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Path-Dependence without Increasing Returns to Scale and Network Externalities

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Abstract: The paper presents a simple model of a locked-in situation. Recent literature on path-dependence has explained locked-in situations with increasing returns to scale or network externalities. The model of this paper is a model of a single firm (there is no network of different agents) with a given size (there are no economies of scale). Our analyses shows that complementarity of a firm's assets and sunk costs can be sufficient for path-dependence.

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1. Introduction

After the publication of the important papers of Paul David (1985) and Brian Arthur (1989) economists have become increasingly interested in the concept of path-dependence. Traditional economists have difficulties to model a certain class of real-world phenomena that can be easily explained by the concept of path-dependence. Among the best known examples are the QWERTY keyboard of typewriters and computers, the left-hand traffic in Britain, and the width of the rail tracks in Russia or Spain versus the rest of Europe. Similar phenomena are the regional concentrations of software producers in the Silicon Valley or of swine and poultry producers in the North West of Germany and the South East of the Netherlands. In all those and many more cases some initial advantage combined with increasing returns to scale and/or network externalities (Arthur, 1989 and 1990) has resulted in what is called "locked-in" situations, i.e. an equilibrium that although it may be inefficient can only be abandoned at extremely high costs. Britain's left-hand side traffic, for example, causes additional costs. Cars built by continental European and American manufacturers for the British market are produced at higher costs. But the costs of a switch to right-hand traffic in Britain would be prohibitively costly due to network externalities. It is impossible to transform the system in a piecemeal manner. All drivers are interconnected to each other and no one can switch on his or her own. The adjustment costs are estimated to be so high that it is very unlikely that the present system will be abandoned in the foreseeable future. On the other hand, the decision of the Swedish government to switch from left-hand to right-hand traffic in the mid-sixties is a well-known example for a case where the adjustment costs were considered not to be prohibitively high because traffic was much less then.

The existence of path-dependence in a system has some interesting economic implications (Arthur, 1989):

- the predictability of the future development can be very small at certain times, at other times very high, when the system is locked-in
- small historical events can become durable effects (non-ergodicity)
- a path, once entered, can possibly only be abandoned at extremely high costs (inflexibility),
- there is a potential inefficiency of the system.

Explaining path-dependence the above mentioned authors emphasize the role of increasing returns to scale and the role of network externalities. In this paper we present a simple model which can explain path-dependence even if increasing returns to scale and network externalities are absent. In our model, the time structure of necessary reinvestments and sunk costs cause the locked-in situation. Section 2 gives a brief description of the traditional path-dependence model. The concepts of sunk costs and hysteresis, which are important for both the traditional view of path-dependence and our model, are discussed in some detail. We present our own model in section 3. Section 4 deals with some modifications. Conclusions follow in section 5.

