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Modeling Adopters'Behaviour in Information Technology Systems: A Multi-Actor Approach

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1. Introduction

1.1 Background

The penetration rate of modern information and communication technologies (ICT) is not only determined by the indigenous qualities of these technologies, but also by the adoption behaviour of other actors using the same network technology. This case of network externalities means that the benefits of adopting a new technology are dependent on the adoption rates of others actors in the market (see, e.g., Capello 1994). In addition to cross-sectional interdependencies among actors, the ICT market exhibits sequential externalities related to the timing of adoption of these technologies. The adoption decisions of ICT users are affected both by the adoption behaviour of earlier user generations and by the expected success of technologies in the future.

This paper aims to model the adopters' behaviour in ICT networks from the viewpoint of both cross-sectional and sequential interdependencies. In particular, it will focus on the economic consequences of (in)compatibilities between network technologies. The adoption decision of a new technology is often made between close substitutes, but frequently a network technology is composed of complementary components (see, e.g., Economides and White 1994). For instance, a user may decide whether he buys a mobile phone or chooses a traditional wired telephone system. If a user wants – in addition to a telephone – a telefax machine, he needs a telephone line in order to use the fax. Then, the choice of a telephone may also be affected by the demand for complementary technologies as well as their availability, i.e. the supply side conditions. We will discuss here two types of interdependent network technologies: (i) complementary technologies a user can buy separately and (ii) complementary technologies forming an inseparable composite good. We examine how the supply side decisions to produce compatible or incompatible components or products – as a result of divergent competitive strategies of the suppliers of network technologies[1] – affects the optimal timing of the adoption of new network technologies.

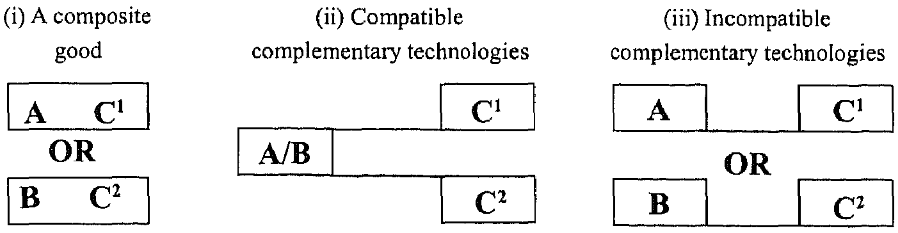
1.2 Aims and Scope

Our paper addresses primarily two strands of literature. First, it aims to investigate the issue of network externalities and network compatibility by highlighting the importance of both cross-sectional and dynamic interdependencies in the economic actors' adoption behaviour in the network technology systems. Second, it also offers a contribution to the broader stream of literature on the diffusion of innovations. These issues have in the past decades received considerable attention from both geographers and economists (see, e.g., Bertuglia et al. 1995, Malecki 1992 and Stoneman 1995). Studies on the geographical diffusion of innovations have for a long time mainly considered two elementary dimensions in the spread of new technologies, viz. time and space (see Hägerstrand 1967). Similarly, the standard economic literature has regarded a diffusion process in two dimensions as a spatial spread of innovation among individuals, firms or population over time. In our paper, we extend the traditional diffusion approach by adding another crucial dimension to the diffusion of innovations; compatibility of technological components. We expect that this third dimension has non-negligible implications for the dispersion of technologies, especially in the case of interdependent network technologies.

Table 1 presents three illustrative examples of the supply of different network technologies. Technology A and B represent both a kind of base technology for which specific technologies C^1 and C^2 provide complementary technologies. Several cases may then be distinguished. First, the supplier(s) of technologies may produce both a base technology and a complementary technology and then integrate them into a single composite good (case (i)). The second possibility is the separate production of base technologies and complementary technologies. In this case, the suppliers of compatible technologies may produce either compatible complementarity technologies with both base technologies (case (ii)) or make a complementary technology compatible only with one (or some) of the base technologies (case (iii)). We will argue that these supply side compatibility and production choices are likely to have prominent implications for the adoption behaviour of economic actors and consequently, for the diffusion speed of network technologies in general.

The prevailing literature provides some theoretical insights into the timing of adoption of network technologies related to the agents' choice among substitute

Table 1. Examples of the supply of network technologies



technologies characterized by network externalities (see Choi 1994, Farrell and Saloner 1986, Koski and Nijkamp 1996)[2]. These studies however, do not pay attention to the role of complementarities and compatibility in the adoption of new network technologies. It is also noteworthy that Church and Gandal (1993) consider network externalities related to the complementary technologies, but their static model ignores interdependence between the user generations.

The current literature contains several interesting empirical studies on the adoption behaviour of economic actors in the context of network technologies. Saloner and Shepard (1995) explore the diffusion of automated teller machines (ATM) in the U.S. banking sector in 1970's. Their study focuses on the existence of network effects in the ATM market. Antonelli (1993) provides evidence on the role of externalities and complementarities in the international diffusion of computers and the demand for telecommunications services. He suggests that the high level of interrelatedness and technical complementarity between computers and telecommunications services results in positive externalities. This means that the demand for telecommunications services is positively related to the diffusion of information technologies. Antonelli's data from 30 countries supports his hypothesis. This result indicates that the diffusion of computers is related to the highly complex and interrelated diffusion processes of new network technologies and that the diffusion speed of information technology is likely to exert significant long-run effects beyond the markets for hardware and software.

Gandal (1994) shows that the users attach more value to spreadsheets compatible with the industry standard and to spreadsheets providing links to external databases. His study supports the presence of network externalities in the computer spreadsheet market and stresses the importance of compatibility of technological components to the network users. Another empirical study on the value of compatible network components is provided by Shurmer (1993). His study on the PC software market points out the heterogeneous preferences of network users and consequently, the different relative importance of network externalities of consumers. Gandal et al. (1995) examine the early microcomputer markets. They suggest that the early and late adopters of network technologies may choose different technologies due to consumer heterogeneity and uncertainty about the development of complementary technologies for incompatible substitute technologies. This theoretical proposition is further supported by their empirical exploration of microcomputer markets in the late 1970's and in the first half of the 1980's.

