasty conclusion would be that "capital reversing" will occur.) According to Pasinetti's criterion, the intersection-point at $r = 0.1$ could be called "switch-point" because the technology changes upon passing that point.

A true switch-point should not depend on the numéraire of prices, as Kurz (1991, 1995) has argued: "The numéraire does not alter the mathematical properties of an economic system". Figs. 2 and 3 show the wage-curves of the same economic system from the perspective of numéraire 2 and 3.

[3] The structure of matrix **A** is borrowed from Pasinetti (1978: 101).

Figure 2

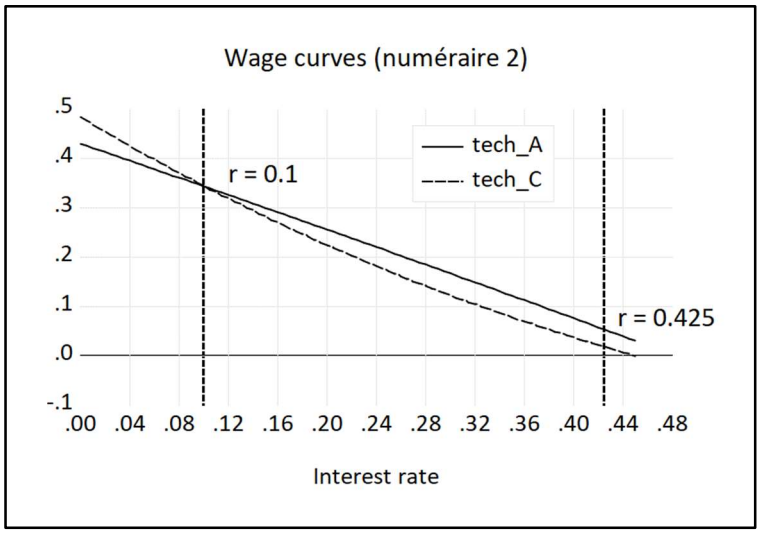
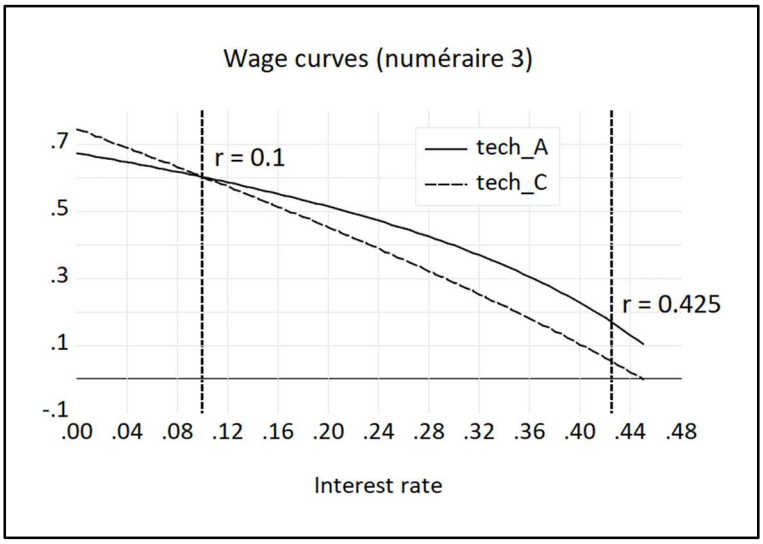


Figure 3



The intersection-point at $r = 0.425$ disappears when observed from the point of view of numéraire 2. The same occurs with numéraire 3 (see Fig. 3), but the intersection point at $r = 0.1$ proves to be stable. Nevertheless, even though the prices are identical at a profit rate of 0.1, it cannot be a switch-point, because, by definition, a "switch-point" should make it possible to take a clear decision which technology prevails left and right of it. This is not the case because the decision depends on the choice of numéraire: Numéraire 1 favours technology *A* for profit rates less than 0.1, but numéraires 2 and 3 put technology *C* in the first place. It follows that Pasinetti's criterion is not sufficient for identifying switch-points in the case of complex technological changes. Kurz's dictum on the neutrality of the choice of numéraire has proven to be an effective means to detect spurious switch-points.