2. The traditional Path-dependence Concept

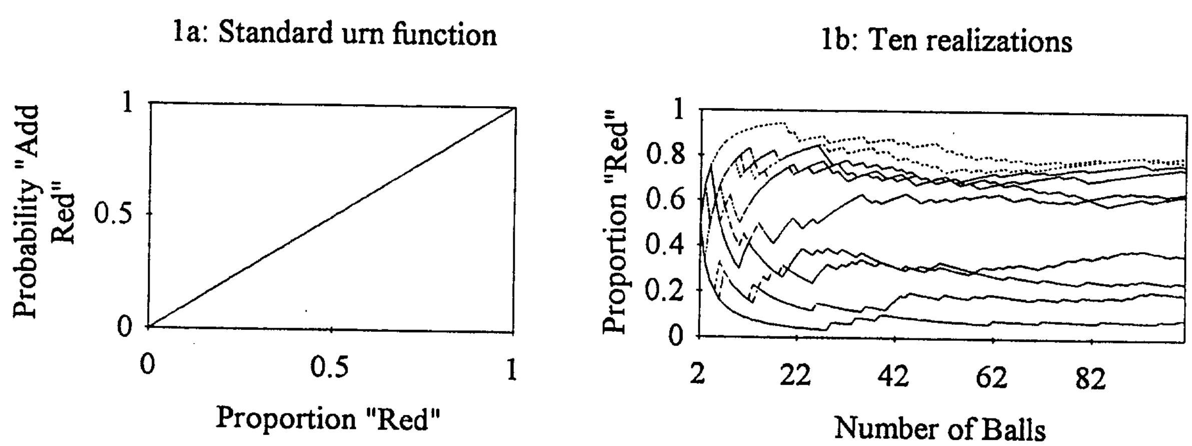
2.1. Illustrations

Path-dependence is generally conceived as being governed by stochastic processes. Although in its original version it is not related to economic problems, the Polya process provides a good analogy.[1] The linear Polya process can be illustrated as follows: Assume an urn containing one red and one blue ball in t = 0. In each of the following periods t = 1, 2, ... one ball is randomly drawn from the urn. Then the ball is returned and another one of the same color is added to the contents of the urn. This can be formalized as follows:

Probability (Add Red_{t+1}) = Proportion (Red_t).

Figure 1a is the corresponding graphical representation. Ten simulations are plotted in Figure 1b.

Figure 1: The standard Polya process



[1] This presentation follows Arthur et al (1987).

Figure 1b shows that in the first periods the proportions are subject to large fluctuations. But as the number of balls increases the effect of an added ball on the proportion decreases. The range in which the proportion varies is shrinking. The consequence of this behavior is a path-dependence. The events of the earlier periods dominate the further development of the system, as well as the system itself becomes more and more locked-in.

The linear Polya process has an infinite number of equally likely equilibria (Arthur et al, 1987). However, non-linear Polya processes are of greater interest to economists. These can be represented by the following equation:

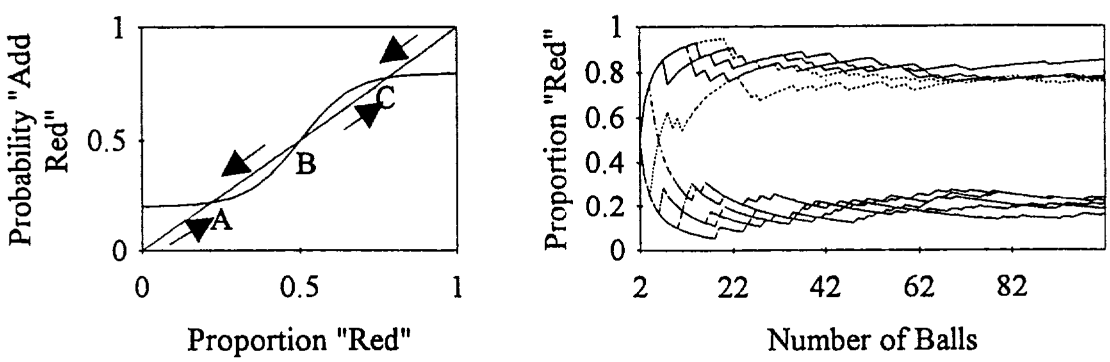
Probability (Add Red_{t+1}) = f(Proportion Red_t), where $f(.)$ is some non-linear function.

As illustrated in Figure 2a this stochastic process results in one unstable (B) and two stable equilibria (A and C). Simulation results are given in figure 2b.

Figure 2: A non-linear Polya process

2a: Non-linear urn function

2b: Ten realizations



To avoid possible misinterpretations; Arthur and other proponents of the traditional path-dependence concept do not claim that the introduction of new technologies (institutions) or regional developments follow simple linear or non-linear Polya processes. However, they suggest that these stochastic processes are subject to complicated and not yet fully understood internal driving forces causing results similar to the above-mentioned non-linear Polya processes.[2]

2 Polya processes are not the only possibility to investigate path-dependences by simulation models. Balmann (1992) applied the concept of cellular automata in a simulation model to investigate the relevance of path-dependences in the development of regional agricultural structure.

2.2. Causes

What causes path-dependence of economic systems? One common explanation are positive feedbacks (Arthur, 1988 and 1990). Figure 2a illustrates such a situation. An economic example is the competition of two firms whose production functions exhibit increasing returns to scale. A situation in which both are equally strong is unstable. The only stable points are (natural) monopolies.