The above discussed studies highlight the significance of complementary components in the adoption and use of network technologies. None of these empirical investigations, however, examines how incompatibility of technological components supplied affect the total demand for these network technologies or the diffusion speed of the new technologies at an aggregate level. Our paper will focus on this issue first by a theoretical analysis and then empirically by exploring cross-national differences in the microcomputer sales in European markets. In summary, our contribution to the existing literature on compatibility and network externalities on the one hand, and to the studies on the diffusion of innovations on the other hand is threefold:

1) Our theoretical model combines both cross-sectional externalities and sequential externalities in the case of complex markets for network technologies offering both substitute and complementary technologies which may be either compatible or incompatible with one another.

2) The paper considers three dimensions – instead of the traditional two ones – of the diffusion of new technologies or innovations: compatibility of technological components, the penetration rate of a new technology, and time.

3) The paper offers empirical evidence on the implications of incompatibility for the diffusion of network technologies.

Section 2 contains a theoretical analysis of the timing of the adoption of complementary network technologies. In section 3, we will first briefly discuss the operating systems market during the past decade and then test the practical propositions – which arise from our theoretical model – on the basis of PC sales data from various European countries. Section 4 concludes the paper with a concise discussion.

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1. We do not discuss here the potential reasons for and types of the suppliers' divergent compatibility strategies. See, e.g., Economides and White (1994) for a discussion on the firms' horizontal compatibility strategies (i.e. whether to make components compatible with the rivals) and Besen and Farrell (1994) for a discussion on vertical compatibility strategies (i.e. whether to make products compatible with the rivals).

2. We may refer also to Farrell and Saloner (1985) and Katz and Shapiro (1985, 1986) for related studies on technology adoption and standardization in industries characterized by network externalities.

2. Timing of Adoption of Complementary Network Technologies

In this section we will successively discuss separable and inseparable complementary network technologies.

2.1 Complementary Technologies a User Can Buy Separately

Let us assume that the market offers two substitute technologies A and B as well as their complementary technologies C^1 and C^2. We assume that technologies C^1 and C^2 are also substitutes and that the market of technologies C^1 and C^2 exhibits a direct network externality[1] Moreover, we assume that an investment in technology A or B is required before technologies C^1 or C^2 can be utilized (e.g. a user has to buy a computer before he can use a communications programme) and that the market of technology A and B may exhibit only an indirect network externality[2]. We ignore here the effects of an installed user base, information spill-overs and scale economies, since our focus is on the intrinsic nature of network technologies and their effects on the diffusion patterns of new technologies. We distinguish here two cases: in the first case, base technologies A and B are compatible substitutes, whereas in the second case considered, technologies A and B are assumed to be incompatible substitutes.

(i) Base technologies A and B are Compatible Substitutes

We assume that the two types of technologies C^1 and C^2 are incompatible substitutes[3], and that any of them can be linked to either technology A or technology B resulting in a composite good. The possible combinations of complementary technologies are A+C^1, B+C^1, A+C^2 and B+C^2 (e.g. A and B are two compatible operating systems both compatible with two communication programmes, C^1 and C^2, which are, however, incompatible with one another). Then, the market of incompatible substitutes C^1 and C^2 exhibits a direct externality implying that an increase in the demand of technology C^1 (C^2) influences the (expected) value of technology C^1 (C^2), and thus its future demand. In addition, the market of complementary technologies A/B+C^1 and A/B+C^2 exhibits an indirect externality meaning that an increase in the demand of technology A or B is likely to increase the supply of technologies (or network services) compatible with C^1 and C^2 and will thus increase the expected value of these complementary technologies. An increase in the demand of technology A or B does not however, affect the relative shares of the users of technologies C^1 and C^2.

We consider here two time periods, t=1,2 and assume that two users arrive sequentially in the market, user 1 at the beginning of the first period and user 2 at the beginning of the second period. In the first period, user 1 can choose technology A, B, technologies A/B+C^1 or A/B+C^2 or wait until the second period. If user 1 adopts only technology A/B in the first period (waits until the second period), he will choose between C^1 and C^2 (A/B+C^1 and A/B+C^2) in the second period. Then, the expected values of technologies C^1 and C^2 are likely to increase as well, but the relative shares of the demand of technologies C^1 and C^2 remain unchanged. We assume that the users' preferences may differ across the time periods, but are identical within the period. This results in identical technology choices of users, if user 1 decides to wait until the second period.

We can denote, for simplicity, technologies A and B by one symbol – say A – due to their compatibility. Assume that the stand-alone values of technologies are non-negative and that they are known at the beginning of the periods, but uncertain in the future. We denote the stand-alone value of technologies A, C^1 and C^2 in the first period by α_1, c_1^1 and c_1^2[4] and in the second period – with the symbols ~ indicating uncertain values of the values conceived – by $\tilde{\alpha}_2$, $\tilde{c}_2^1$ and $\tilde{c}_2^2$, respectively. The external benefit from the compatible technology choice with another user – i.e. the value of network externality related to technologies C^1 and C^2 – is denoted by Δ.

The possible combinations of complementary technologies are A+C^1 and A+C^2. We denote the possible values of the technologies in period 2 by $\Omega = \left\{ \left(\tilde{\alpha}_2,\ \tilde{c}_2^1,\ \tilde{c}_2^2 \right); \left(\tilde{\alpha}_2,\ \tilde{c}_2^1,\ \tilde{c}_2^2 \right);\ \in\ R^3 \right\}$. We define the following subsets in Ω which we will utilize in our calculations below:

$$\begin{aligned} E_0 &= \Big\{ \left(\tilde{\alpha}_2,\ \tilde{c}_2^1,\ \tilde{c}_2^2 \right);\ \tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta \geq \tilde{\alpha}_2 + \tilde{c}_2^2 + \Delta \\ &\qquad\qquad \Leftrightarrow c_2^1 \geq c_2^2; \left(\tilde{\alpha}_2,\ \tilde{c}_2^1, \tilde{c}_2^2 \right) \in R^3 \Big\} \\ E_1 &= \left\{ \left(\tilde{\alpha}_2,\ \tilde{c}_2^1,\ \tilde{c}_2^2 \right);\ \tilde{c}_2^1 + \Delta \geq \tilde{c}_2^2; \left(\tilde{\alpha}_2,\ \tilde{c}_2^1, \tilde{c}_2^2 \right) \in R^3 \right\} \\ E_2 &= \left\{ \left(\tilde{\alpha}_2,\ \tilde{c}_2^1,\ \tilde{c}_2^2 \right);\ \tilde{c}_2^1 + 2\Delta \geq \tilde{c}_2^2; \left(\tilde{\alpha}_2,\ \tilde{c}_2^1, \tilde{c}_2^2 \right) \in R^3 \right\}, \end{aligned}$$

where $E_0 \subseteq E_1 \subseteq E_2$. The complement of subset E_i with respect to space Ω is denoted by E_i^c.