4. **True switch-points**

According to Helmedag (2024: 265) and others, there cannot be a true switch-point if more than one branch is affected by a complex technological alternative: “As can be shown, a technology that replaces another technology at switch-points differs only in the production of a single (basic) commodity.”[4] However, let us look at the following example, contradicting Helmedag’s claim.

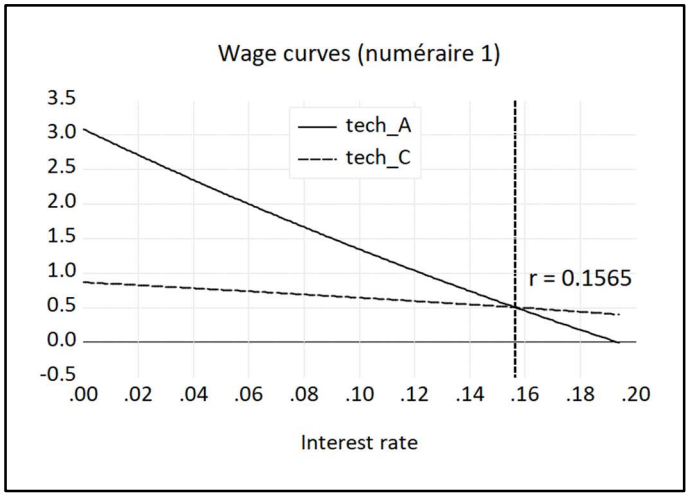
Consider the following representation of an economic system:

$$\mathbf{A} = \begin{Vmatrix} 0.7 & 2.85 & 0.5 \\ 0.023 & 0.18 & 0.09 \\ 0.02 & 0.2 & 0.18 \end{Vmatrix} \quad \mathbf{C} = \begin{Vmatrix} 0.5 & 1.1428 & 0.28 \\ 0.02 & 0.5238 & 0.05 \\ 0.04 & 0.27 & 0.5 \end{Vmatrix}$$

$$\mathbf{l}^A = \begin{bmatrix} 0.00825 & 0.79988 & 0.91322 \end{bmatrix} \; \mathbf{l}^C = \begin{bmatrix} 0.41 & 0.248 & 0.4302 \end{bmatrix}$$

The model produces crossing wage-curves at $r = 0.1565$ irrespective of the choice of numéraire.

Figure 4



[4] In the original: “Wie man zeigen kann, unterscheiden sich Techniken, die einander in Switchpunkten ablösen, nur in der Produktion einer (Basis-) Ware…”

If a different numéraire is chosen, then the shape of both curves changes, but not the point where they intersect (see Figs. 5 and 6). Therefore, even if more than one industry is affected, a switch-point may exist. Moreover, the second example of a three-sector-model makes an unambiguous decision possible which technology should be chosen for the best comfort of employees and entrepreneurs.

Figure 5

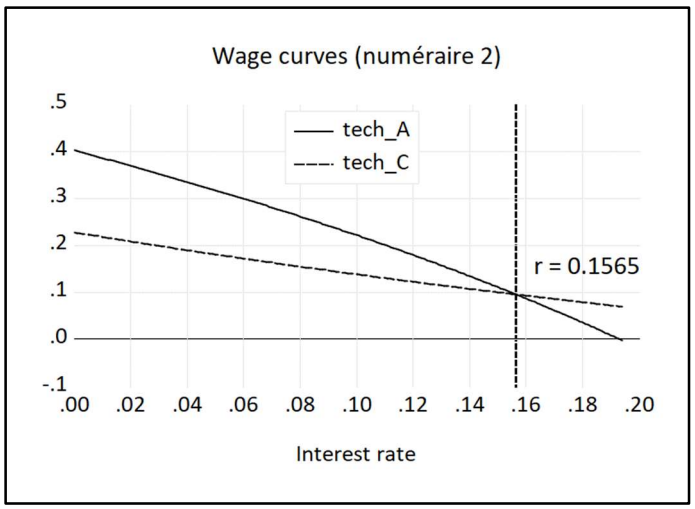
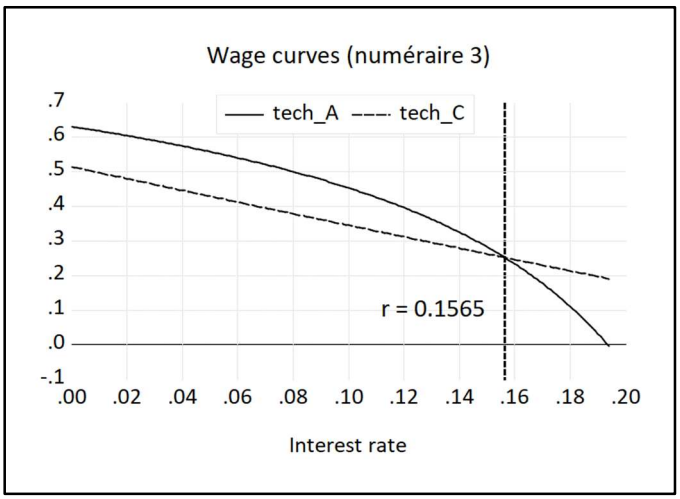