Another explanation are network externalities.[3] Network externalities cause positive feedbacks that are based on interactions between parts of the system. Each part of the system has positive externalities on other parts. Network externalities are often used to explain the evolution of industrial standards like the typewriter keyboard QWERTY or the videotape system VHS.[4] The key feature of network externalities are possible inefficiencies from uncoordinated behavior of the parts of the system.

Economies of scale and network externalities are not sufficient to explain path-dependence. Sunk costs are of major importance when locked-in situations occur. Consider a natural monopoly held by firm F. This firm has a plant which cannot be sold, and therefore, has no better option than to stay in the market despite the attempts of a potential entrant E to take over the monopoly. F will hold the monopoly as long as sunk costs are significant. If all costs were variable, E could threaten to enter at any time. There is an inherent historical character in such locked-in situations. This historical character shows up in sunk costs.

Baumol (1987) defines sunk costs as follows:

> "A sunk cost may or may not be larger than the minimum outlay a firm needs to operate but, once incurred, it cannot be withdrawn for some substantial period without significant loss."

This means, for example, that if a firm has already invested in a plant, this plant cannot be sold at the same price even if it has not been used. Given the plant can be sold at the same price, sunk costs may also have arisen from transaction costs. Transaction costs are often non-monetary outlays. They can also lower the resale price.

But how should sunk costs been calculated? A firm has to compare the returns to production with the opportunity costs of the asset. If the returns are not high enough to cover the opportunity costs, the plant should be sold. Accordingly, sunk costs should be defined as the difference between the outlay for an asset and its opportunity costs.

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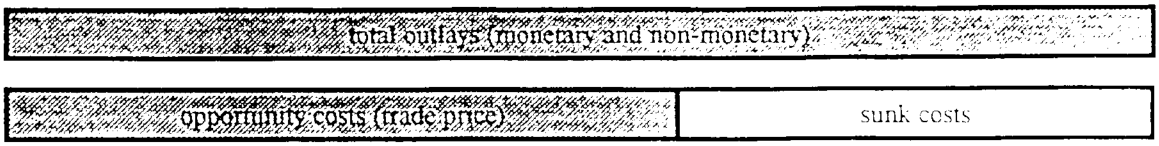
3 Katz und Shapiro (1985).

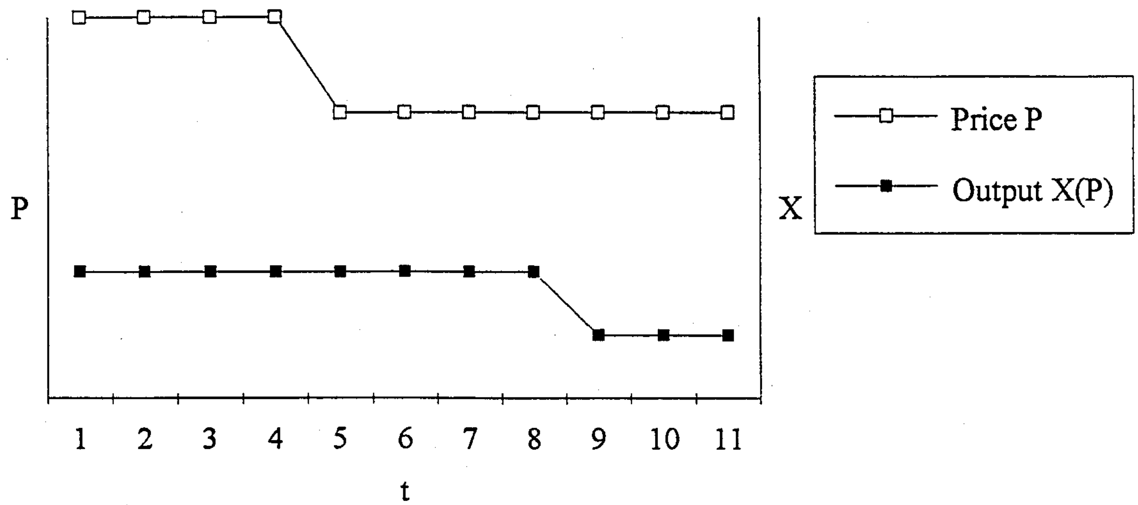
4 Arthur (1988), (1990), Katz und Shapiro (1985).