We use backward induction for modelling the actors' behaviour in regard to the adoption of a new network technology. The technology choices of user 2 depend on the choices of user 1 in the first period. If user 1 adopts both technology A and technology C^1 in the first period, user 2 chooses the same combination of technologies if and only if:

$$\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta \geq \tilde{\alpha}_2 + \tilde{c}_2^2 \Leftrightarrow \tilde{c}_2^1 + \Delta \geq \tilde{c}_2^2. \quad (1)$$

Otherwise, he will choose technologies A and C^2. If user 1, instead, decides to wait until the second period or adopts just the base technology A – which does not exhibit direct network externalities – both users will choose technologies A and C^1 if and only if:

$$\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta \geq \tilde{\alpha}_2 + \tilde{c}_2^2 + \Delta \Leftrightarrow \tilde{c}_2^1 \geq \tilde{c}_2^2. \quad (2)$$

Now the expected private and social value of adoption of technology A by user 1 in the first period ($V(A)_1$ and $S(A)_1$), the expected private and social value of adopting technology A+C^1 in the first period (V(A+C^1)$_1$ and S(A+C^1)$_1$) and the expected private and social value of waiting until the second period (V(W)$_1$ and S(W)$_1$) can be written as follows[5]:

$$V(A)_1 = \alpha_1 + \delta\left[\int_{E_0}(\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta)dG(\tilde{\alpha}_2, \tilde{c}_2^1, \tilde{c}_2^2) + \int_{E_0^c}(\tilde{\alpha}_2 + \tilde{c}_2^2 + \Delta)dG(\tilde{\alpha}_2, \tilde{c}_2^1, \tilde{c}_2^2)\right] \qquad (3)$$

$$S(A)_1 = \alpha_1 + \delta\left[\int_{E_0}2(\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta)dG(\tilde{\alpha}_2, \tilde{c}_2^1, \tilde{c}_2^2) + \int_{E_0^c}2(\tilde{\alpha}_2 + \tilde{c}_2^2 + \Delta)dG(\tilde{\alpha}_2, \tilde{c}_2^1, \tilde{c}_2^2)\right] \qquad (4)$$

$$V(A + C^1)_1 = \alpha_1 + c_1^1 + \delta\left[\int_{E_1}(\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta)dG(\tilde{\alpha}_2, \tilde{c}_2^1, \tilde{c}_2^2) + \int_{E_1^c}(\tilde{\alpha}_2 + \tilde{c}_2^1)dG(\tilde{\alpha}_2, \tilde{c}_2^1, \tilde{c}_2^2)\right] \qquad (5)$$

$$S(A + C^1)_1 = \alpha_1 + c_1^1 + \delta\left[\int_{E_2}2(\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta)dG(\tilde{\alpha}_2, \tilde{c}_2^1, \tilde{c}_2^2) + \int_{E_2^c}(2\tilde{\alpha}_2 + \tilde{c}_2^1 + \tilde{c}_2^2)dG(\tilde{\alpha}_2, \tilde{c}_2^1, \tilde{c}_2^2)\right] \qquad (6)$$

$$V(W)_1 = \delta\left[\int_{E_0}(\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta)dG(\tilde{\alpha}_2, \tilde{c}_2^1, \tilde{c}_2^2) + \int_{E_0^c}(\tilde{\alpha}_2 + \tilde{c}_2^2 + \Delta)dG(\tilde{\alpha}_2, \tilde{c}_2^1, \tilde{c}_2^2)\right] \qquad (7)$$

$$S(W)_1 = \delta\left[\int_{E_0}2(\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta)dG(\tilde{\alpha}_2, \tilde{c}_2^1, \tilde{c}_2^2) + \int_{E_0^c}2(\tilde{\alpha}_2 + \tilde{c}_2^2 + \Delta)dG(\tilde{\alpha}_2, \tilde{c}_2^1, \tilde{c}_2^2)\right] \qquad (8)$$

In the above equations, $G(\tilde{\alpha}_1, \tilde{c}_2^1, \tilde{c}_2^2)$ denotes a joint probability distribution of the value of technologies – which will be written shortly as G(·) from now on – and δ is the discount factor. We may also derive the corresponding equations for the adoption decision regarding A+C^2, but since this technology combination is symmetric with A+C^1, it is sufficient to consider only one of these technology combinations. In period 1, a private agent will choose max [V(A)$_1$, V(A+C^1)$_1$, V(A+C^2)$_1$, V(W)$_1$], whereas a social planner will choose max [S(A)$_1$, S(A+C^1)$_1$, S(A+C^2)$_1$, S(W)$_1$].