Figure 6



The opinion that a technology differs only in the production of one (basic) commodity when replacing another technology at a switch-point is apparently wrong. The underlying prejudice has to be revised. According to Schefold (2022: 15, footnote 3) there is a continuing need for research: “If the intersection is below/ between two systems using different methods in several industries, the optimal combination of these methods has still to be found.”

5. **Analysis of complex industrial innovations**

Pasinetti's rule to restrict the analysis of technological changes to a single sector suggests that the analysis of joint technological innovations occurring in multiple branches should be executed in a stepwise fashion. Using the model from the previous section to reconstruct the transition from technology *A* to technology *C*, three steps are sufficient. For example, the technology of the three branches can be changed one after the other, beginning with branch 1, followed by branch 2, and finally branch 3. The following captures that progression in shorthand and characterises each matrix by its columns:

aaa → caa; caa → cca; cca → ccc

Such a stepwise change can be called a "path". For each individual step, the decision in favour of the best technology should be clear in the vicinity of a (true) switch-point. However, there are more than one path that leads from *A* to *C*. For example, the technology in branch 3 could be switched first, followed by the one in branch 1 and, at last, the one in branch 2:

aaa → aac; aac → cac; cac → ccc

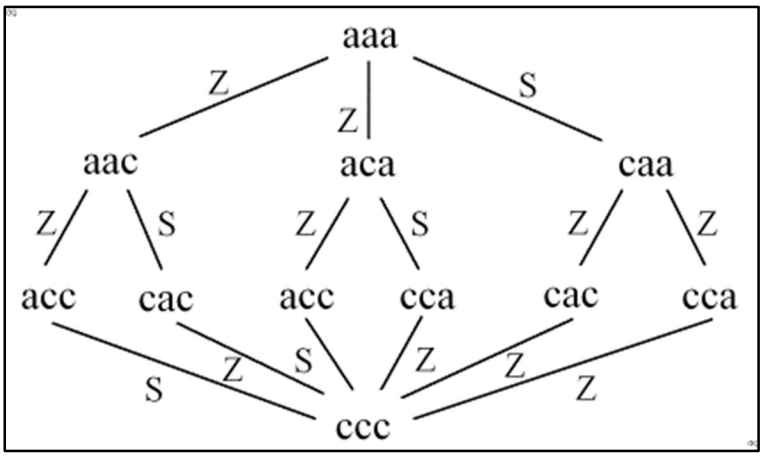
After all possible paths leading from *A* to *C* are put together, the steps that they entail need to be analysed in detail regarding the switch-points and the superior technology in their environment; not to mention the answer to the question whether the superior technology is influenced by the choice of numéraire. Table 1 lists all theoretically possible steps and summarises the results of the analysis.