Figure 3: Sunk costs and outlays



The existence of sunk costs may cause limited path-dependences. For an entrepreneur who considers an investment, the net present value of the expected yields and outlays must not be negative. Once the investment is made, the outlays on investment should not be taken into account for any further decision if opportunity costs are zero and the total outlay is sunk. For any production decision the entrepreneur only has to compare the returns to production and the variable costs. If product prices decrease he will continue production, while other firms that will have to invest do not enter the market. But in the long run the plant has to be replaced. If reinvestment is considered, all costs are variable and production is suspended. This phenomenon of delayed reactions is called *hysteresis*, a kind of inertia.[5] Because every asset can be used for a limited time only, management theory claims that in the long run all costs are variable.

Figure 4: Hysteresis



Hysteresis can be interpreted as a sort of short-term locked-in situation. We are now going to present our model where sunk costs lead to a locked-in situation of infinite duration.

5 Some examples and theoretical reflections about investment and hysteresis can be found in Dixit, 1992.

3. The Model

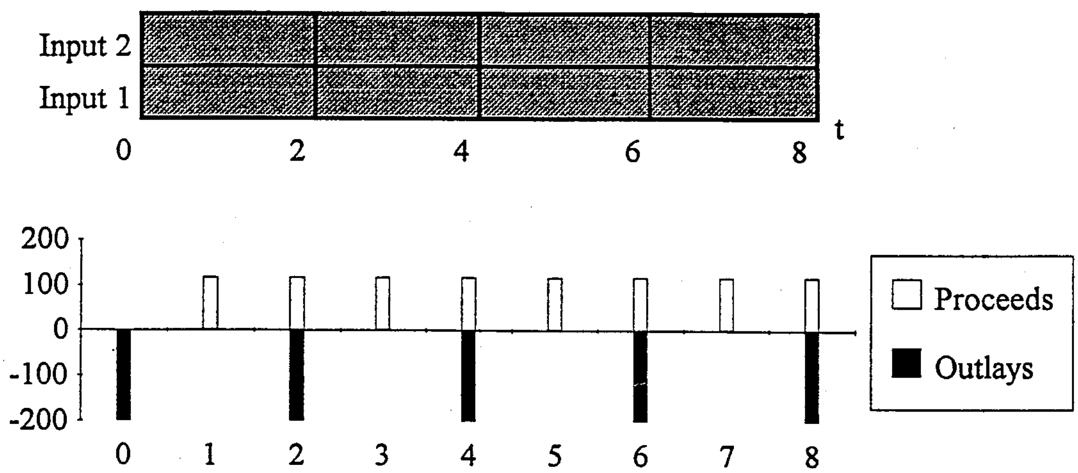
3.1. An Example

We introduce a simple model where path-dependence of infinite duration occurs even if economies of scale and network externalities are absent. To show this, assume a price-taking firm whose output per period is either 0 or 1. Production requires two indivisible identical inputs with cash outlay of c=100 each and a lifetime of t=2 periods. Assuming an interest rate of i=0.1 and input synchronicity, the threshold price P for a profit-maximizing firm is

$$P \geq 2 \cdot c \cdot \left(\frac{(1+i)^2 \cdot i}{(1+i)^2 - 1} \right) = 115.2$$

Figure 5 illustrates the input synchronicity case and the corresponding cash flow for P=115.2. Due to the fact that the initial outlays cannot be fully recovered and, thus, have to be considered as sunk costs, investment decision need only be made in periods 0, 2, 4, ...