Next, we compare the private and social incentives to wait until the second period. We can see straigthforward that if $\alpha_1 \geq 0$, then $V(A)_1 \geq V(W)_1$, and thus user 1 prefers the adoption of technology A to waiting. The timing of the adoption of technology A is also optimal from the society point of view, as it can be easily calculated that $[S(W)_1\text{-}V(W)_1]\text{-}[S(A)_1\text{-}V(A)_1]=0$.[6] It can be also easily calculated – since $c_1^1 \geq 0$ by definition – that $S(A+C^1)_1 \geq S(A)_1$ and $V(A+C^1)_1 \geq V(A)_1$. This means that both the social planner and the private agent prefer the adoption of a base technology plus a complementary technology in the first period. We may thus conclude that, in order to compare private and social incentives to wait, it is sufficient to calculate the difference between $[S(W)_1\text{-}S(A+C^1)_1]$ and $[V(W)_1\text{-}V(A+C^1)_1]$. Note that $\left[E_1 - E_0\right] = \left[E_0^c - E_1^c\right]$ and $\left[E_2 - E_1\right] = \left[E_1^c - E_2^c\right]$.
Then, $[S(W)_1\text{-}V(W)_1]\text{-}[S(A+C^1)_1\text{-}V(A+C^1)_1]$:

$$= \delta \int_{E_1-E_0} (\tilde{c}_2^2 - \tilde{c}_2^1) dG(\cdot) + \int_{E_2-E_1} (\tilde{c}_2^2 - \tilde{c}_2^1 - \Delta) dG(\cdot) + \int_{E_2^c} (\Delta) dG(\cdot)] \geq 0. \tag{9}$$

(See for more detailed calculations in Annex 1)

The sign of equation (9) is unambiguously positive due to the definitions of $\left[E_1 - E_0\right]$, $\left[E_2 - E_1\right]$ and E_2^c. This implies an inefficiently fast adoption of a complementary technology, but it should be kept in mind that the analysis ignores several factors characteristic to network technologies – like information spill-overs – which are likely to influence on the optimal timing of the adoption of technologies (see Koski and Nijkamp 1996). Our aim here however is not to focus on the question whether the diffusion of new network technologies is likely to be too slow or fast from the society's point of view. Our calculations point out that the divergence between private and social incentives to wait – i.e. the optimal timing of adoption of network technologies – depends merely on the value of and network externalities related to the components which exhibit direct network externalities. The stand-alone values of complementary technologies C^1 and C^2 – not the stand-alone values of base technologies A and B – and network externalities related to these complementary technologies affect the optimal timing of the adoption of the technologies.[7] We could derive analogous results in respect to technology C^2 and taking into account technology B which is compatible with technology A.

(ii) Base Technologies A and B are Incompatible Substitutes

In this second case, we assume that complementary technologies C^1 and C^2 are also incompatible substitutes, but now they are only compatible with specific base technologies such that technology C^1 can only be linked with technology A, whereas technology C^2 can form a composite good only with technology B (e.g. A and B are two incompatible operating systems which are compatible with incompatible communication programmes, C^1 and C^2, respectively). This means that in the first period, user 1 is able to choose technology A, B, technologies A+C^1 or B+C^2 or to wait until the second period. We can show that even if technologies A and B do not exhibit direct network externalities, the private and social incentives to postpone the adoption decision of complementary technologies depends on the values of relevant factors (e.g. information spill-overs) related to all components A, B, C^1 and C^2 due to the incompatibility of technologies A and B.

Again, the market of technologies C^1 and C^2 exhibits a direct externality and the market of complementary technologies A+C^1 and B+C^2 exhibits an indirect externality meaning that an increase in the demand of technologies A (B) is likely to increase – due to an increase in the supply and the demand of compatible technologies – the expected value of technology C^1 (C^2). As technology A is incompatible with technology B, the diffusion of complementary technologies C^1 and C^2 is closely related to the diffusion of technologies A and B. Now, it does make a difference whether the early users adopt technology A or technology B and their decisions are also likely to affect the relative shares of the users of technologies C^1 and C^2.

We define the following subsets in Ω:

$$E_0 = \left\{(\tilde{\alpha}_2, \tilde{\beta}_2, \tilde{c}_2^1, \tilde{c}_2^2); \tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta \geq \tilde{\beta}_2 + \tilde{c}_2^2 + \Delta;\ (\tilde{\alpha}_2, \tilde{\beta}_2, \tilde{c}_2^1, \tilde{c}_2^2) \in R^4\right\}$$

$$E_1 = \left\{(\tilde{\alpha}_2, \tilde{\beta}_2, \tilde{c}_2^1, \tilde{c}_2^2); \tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta \geq \tilde{\beta}_2 + \tilde{c}_2^2;\ (\tilde{\alpha}_2, \tilde{\beta}_2, \tilde{c}_2^1, \tilde{c}_2^2) \in R^4\right\}$$

$$E_2 = \left\{(\tilde{\alpha}_2, \tilde{\beta}_2, \tilde{c}_2^1, \tilde{c}_2^2); \tilde{\alpha}_2 + \tilde{c}_2^1 + 2\Delta \geq \tilde{\beta}_2 + \tilde{c}_2^2;\ (\tilde{\alpha}_2, \tilde{\beta}_2, \tilde{c}_2^1, \tilde{c}_2^2) \in R^4\right\}$$

Consider first the adoption decision regarding combination A+C^1. Now, the respective expected private and social values of adopting technology(/ies) in the first period and the expected private and social values of waiting are:

$$V(A)_1 = \alpha_1 + \delta[\int_{E_1} (\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta) dG(\cdot) + \int_{E_1^c} (\tilde{\alpha}_2 + \tilde{c}_2^1) dG(\cdot)]$$

$$S(A)_1 = \alpha_1 + \delta[\int_{E_2} 2(\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta) dG(\cdot) + \int_{E_2^c} (\tilde{\alpha}_2 + \tilde{\beta}_2 + \tilde{c}_2^1 + \tilde{c}_2^2) dG(\cdot)]$$

$$V(A + C^1)_1 = \alpha_1 + c_1^1 + \delta[\int_{E_1} (\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta) dG(\cdot) + \int_{E_1^c} (\tilde{\alpha}_2 + \tilde{c}_2^1) dG(\cdot)]$$

$$S(A + C^1)_1 =$$

$$\alpha_1 + c_1^1 + \delta[\int_{E_2} 2(\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta) dG(\cdot) + \int_{E_2^c} (\tilde{\alpha}_2 + \tilde{\beta}_2 + \tilde{c}_2^1 + \tilde{c}_2^2) dG(\cdot)]$$

$$V(W)_1 = \delta[\int_{E_0} (\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta) dG(\cdot) + \int_{E_0^c} (\tilde{\beta}_2 + \tilde{c}_2^2 + \Delta) dG(\cdot)]$$