The third row in Table 1 indicates for $r < r_{sp}$ that the starting technology *A* is always favoured, regardless of the chosen numéraire. The subsequent rows show the individual steps that could lead to technology *C* if they are performed one after the other. The last three rows show that the choice of technology, broken down into individual steps, does not lead to a clear result: It is path dependent. (S = starting technology; Z = target technology; SP = switch-point)

Table 1: Single-step decisions

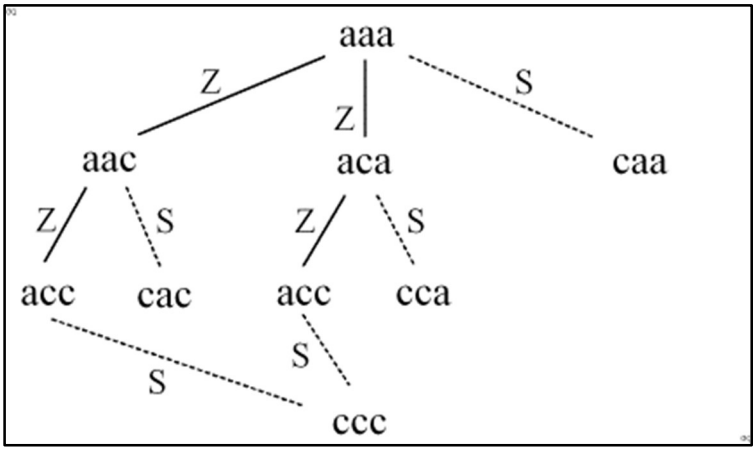
S	Z	SP	superior technology for $r < r_{sp}$		
		N1, N2, N3	N1	N2	N3
aaa	ccc	0.1565	S	S	S
aaa	aac	0.1565	Z	Z	Z
aaa	aca	0.1565	Z	Z	Z
aaa	caa	0.1565	S	S	S
aac	acc	0.1565	Z	Z	Z
aac	cac	0.1565	S	S	S
aca	acc	0.1565	Z	Z	Z
aca	cca	0.1565	S	S	S
caa	cac	0.1565	Z	Z	Z
caa	cca	0.1565	Z	Z	Z
acc	ccc	0.1565	S	S	S
cac	ccc	0.1565	Z	Z	Z
cca	ccc	0.1565	Z	Z	Z

Figure 7: Path diagram



Considering that a decision is made in favour of the superior technology at each step, all paths that favour the starting technology break off. In the example provided, all paths end before they reach technology *C* (Fig. 8). It thus follows that the comparison of technology *A* with technology *C* cannot theoretically be reconstructed by breaking it down into individual steps.

Figure 8: Viable paths



As an interim result, the analysis of complex technological changes using a stepwise method shows that it is path-dependent, such that no clear result can be achieved. In the given case it also proves to be unfeasible, because the selection of the best technology prevents a theoretical reconstruction that reaches the goal.

6. **Towards a general theory of switch-points**

The prices in equations (1) and (2) are expressed in terms of labour commanded, if:

$$w^A = w^C = 1.^5 \tag{3}$$

With that assumption, the systems of price equations can be solved unambiguously for each r within the interval $0 \le r < r_{\max}$ not only for the relative prices, but also regarding their level: for the technologies being compared, there are uniquely determined price vectors $\mathbf{p}^A$ and $\mathbf{p}^C$ expressed in labour commanded as numéraire. Because prices reflect costs of labour and capital, the technology with engenders the lowest (costs and) prices will be favoured. The decisions to implement an alternative technology are made only in sectors that are affected by the innovation. Here, the criterion is whether the prices of their goods has fallen or not.

In the following, we assume that the two price vectors are already determined by the price equations for all economically meaningful profit rates and, as a consequence, fulfil the following equations:

$$\mathbf{p}^A\left[\mathbf{I}-\left(1+r^A\right)\mathbf{A}\right]=\mathbf{l}^A \tag{4}$$

$$\mathbf{p}^C\left[\mathbf{I}-\left(1+r^C\right)\mathbf{C}\right]=\mathbf{l}^C \tag{5}$$

Furthermore, if technology A is set as the *reference* technology, then matrix C represents the economy with newly implemented or yet to be implemented technological *innovations*. The resulting alternative to technology A can be captured by a difference matrix and a difference vector:

$$\mathbf{D}=\mathbf{C}-\mathbf{A} \text{ und } \mathbf{l}^D=\mathbf{l}^C-\mathbf{l}^A \tag{6}$$