Figure 5: Synchronicity



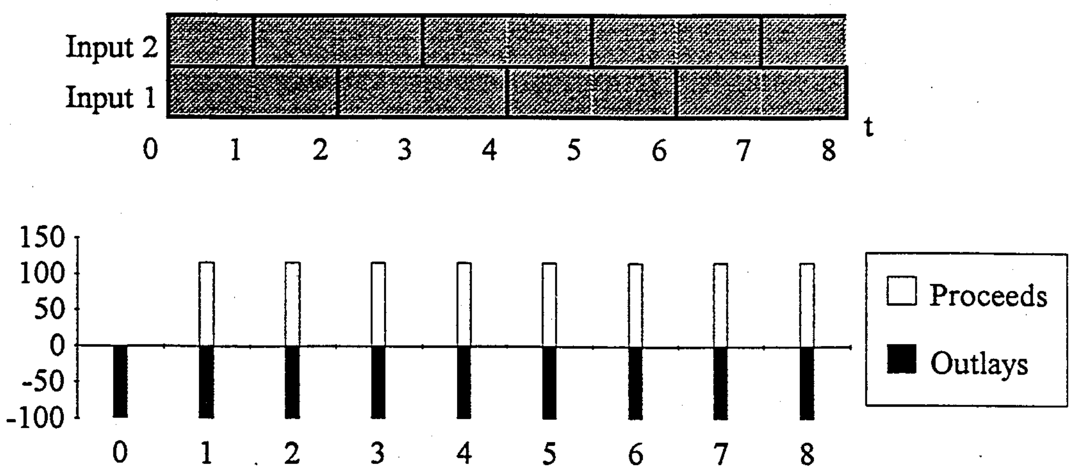
Let us now assume that, for some historic reason, the input structure of our firm is characterized by asynchronicity (Figure 6). In this case the entrepreneur has to decide in each period whether or not to continue production. It is most interesting that, due to the sunk cost character of the inputs, the minimum price for the asynchronous firm is below the minimum price for the synchronous firm. At any time period the asynchronous firm has to consider an infinite planning horizon and will purchase one input if the net present value of the cash flow is positive:

$$NPV: = -c + \frac{P-c}{i} > 0 .$$

This is equivalent to

$$P > c(1+i) \quad \text{which gives} \quad P > 110.$$

Figure 6: Asynchronicity

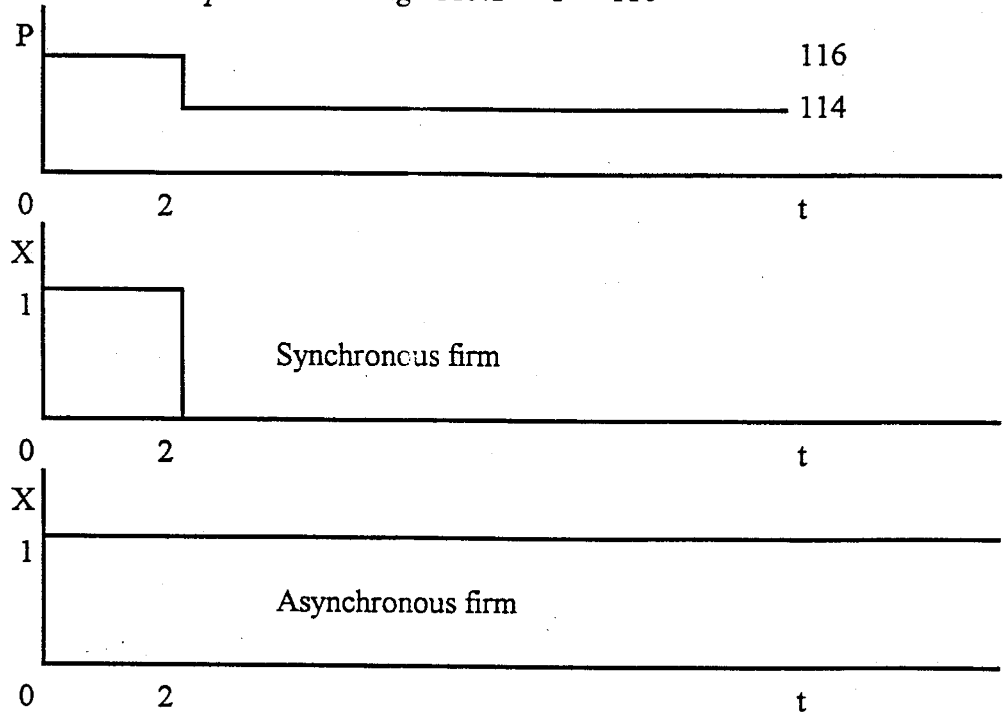


Therefore, within the price range

$$2 \cdot c \cdot \left(\frac{(1+i)^2 \cdot i}{(1+i)^2 - 1} \right) - c \cdot (\ + i) = 5.2$$

we can observe path-dependence of infinite duration as illustrated by Figure 7.