$$S(W)_1 = \delta[\int_{E_0} 2(\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta) dG(\cdot) + \int_{E_0^c} 2(\tilde{\beta}_2 + \tilde{c}_2^2 + \Delta) dG(\cdot)],$$

where $dG(\tilde{\alpha}_2, \tilde{\beta}_2, \tilde{c}_2^1, \tilde{c}_2^2) = dG(\cdot)$. Next, we compare the private and social incentives to wait. As $[S(A+C^1)_1 - S(A)_1] = [V(A+C^1)_1 - V(A)_1] = c_1^1$, it follows straightforward that $S(A+C^1)_1 \geq S(A)_1$ and $V(A+C^1)_1 \geq V(A)_1$. Thus, as above, it is sufficient to calculate merely the difference between $[S(W)_1 - S(A+C^1)_1]$ and $[V(W)_1 - V(A+C^1)_1]$ (see Annex 1 for more detailed calculations):

$$\begin{aligned}&\delta^{-1}\ [S(W) - V(W)] - [S(A+C^1) - V(A+C^1)] = \\ &\int_{E_2-E_1} (\tilde{\beta}_2 - \tilde{\alpha}_2 + \tilde{c}_2^2 - \tilde{c}_2^1 - \Delta)dG(\cdot) + \\ &\int_{E_0} (\tilde{\alpha}_2 + \tilde{c}_2^1 - \tilde{\beta}_2 - \tilde{c}_2^2)dG(\cdot) + \int_{E_1} (\tilde{\beta}_2 + \tilde{c}_2^2)dG(\cdot) + \int_{E_2^c} (\Delta)dG(\cdot)\end{aligned} \quad .(10)$$

Now, the divergence between private and social incentives to wait depends on the values of all components A, B, C^1 and C^2. Also, other relevant factors characteristic to the network technologies – e.g. an installed base of users of any component, scale economies or information spill-overs related to them – affect the optimal timing of the adoption of the complementary technologies irrespective of whether a component exhibits direct or indirect network externalities. Similar conclusions may be found – due to the symmetry of technologies –, if we compare S(W)-V(W) to $S(B+C^2)$-$V(B+C^2)$.

These results indicate that the compatibility strategies of the suppliers of network technologies may also influence the optimal timing of the adoption of the technologies which do not exhibit direct network externalities. These components – even though they do exhibit indirect network externalities – may be adopted at the optimal time from a social point of view as long as they are compatible with their substitutes. However, if these technologies are incompatible, their adoption may occur too early or too late from the society's point of view.

2.2 Complementary Technologies Forming an Inseparable Composite Good

Consider next the case of complementary technologies which a user cannot buy separately, since the technologies are included as components in a single composite good. Assume that the market offers two incompatible substitutes, AC^1 and BC^2, characterized by direct network externalities. Technology AC^1 (BC^2) is composed of two inseparable components A and C^1 (B and C^2). We assume that technologies A and B are a kind of base technologies, whereas technologies C^1 and C^2 represent accessories increasing the value of a composite good (e.g. car and safety airbag).

The mathematical models for the timing of the adoption of technologies AC^1 and BC^2 are identical to the ones presented in earlier studies (see Choi 1994 and Koski and Nijkamp 1996), apart from the fact that here – instead of two independent

3. Empirical Evidence from the European PC Market

3.1 Practical Suggestions of the Theory

Our theoretical examination above provides the following practical suggestions for applied work:

1) The (expected) total value of technological components determine the diffusion of network technologies which form a composite good.
2) If complementary technologies are compatible with all technologies supplied on the market, then the adoption of components which do not exhibit network externalities may take place at the optimal time irrespective of uncertainty related to the relative qualities or stand-alone values of their complementary technologies.
3) If complementary technologies are incompatible, the diffusion of all components is affected by the expected diffusion of all other components and their (expected) stand-alone values. Thus, the adoption of technologies which do not exhibit any direct network externalities may take place at the non-optimal time as well.

All of these proposition are however, not directly testable with the databases we have access to. Our data on the microcomputer market provides information on the diffusion of a network technology which does not exhibit (direct) network externalities itself, viz. operating systems. Due to (in)compatibility choices of the producers of operating systems, the market offered mainly two operating system types (in the period of 1985-1994) which were able to run only their own software programs that were incompatible with the programmes run by another operating system. We assume that there exists positive network externalities related to the use of compatible software programs (e.g. via the change of files or information). We do not have direct information on the expectations of economic actors regarding the intrinsic values of different operating systems or their expectations on the value and availability of software programs. However, we have the sales information regarding incompatible operating systems. This data allows a kind of partial empirical analysis of our theory; we are able to test some of the propositions our theoretical examination have pointed out.

We assume that the more heterogeneous the technology choices of actors in an economy are, the more uncertainty the subsequent potential technology adopters face. Since an increase in uncertainty is reflected as a decrease in expected utility, enhanced uncertainty means that the expected value of waiting exceeds the value of adopting the technology in the majority of cases and consequently, more people are likely to postpone their adoption decision. Based on this reasoning, we will test the following hypotheses: (i) the diffusion speed of computers among countries varies with the degree of compatibility of microcomputers sold, and (ii) the higher (lower) the degree of compatibility of microcomputers sold, the higher (lower) the diffusion speed of microcomputers in general. Before we present the results of our empirical examination, we will in the next section shortly discuss the recent history of the microcomputer markets and the data we have used in the empirical estimations.