There are as many nonzero columns in these objects as industries are jointly affected by the innovation. Without loss of generality, we assume that only the first m $\left(0 < m \le n\right)$ columns of the matrix **D** are not null-vectors. Every non-zero column consists of a mixture of positive, negative and zero elements. It can be ruled out that all elements of a column are either positive or negative, for such uniformity would mean that one technology is superior to the other technology independently of r. Similar to the provisions made for entire industries, equation (6) supposes that none of the m columns of **D** can be presented as a linear combination of other columns – that is, that every innovation is unique. At a common profit rate $r = r^A = r^C$, equation (5) can be written as equation (7) if equation (6) is taken into account:

$$\mathbf{p}^C\left[\mathbf{I}-\left(1+r\right)\left(\mathbf{A}+\mathbf{D}\right)\right]=\mathbf{l}^A+\mathbf{l}^D \tag{7}$$

When equation (4) is subtracted from equation (7), the result is:

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[5] A price of a good expressed in terms of labour commanded informs how much labour has to be sold to purchase that good.

$$\left(\mathbf{p}^C - \mathbf{p}^A\right)\left[\mathbf{I} - \left(1+r\right)\mathbf{A}\right] - \left(1+r\right)\mathbf{p}^C\mathbf{D} = \mathbf{l}^D \tag{8}$$

(i) If the prices of the same sort of goods coincide at *r*, then, regardless of what technology has produced the corresponding goods, (i.e. $\mathbf{p}^C = \mathbf{p}^A$), a system of equations embedded in equation (8) is fulfilled:

$$-\left(1+r\right)\mathbf{p}^C\mathbf{D} = \mathbf{l}^D \tag{9}$$

The fulfilment of equation (9) at a certain point of *r* is therefore a *necessary condition* for the identity of the price vectors.

(ii) Conversely, if equation (9) is fulfilled, then equation (8) dictates that the price difference satisfies the following system of equations:

$$\left(\mathbf{p}^C - \mathbf{p}^A\right)\left[\mathbf{I} - \left(1+r\right)\mathbf{A}\right] = \mathbf{0} \tag{10}$$

Thus:

$$\mathbf{p}^C\left[\mathbf{I} - \left(1+r\right)\mathbf{A}\right] = \mathbf{p}^A\left[\mathbf{I} - \left(1+r\right)\mathbf{A}\right] \tag{11}$$

In the realm of economically meaningful profit rates, the determinant of the matrix in square brackets is not equal to zero. Therefore, equation (11) can be multiplied from the right by the corresponding inverse matrix getting the following result:

$$\mathbf{p}^C\left(r\right) = \mathbf{p}^A\left(r\right) \tag{12}$$

The two price vectors match. If (9) is fulfilled, all *n* prices are equal.

(iii) The identity of the price vectors is a sufficient and necessary condition for the fulfilment of equation (9). It can be called the *system of innovations* embedded in the system of price equation (8). In economic terms, the fulfilment of equation (9) means that for each industry affected by the innovation, the cost difference in the consumption of the means of production caused by the alternative technology and valued with a mark-up for profit is compensated by the cost difference in the labour input. In that special case, it is not worth changing the technology, especially because the costs of implementing the new technology are not considered here. But it is a candidate of being a true switch-point that, if represented with wage curves for *A* and *C*, always occurs at the same profit rate, regardless which numéraire is used to present those curves.

For intersection points being true switch-points it is necessary that for ε with $0 < \varepsilon \ll 1$ we have:

$$\mathbf{p}_i^A\left(r+\varepsilon\right) > \mathbf{p}_i^C\left(r+\varepsilon\right) \text{ or } \mathbf{p}_i^A\left(r+\varepsilon\right) < \mathbf{p}_i^C\left(r+\varepsilon\right) \quad (i = 1,\ldots,m)$$

Unlike in the single-sector case which is analysed by Pasinetti (1978: 158–159), it is not necessarily the case that those conditions are satisfied. (See example 1 at $r = 0.1$.)