Figure 7: Production path in the range 115.2 > P > 110



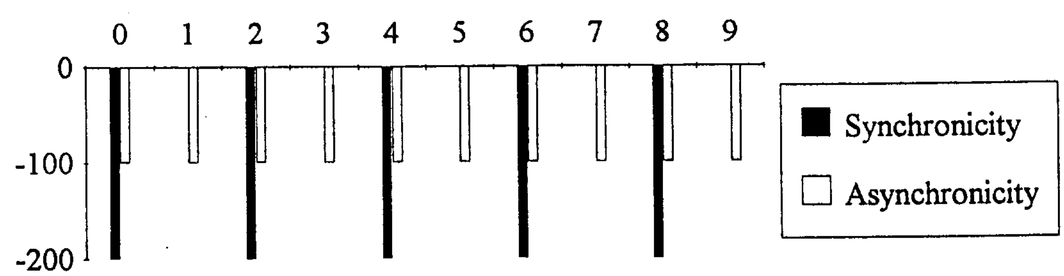
Thus we have shown that two otherwise identical, profit-maximizing firms will, under certain conditions, react completely differently to changes in expected prices. A firm that has inherited input asynchronicity is forced to continue production although the price does not cover the costs of production for newly established firms or for firms with input synchronicity.

To be sure, the input complementarity assumption in our model corresponds to the network externalities in the traditional path-dependence concept. Our model reveals a very basic feature of path-dependence. It is not necessary to have a complicated network of producers and consumers that leads to the adoption of industrial standards, regional concentration, etc.. Rather a simple complementarity is the necessary ingredient.

Necessary and sufficient conditions for infinite path-dependence are a positive interest rate, a certain price path, input complementarity combined with indivisibilities, asynchronicity, and sunk costs. We will work out these conditions more precisely in the next section.

An intuitive explanation of the occurrence of infinite path-dependence in our model follows. Compare the cost streams of the two firms in figure 8. These are only equivalent if i=0. For any positive interest rate the cost structure of the asynchronous firm is more favorable, resulting in a lower minimum price.

Figure 8: Cost streams



3.2. Conditions

We now investigate the reason for the infinite duration of the path-dependence in more detail. Let S denote the synchronous firm and let A denote the asynchronous firm. Given input complementarity and indivisible inputs as in the above example, it is sufficient for infinite path-dependence that the average costs of S (AC_S) are higher than the expected price P and the average costs of A (AC_A) are lower than P:

$$AC_S > P > AC_A \qquad \text{with}$$

$$AC_S = 2 \cdot i \cdot c \cdot CRF_{i,N} \sum_{t=1}^{\infty} (1+i)^{-t} \quad \text{and}$$

$$AC_A = i \cdot c \cdot CRF_{i,N} \left(\sum_{t=1}^{\infty} (1+i)^{-t} + \sum_{t=1}^{\infty} (1+i)^{-(t+N-n)} \right)$$

where c is the outlay for an investment, $CRF_{i,N}$ is the capital recovery factor for interest rate i and N periods. N is the lifetime of a new plant. N-n is the rest of a plant's lifetime at the time of decision.

A necessary condition is

$$AC_S > AC_A \quad \text{or}$$

$$0 < AC_S - AC_A$$

$$\Leftrightarrow 0 < c \cdot i \cdot CRF_{i,N} \left(\sum_{t=1}^{\infty} (1+i)^{-t} - \sum_{t=1}^{\infty} (1+i)^{-(t+N-n)} \right)$$

This holds if:

$$c > 0,$$

$$i > 0 \quad \text{and}$$

$$\sum_{t=1}^{\infty} (1+i)^{-t} - \sum_{t=1}^{\infty} (1+i)^{-(t+N-n)} > 0 \Leftrightarrow i > 0; N > n$$

Further, the necessary conditions are a positive outlay, a positive interest rate and a plant's age that is strictly less than its lifetime.