3.2 The PC Market from the 1980's to 1994

Our empirical exploration considers the microcomputer market from the 1980's to 1994. Several suppliers competed in the operating systems market until 1985. The dominating systems in the computer market at the early 80's were Apple, MS-DOS and CP/M.[1] The early PC users were mostly technically sophisticated hobbyists. In 1984, Apple launched its revolutionary Apple MacIntosh computers. At the same time CP/M continuously lost its market share to MS-DOS and eventually, the CP/M computers were supplanted by 1985. The study of Gandal et al. (1995) indicates that this outcome – the success of MS-DOS compared to CP/M – emerged as a result of the availability of complementary software: the market offered a larger number of MS-DOS compatible software than CP/M compatible software to the computer users. Two operating systems dominated the markets for operating systems from 1985 to 1994: MS-DOS and Apple. New computers were more user friendly and consequently, the diffusion of PCs from expert use to the more general purpose use intensified. It is argued that Apple held technical leadership in personal computer technology for most of the ten years' period 1984-1994[2]. However, it adopted a business strategy which appeared to be unsuccessful and which have been accused to be a main reason for the Apple's relatively small market share in the world PC market: Apple chose to produce machines with closed architecture. This decision meant that the computers with MS-DOS operating system were not able to run the software programs developed for the Apple machines and vice versa. Thus, a consumer buying either an Apple computer or a MS-DOS computer faced the risk of an uncertain supply of compatible software programs in the future. The expected future supply of software was likely to be determined by the relative success and the diffusion of these operating systems. The theory we presented in section 2 indicates that the diffusion of network technologies is likely to be influenced by the incompatibility of technological components – even if they do not exhibit direct network externalities –, when technologies make up a composite good with the complementary components exhibiting direct network externalities. In the spatial context, this means that it is possible – when the markets offer incompatible network technologies – that the speed of diffusion of new technologies in a certain region or country depends on how homogeneous or compatible the technologies chosen by the adopters are. A wider variety of incompatible network technologies may result in a slower diffusion of a network technology in general.

The PC adopters between 1985 and 1994 were "locked-in" to their operating systems' choice in the sense that they were not able to use compatible software programmes and, for instance, to share files with other PC users having different operating system in their computers.[3] We argue that this incompatibility of the operating systems engendered further uncertainty in the PC market and influenced the adoption behaviour of economic agents. In particular, we may expect that the higher the incompatibility of the adopted PCs, the slower the diffusion of computers in general. Better availability of software is often pointed out as an explanation for the success of MS-DOS compared to the Apple. Our aim here however, is not to analyse the reasons for the relative success of divergent network technologies, but to focus on the implications of incompatibility to the diffusion speed of new technologies in the aggregate level. We test our hypothesis on the negative relationship between technological incompatibility and the diffusion speed of new technologies by the PC sales data from various European countries.

The microelectronics industry has experienced drastic technological progress during the last decade. Simultaneously with a continuous decline in computer prices, the markets have constantly introduced better and more efficient microcomputer models. Due to this fast stage of development we are not able to measure directly the diffusion speed of PCs in the relevant countries; we do not have information on the number of new users of computers and the number of disposed machines and consequently, we do not have exact information on the size of an installed base of computers. We will use, instead, the change in the PC sales – or PC sales growth – as a proxy for the change in the penetration rate of microcomputers in an economy.

Our PC sales data is based on the IDC (International Data Corporation) microcomputer sales statistics and covers the period 1985-1994. The countries considered are Finland, Netherlands, Germany, France, United Kingdom, Spain, Sweden and Italy. The database comprises the annual number of Apple computers sold and the annual number of microcomputers sold in total in each country.[4] Since the MS-DOS operating system and its compatible clones have covered – when the market

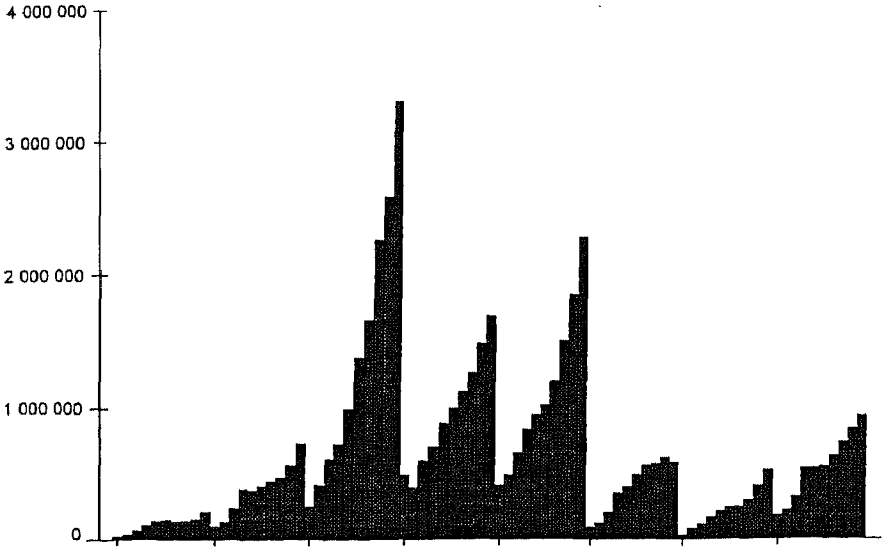

Figure 1. The number of PCs sold (1985-1994).
Note: the data do not include the sales of 8-bit computers. Source: IDC, 1996.

share of Apple is excluded – almost the rest of the market we suppose that the difference between the total number of computers sold and the number of Apples sold provides a satisfactory proxy for the compatible computer base.

Figure 1 and 2 reflect a general trend in the microcomputer market over the period of 1985-1994: the annual number of computers sold has constantly increased during the period. Figure 1 describes the number of computers sold per year in the sampled countries. In 1985, less than 2 million PCs were sold in total, whereas the corresponding number in 1994 was over 10 million. This means that – on the aggregate – the annual computer sales has increased five-fold in a decade. Figure 1 shows the differences in the volume of computer sales among the countries. The volume of computer sales is however, a rather poor measure for the diffusion of microcomputers in a cross-national comparison. The country sizes vary a lot and the sales volume do not supply any information on the penetration rate of information technology in the economies. In order to be able to compare the relative PC sales of the countries concerned, we divided the number of PCs sold by population[5]. From figure 2 we can see that the divergencies in the computer sales relative to population are less dramatic than the differences in the volume of PCs sold in the sample countries.