The two difference matrices $\mathbf{D}$ and $\mathbf{l}^D$ are given due to the specific nature of the alternative and of the reference- technology. Because the prices of the goods produced under the alternative technology are not determined by equation (9), but by equation (5), the price vector $\mathbf{p}^C$ in equation (9) is also given. However, because all equations depend on the profit rate *r*, whether and, if so, at which point the embedded system is fulfilled has to be assessed for the entire range of economically senseful profit rates. If such is the case for a certain profit rate, then the two price vectors are identical, as shown above. In that case, the additional or reduced costs of the alternative means of production and the additional or reduced costs of the alternative labour input are balanced out.

7. **The number of switch-points**

The embedded equation (9) cannot be used to determine price vector $\mathbf{p}^C$ because it is already determined by equation (2) under the condition of equation (3). Substituting equation (2) in consideration of the conditions (3) into equation (9) results in:

$$-(1+r)\mathbf{l}^C\left[\mathbf{I}-(1+r)\mathbf{C}\right]^{-1}\mathbf{D}=\mathbf{l}^D \tag{13}$$

The inverse matrix in equation (13) is positive for $0 \le r < r_{\max}$ and can be notated as:

$$\left[\mathbf{I}-(1+r)\mathbf{C}\right]^{-1}=\lambda\frac{\mathbf{B}(\lambda)}{\Delta(\lambda)} \text{ with } \lambda=\frac{1}{1+r} \text{ and } 1\ge\lambda>\lambda_{\max} \tag{14}$$

in which $\lambda_{\max}$ is the Frobenius eigenvalue of matrix $\lambda\mathbf{I}-\mathbf{C}$. 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 are positive for $1\ge\lambda>\lambda_{\max}$. $\mathbf{B}(\lambda)$ consists of *n* column vectors. Because $\mathbf{B}(\lambda)$ is a $(n-1)\times(n-1)$ minor of $\Delta(\lambda)$ its elements are polynomials of degree (*n*–1) at most. The determinant itself is a polynomial of degree *n*. Applying equation (14), equation (13) can be written as follows:

$$\mathbf{l}^C\mathbf{B}(\lambda)\mathbf{D}+\Delta(\lambda)\mathbf{l}^D=0 \tag{15}$$

The literature contains the following seemingly plausible argument: $\mathbf{B}(\lambda)$ is a matrix of polynomials of degree *n*–1 and $\Delta(\lambda)$ is a polynomial of degree *n*. Together, they can have *n* roots. However, a certain problem with that argument is that in the area $1\ge\lambda>\lambda_{\max}$ both polynomials taken separately have no roots at all. Following Bruno et al. (1966: 539), the roots of the combination of two vector polynomials have to be identified. However, departing from those authors, the possibility that a certain technology, let us say *A*, is preferred to another technology *C* near the switch-point cannot be taken for granted because Section 3 shows that that evaluation can be contradictory in case of a technological alternative that implies a joint change of more than one branch.

7.1 **Case analysis**

(i) In the simple case that there is an alternative technology for a single branch only, innovation matrix **D** consists of exactly one single non-zero column. Without loss of generality, the non-zero column can be assumed to be the first one of **D**. Accordingly, only the first element of the row vector $\mathbf{l}^D$ differs from zero.

In that case, the first column (= vector **x)** of the product matrix $\mathbf{B}(\lambda)\mathbf{D}$ is a linear combination of the columns of $\mathbf{B}(\lambda)$:

$$\mathbf{x} = \left(\sum_i b_{1i} d_{i1} \quad \sum_i b_{2i} d_{i1} \quad \dots \quad \sum_i b_{ni} d_{i1} \right) \tag{16}$$

Here, **x** is a vector of polynomials of degree *n*–1 at most. Vector **x** multiplied by the vector $\mathbf{l}^C$ produces a weighted sum of the elements in equation (16), which is the first element of row vector $\mathbf{l}^C\mathbf{B}(\lambda)\mathbf{D}$. Adding the non-vanishing element of $\Delta(\lambda)\mathbf{l}^D$ results in a polynomial of degree *n* that can be written as:

$$(\lambda - \lambda_1)(\lambda - \lambda_2)\cdots(\lambda - \lambda_n) = 0 \tag{17}$$

Some of the roots λ_i might be identical, negative, imaginary or even equal to zero; moreover, they are functions of the parameters in equation (15). It thus follows that there can be at most *n* roots that fulfil the embedded equation.