4. Modifications

The model above is very specific. Some modifications and further investigations may be helpful to generalize the results. But there are a many possible modifications. We cannot investigate them all. So we will concentrate on opportunity costs and on the case of heterogeneous inputs.

4.1. Relevance of Opportunity Costs

For the calculations above the costs for the already existing plant were assumed to be totally sunk. Now we drop this assumption. The difference of the average cost of the two firms is equal to the interest of the remaining value of the existing plant ($1/CRF_{i,N}$ is the present value of an annuity).

$$AC_S - AC_A = i \cdot c \cdot CRF_{i,N} \sum_{t=1}^{N-n} (1+i)^{-t} = i \cdot c \cdot \frac{CRF_{i,N}}{CRF_{i,N-n}}$$

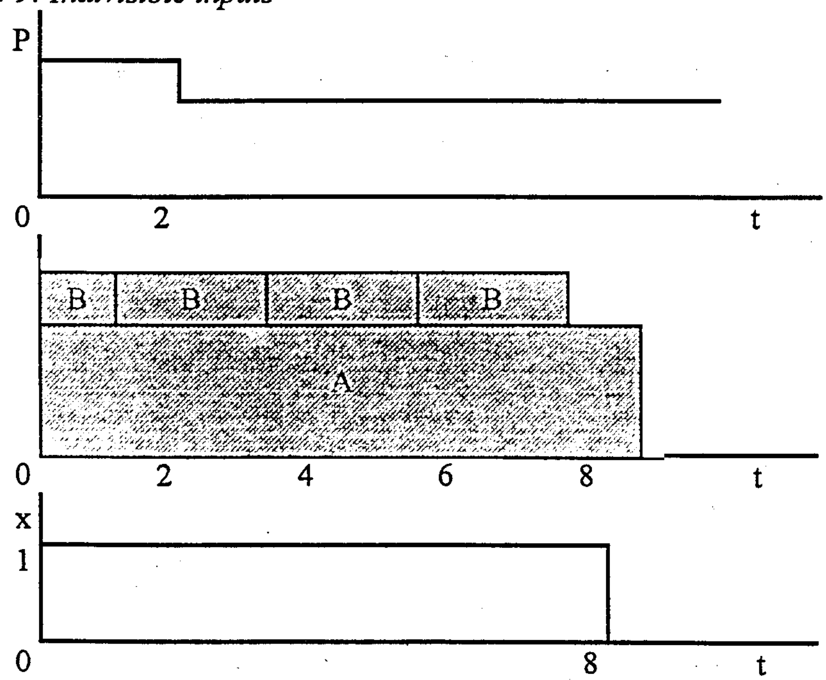
This means that if in situation A the existing plant could be sold at its imputed value, sunk costs would be zero. In this case the difference AC_S - AC_A would also be zero, and the necessary condition would not be met.

If sunk costs are positive, opportunity costs of the already existing inputs are lower than their calculatory value. This means that this kind of path-dependence is caused by too low opportunity costs.

4.2. Complementary Inputs with Different Cost Structure and Life Time

Under the assumptions of subsections 3.1 and 3.2, path-dependence will either be of infinite duration or not occur at all. However, one can easily imagine conditions where path-dependences will disappear after a finite time period. For example, think of two complementary inputs with cost structure and lifetime as illustrated in figure 9. Provided the price path follows certain conditions, a profit-maximizing firm will reinvest input B in t=2, 4, 6, but not in t=8. Obviously, this situation can be classified somewhere in between pure hysteresis and infinite path-dependence. However, in contrast to the case of infinite path-dependence, the interest rate may be zero here.

Figure 9: Indivisible inputs



If the interest rate is larger than zero an asynchronous situation with cost structure and lifetime as in figure 9 may, compared to the case of synchronicity, lead to path-dependence, too. For this it is, again, necessary and sufficient that

$$AC_S > P > AC_A \qquad \text{at any time } t.$$

For this to hold it is necessary that positive sunk costs exist at any time t.