We will use here the (logarithmic) difference in the number of PCs sold in relation to the population ("DPC") as a dependent variable for two reasons. First, the series of PC sales per population appeared to be a difference-stationary process, which

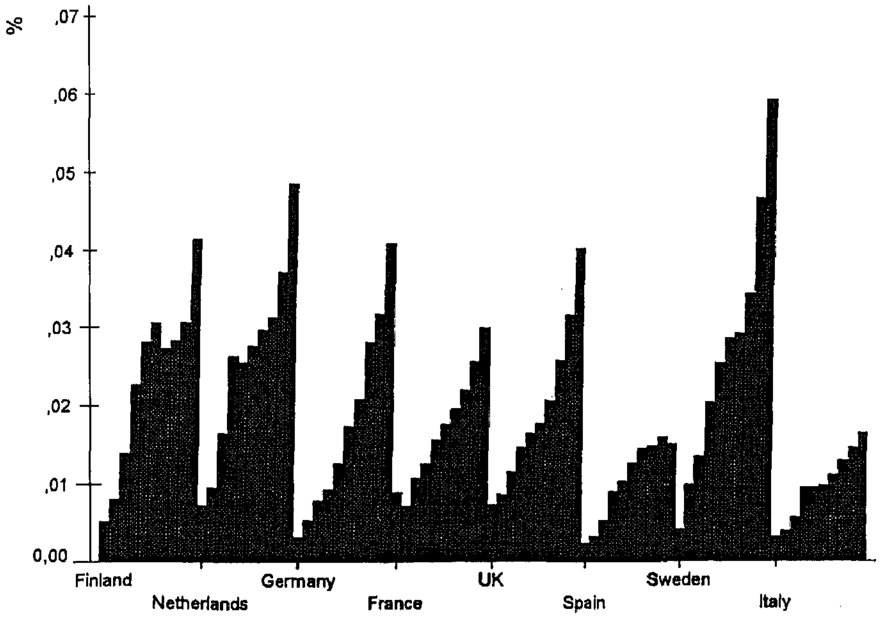

Figure 2. The number of PCs sold per population (1985-1994).
Note: the data do not include the sales of 8-bit computers. Source: IDC, 1996.

implies that the best method for eliminating the trend is differentiation. We used the Dickey-Fuller test for testing whether the time series is trend-stationary or difference-stationary.[6] In other words, we tested the hypothesis H_0: $\rho=1$ and $\beta=0$ in the following equation:

$$PC_t = \alpha + \rho\, PC_{t-1} + \beta t + \varepsilon_t,$$

where $PC_t(PC_{t-1})$ describes the PC sales per population at time t (t-1). On the basis of our estimation results, we calculated the following t-test value: $t = (\hat{p}-1)/SE(\hat{p}) \approx -2.02$. This value indicates, when it is compared to the corresponding critical t-value, that hypothesis H_0 cannot be rejected; the series is clearly difference-stationary. Another reason for using differentiated sales data arose from the interpretation of the first difference as a measure of change (or speed). This transformation corresponds to our intention to explore cross-national divergencies in the microcomputer sales growth.

We measure the compatibility of PCs sold by the (log) total number of computers sold per year divided by the number of Apples sold per year. Consequently, a higher value of the variable indicates higher compatibility. Figure 3 suggests an increase in compatibility over time in all countries. The Apple sales data from 1985 to 1987 were available only from Finland and Sweden. We used the first difference of compatibility (COMP1) and the second difference of compatibility (COMP2) as explanatory

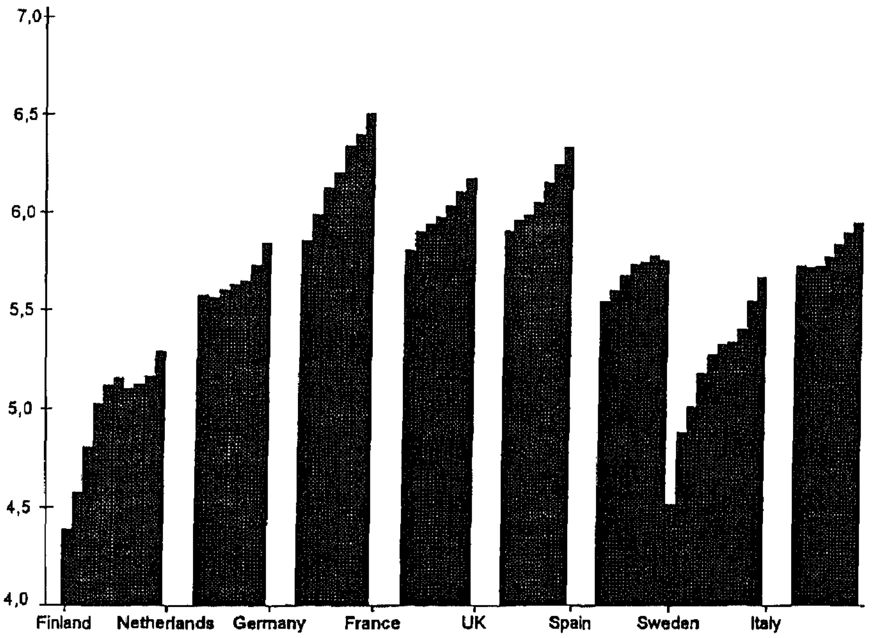

Figure 3. Compatibility of PCs sold (1985-1994).
Note: the data do not include the sales of 8-bit computers. Source: IDC, 1996.

variables. In addition to the microcomputer sales data, we also used the following potentially relevant variables affecting the diffusion of PCs as explanatory variables:

- PRICE = (log) price index for the office machinery and computers in Finland, 1985-1994 (Statistics Finland). We suppose that the computer prices are negatively related to the demand for microcomputers. We apply the index describing the development of computer prices in Finland for the rest of the countries, as this is in our opinion a rather good proxy for the world wide change in computer prices during the year 1985-1994, so that we may then be able to capture the dynamic relationship of demand for the computers and the PC prices.

It also seems plausible that the demand for microcomputers is positively related to the income level. As the demand for computers is composed of two components – the final demand of the household and the derived demand of the enterprises – we use the following three measures of income to explore this relationship:

- GDP = gross domestic product at market prices in purchasing power parities.[7] Gross domestic product converted in purchasing power standards eliminates the effect of cross-national differences in the price leves and enables a comparison of the volume of goods and services produced and used in different countries. This measure does not separate the demand of the households and firms. Earlier evidence is provided by Antonelli (1993) whose empirical exploration points out a positive relationship between GDP and intensivity of sales of telecommunications services.
- EINC = external balance of property and entrepreneurial income in current prices (% of GNP).[8] This measure of net operating surplus comprises total property and entrepreneurial income from production. It is used for exploring the relationship between the demand for computers and entrepreneurial income.
- W = (log) compensation of employees at current prices and purchasing power parities.[9] This measure provides a measure of the households' income. For example, the study of Antonelli (1989) on the regional diffusion of telefaxes and modems indicates that the wage level of the labour force is positively related to the diffusion of information technology.