(ii) Now let us suppose that there is a technological alternative that comprises two branches jointly. (The change affects two branches together.) Without any loss of generality, it can be assumed that branches 1 and 2 are affected. In addition to the column vector in equation (16), a second one can be obtained:

$$\mathbf{y} = \left(\sum_i b_{1i} d_{i2} \quad \sum_i b_{2i} d_{i2} \quad \dots \quad \sum_i b_{ni} d_{i2} \right) \tag{18}$$

Let us stipulate for a moment that the innovation produces the same roots in branch 2 as in branch 1, as shown in equation (17). Then the conclusion is necessarily that $\mathbf{y} = \mathbf{x}$, which can be the case only if the first column of **D** coincides with its second column. However, that circumstance contradicts the uniqueness of the innovations. It follows that at least one root needs to be different in branch 2. The maximal number of common roots reduces to *n*–1, meaning that there can be no more than *n*–1 switch-points.

(iii) Let us now assume that there is an innovation that requires a joint change in the technology of $m \le n$ industries. Repeating the same lines of arguments as in (i) and (ii), there can be at most $n-(m-1) = n-m+1$ common roots of the embedded equation system. If *m* equals *n*, then there can be only one switch-point. The example in Section 4 shows such a case. Here, the Samuelson – Levhari (1965: 103) theorem on the impossibility of re-switching would be correct.

(iv) Even if there are $n-m+1$ roots of the system of embedded equations, it does not guarantee that there are the same number of true switch-points. If there are identical prices in pairs as in the first example, then it cannot be taken for granted that the prices behave in an

epsilon environment of the intersection point in the same way as Bruno et al. (1966: 541) have mistakenly assume. The pairwise coincidence of all prices is a necessary but not a sufficient condition for the existence of a switch-point. Therefore, it has to be checked whether in the near area to the left (or right) of the intersection-point *the prices* of goods produced by technology *A* in the affected branches are less (alternatively: higher) than those produced by technology *C*. At the intersection point, the behaviour of prices can be detected by consulting the differences between the first derivatives with respect to the profit rate:

Table 2: Identifying false and true switch-points

Tech.	Example 1			Tech.	Example 2		
	p_1'	p_2'	p_3'		p_1'	p_2'	p_3'
A	0.87	7.37	2.16	A	53.66	255,78	76.06
C	0.42	10.98	4.03	C	10.19	76.46	25.50
C-A:	-.45	3.61	1.87	C-A	-43.47	-179.32	-50.56

Thus, the criterion is that if the signs of the difference are mixed, then the alleged switch-point is spurious.

7.2 **An empirical note**

If we accept the assumption that the probability of switching tends to zero with a rising number of sectors that are affected by innovations, the question emerges how technical progress might have been possible at all. The answer is as simple as the theory is complicated: the concept of switch-points is a theoretical one. It assumes that the prices of all the goods produced by the affected sectors necessarily fall after the alternative technology is implemented. In reality, it might well be that some of the prices rise whereas only a few dominant sectors have falling costs and can afford lower prices of their products.

8. **Summary**

(i) Although the distinction between true and false switch-points is seldom mentioned in the literature, complex industrial changes in technology can lead to both, to true or, alternatively, to spurious switch-points.

(ii) A change in the numéraire does not change the essential features of an economic system but can nevertheless help to detect spurious switch-points.

(iii) Restricting analyses to technological changes in only one branch, as done in the literature and even demanded by some authors, proves to be path-dependent and possibly unfeasible when analysing complex technological changes in multiple industries.

(iv) The chief feature of true switch-points is that prices of the same sorts of goods coincide and are consistently either larger or smaller on one side of the immediate vicinity of the intersection point – compared to the prices engendered by the other technology.

(v) The maximal number *n* of algebraically possible switch-points is reduced by the number of branches that are jointly affected by a technological alternative and by ambiguous price changes in the vicinity of intersecting wage curves.

9. **Appendix**

The maximal number of roots in the case of a joint innovation in two branches

Lemma:

If an innovation concerns two branches together, but in different ways, there can be no more than *n*-1 common roots of the system of embedded equations.