5. Conclusions

We have presented a simple model which shows that, under certain conditions, complementarity and sunk costs lead to a locked-in situation of infinite duration. Production and investment decisions differ significantly in situations with or without sunk costs. Despite its simplicity, the model may help to understand real world phenomena. Consider, for example, the problem of educational choice in agriculture. Investments made some time ago cause sunk costs. Thus it may seem attractive to a farmer's son or daughter to have an agricultural education and take over the farm. At some later stage further investments are necessary. Costs for education are sunk and often, opportunity costs (earning possibilities in the non-agricultural sector) are low. Therefore, an investment will be the right decision. This complementarity and asynchronicity of labor and capital can cause path-dependence, as in our model. This offers an additional explanation for slow structural change in agriculture.

So far we have not mentioned the concept of efficiency. In our example both firms decide rationally with regard to their starting position. But which situation is more favorable, the synchronicity or the asynchronicity case? At a first glance, asynchronicity seems favorable since it is possible to realize a higher interest rate for the liquid capital compared to any investment in the capital market. This conclusion does not, of course, hold if one takes into account the fixed capital ($c \cdot CRF_{i,N} / CRF_{i,N-n}$ in the example of section 3.2). Then an asynchronous firm has the same threshold price as a synchronous firm to make profits.

Table 1 shows the net present values of three firms (of the type described in section 3.2) which differ with respect to their sunk costs for different price expectations. A denotes a firm with asynchronicity, S_0 denotes a firm with synchronicity and no assets at t_0. S_1 is a synchronous firm which has invested at t_{0-n}. The firms' performance is equally good if the price is higher than the threshold price. The only case where the asynchronous firm becomes superior to the synchronous firm S_1 is when the price decreases below $c\ CRF_{i,N}$ (half of the threshold price). In all other cases synchronous firms, S_1 or S_0, are superior. The differences between the firms are due to the structure of sunk costs. If we leave aside the extreme case where the price is less than $c\ CRF_{i,N}$ we can conclude that inefficiencies are more likely to occur with input asynchronicity.

Table 1: Net present values for synchronous and asynchronous firms

Expected Price P	A		S_1		So
$P < c\ CRF_{i,N}$	$-c\cdot\frac{CRF_{i,N}}{CRF_{i,N-n}}$	$>$	$\frac{P-2\cdot c\cdot CRF_{i,N}}{CRF_{i,N-n}}$	$<$	0
$c\ CRF_{i,N} < P$ $P < c(1+i)$	$-c\cdot\frac{CRF_{i,N}}{CRF_{i,N-n}}$	$<$	$\frac{P-2\cdot c\cdot CRF_{i,N}}{CRF_{i,N-n}}$	$<$	0
$c(1+i) < P$ $P < 2\ c\ CRF_{i,N}$	$-c\cdot\left(1+\frac{CRF_{i,N}}{CRF_{i,N-n}}\right)+\left(\frac{P-c\cdot CRF_{i,N}\left(1+(1+i)^{n-N}\right)}{i}\right)$	$<$	$\frac{P-2\cdot c\cdot CRF_{i,N}}{CRF_{i,N-n}}$	$<$	0
$2\ c\ CRF_{i,N} < P$	$=\frac{P-2\cdot c\cdot CRF_{i,N}}{i}$	$=$	$\frac{P-2\cdot c\cdot CRF_{i,N}}{i}$	$=$	$\frac{P-2\cdot c\cdot CRF_{i,N}}{i}$

Another aspect of inefficiency may arise when the continuation of production and investment has negative side-effects on the development of other firms. This would be true if the firms involved compete for the same scarce factors such as land in the case of agricultural production.

Our conclusion that sunk costs may cause inefficiencies and that the duration of this situation is not necessarily limited by the years of use of the single investments has implications for policy making. Whenever political signals (e.g. subsidies) are misleading in the sense that they stimulate investments in otherwise nonprofitable production, the consequences become more severe in a situation of path-dependence. With regard to the transformation process of the agricultural sector in East Germany and Eastern Europe such considerations are actually relevant.

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