Proof:

Embedded system of equations:

$$\mathbf{l}^C\mathbf{B}(\lambda)\mathbf{D}+\Delta(\lambda)\mathbf{l}^D=0 \tag{15}$$

Presuppositions:

$$\mathbf{l}^C>\mathbf{0};\ \mathbf{B}(\lambda)=\left\|b_{ij}(\lambda)\right\|_1^n$$

$$1\geq\lambda>\lambda_{\max}\ \Rightarrow\ \mathbf{B}(\lambda)>\mathbf{0};\ \Delta(\lambda)>0;\ \Delta\left[B(\lambda)\right]=\left[\Delta(\lambda)\right]^{n-1}>0$$

$$\mathbf{D}=\left[\mathbf{d}_1\quad\mathbf{d}_2\quad 0\quad\ldots\quad 0\right];\ \mathbf{d}_i=\left(d_{1i}\quad d_{2i}\quad\ldots\quad d_{ni}\right);$$

$$\mathbf{d}_1\neq\mathbf{d}_2 \tag{19}$$

$$\mathbf{l}^D=\left[l_1^D\quad l_2^D\quad 0\quad\ldots\quad 0\right]$$

Structure of term $\mathbf{l}^C\mathbf{B}(\lambda)$:

The elements of $\mathbf{B}(\lambda)$ are polynomials of λ.

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

The highest grade of the polynomials is $n-1$ and can be found in $b_{ii}(\lambda)$ for $i=1,\ldots,n$. Those elements are linked with the positive coefficient l_i^C if the indices of both coincide. The polynomials can be ordered by powers of λ. We define a row-vector

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

and a matrix **P** with the coefficients of the polynomials:

$$\mathbf{P} = \begin{Vmatrix} l_1^C & l_2^C & \dots & l_n^C \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ p_{n1} & p_{n2} & \dots & p_{nn} \end{Vmatrix}$$

With definitions from above we get:

$$\mathbf{l}^C \mathbf{B}(\lambda) = \mathbf{\Lambda P}$$

Because $\Delta\left[B(\lambda)\right] \neq 0 \Rightarrow \Delta(\mathbf{P}) \neq 0$, i. e., all polynomials are different from each other and therefore $\operatorname{rank}(\mathbf{P}) = n$. It follows what we need for the ultimate proof:

if $\mathbf{\Lambda P x} = \mathbf{0} \Rightarrow \mathbf{x} = \mathbf{0}$.

The structure of term $\Delta(\lambda)\mathbf{l}^D$:

$$\Delta(\lambda)\mathbf{l}^D = \left\| l_1^D \Delta(\lambda) \quad l_2^D \Delta(\lambda) \quad \dots \quad l_n^D \Delta(\lambda) \right\|$$

with $\Delta(\lambda) = \lambda^n - p_1 \lambda^{n-1} - \dots - p_1$.

We define a column-vector $\mathbf{p} = \begin{pmatrix} p_1 & p_2 & \dots & p_n \end{pmatrix}$ with the coefficients of $\Delta(\lambda)$. With the former defined vector $\mathbf{\Lambda}$ we get the formula $\Delta(\lambda) = \lambda^n - \mathbf{\Lambda p}$. Now equation (15) can be written as follows:

$$\varphi_i(\lambda) = 0 \text{ with } \varphi_i(\lambda) = \mathbf{\Lambda P d}_i + l_i^D \left(\lambda^n - \mathbf{\Lambda p} \right)$$

If $\varphi_1(\lambda) \equiv \varphi_2(\lambda)$ it follows $l_1^D = l_2^D$ because λ^n is only part of the second term.

If $\varphi_1(\lambda) \equiv \varphi_2(\lambda)$ and $l_1^D = l_2^D$ it follows $\mathbf{\Lambda P d}_1 = \mathbf{\Lambda P d}_2$ and thus $\mathbf{d}_1 = \mathbf{d}_2$. This contradicts condition (19). Therefore: There is at least one root in $\varphi_2(\lambda)$ that is different from the roots of $\varphi_1(\lambda)$. q. e. d.

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