3.3 Econometric Results

We assumed that heteroskedasticity between the observation groups might be possible in our panel data set of eight countries during the ten years period. However, the Lagrange multiplier test rejected this hypothesis; it favoured the ordinary least squares model to the random effect model in all cases (see results in table 1).[10] It seemed intuitively plausible that three different income indicators may be highly correlated and correspondingly, their estimation in the same model may cause the problem of near collinearity with the unreliable estimates. To explore the relationship between income variables, we calculated the Pearson correlation coefficients. The correlation coefficient between EINC and GDP and EINC and W was over 0.60, and between W and GDP as high as 0.94 indicating near collinearity. Thus, we estimated the income variables separately in the following three models:

$DPC = \alpha_i + \beta_1 DCOMP + \beta_2 D2COMP + \beta_3 PRICE + \beta_4 EINC$ (Model 1),
$DPC = \alpha_i + \beta_1 DCOMP + \beta_2 D2COMP + \beta_3 PRICE + \beta_4 W$ (Model 2),
$DPC = \alpha_i + \beta_1 DCOMP + \beta_2 D2COMP + \beta_3 PRICE + \beta_4 GDP$ (Model 3).

We will further test the specification of our empirical models by model 4 which excludes all income variables: $DPC = \alpha_i + \beta_1 DCOMP + \beta_2 D2COMP + \beta_3 PRICE$ (Model 4).

Table 2 presents the estimation results of the models. All models support our hypothesis on the positive relationship between the microcomputer sales growth and compatibility of PCs sold. The first difference of the variable reflecting the degree of compatibility is highly significant, whereas as the second difference of the variable

Table 2. The OLS estimates of the models for the PC sales

Variables	Model 1	Model 2	Model 3	Model 4
constant	20.212	22.429	22.493	27.557
	(2.235)	(2.356)	(2.458)	(3.908)
comp1	4.2610	4.2362	4.2453	4.6922
	(3.165)	(3.169)	(3.207)	(3.894)
comp2	0.72728	0.71811	0.71350	0.79589
	(1.051)	(1.047)	(1.051)	(1.274)
price	-4.4398	-4.8466	-4.8950	-6.0592
	(-2.222)	(-2.341)	(-2.433)	(-3.883)
inc	-0.014726			
	(-0.281)			
w		-0.064032		
		(-0.732)		
gdp			-0.092643	
			(-1.094)	
Nobs	38	38	38	44
R^2	0.66	0.67	0.67	0.72
LM-test	2.18*)	1.84*)	1.66*)	5.09**)
LR-test41.17	41.69	42.43	57.99	

Note: t-value in the brackets
*) Favours OLS to random effect model by p-value >0.10.
**) Favours OLS to random effect model by p-value >0.01.

appears to be statistically insignificant. The higher significance of the first difference indicates that the adoption behaviour of economic actors in the microcomputer market is more affected by the short-run dynamics or quite recent PC purchasing decisions of other actors than the technology choices made in the past (even two years before). This finding is probably related to the rapid progress in the microelectronics industry, which is reflected as continuously changing information of the microcomputer market the economic actors' use in their adoption decisions.

The price of microcomputers, as expected, is negatively and statistically significantly related to the demand for microcomputers in all models. High coefficients of the estimates of the price variable indicate that the demand for computers is highly price-elastic. However, we should keep in mind that the price variable used describes the change in microcomputer prices in one of the sample countries and may only roughly approximate the real price changes in the other countries. The estimates of all income variables (inc, w, gdp) appear to be statistically insignificant. Even if all models succeed fairly well in explaining the phenomenon both measured by LR-test values and by R^2, it seems that model 4 – which excludes all income variables – provides a better fit than any of the models from 1 to 3. These results indicate that our aggregate income variables are not able to explain cross-national differences in the microcomputer sales among the sample countries.

Our estimation results suggest that the diffusion speed of microcomputers vary with the compatibility of microcomputers sold. Moreover, it seems that incompatibility of technological components is negatively related to the diffusion speed of network technologies in general. When the market offer incompatible microcomputers, the total demand for computers is likely to be hindered. This may happen due to uncertainty related to the technology choices of later user generations and uncertain developments of compatible software programmes. The PC prices play also a remarkable role in the diffusion of microcomputers. The relationships between income variables and the PC sales – at least in the aggregate level – are less apparent. The microlevel data on the economic actors' investment behaviour in information technology systems might provide more accurate information in this respect and may be able to better separate some income groups.

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1. See Gandal et al. (1995) for a discussion on the early operating systems market.
2. The Economist, December 10th 1994, p. 23.
3. In September 1994, Apple announced that it is willing to license its operating system.
4. The data do not include the sales of 8-bit computers.
5. Source: Eurostat Yearbook 1995.
6. If a series is trend-stationary, the trend may be eliminated by regressing the series – in addition to other explanatory variables – by time. In case of difference-stationary series, the usual least square theory is not valid; differentiation is necessary for eliminating the trend and for obtaining efficient estimates.

4. Conclusions

Our analysis suggests that inefficiencies may emerge in the timing of the adoption of network technologies which do not exhibit (direct) network externalities. The supply of incompatible complementary technologies to the technologies characterized by direct network externalities, may give rise to non-optimal diffusion patterns of network technologies. As long as complementary network technologies are compatible, the diffusion of components which do not exhibit direct network externalities may be optimal from the society's point of view.

Empirical evidence from the European microcomputer market supports our hypothesis that the diffusion speed of computers among countries vary with the degree of compatibility of microcomputers sold. Also, the data suggest that the higher (lower) the degree of compatibility of microcomputers sold, the higher (lower) the diffusion speed of microcomputers in general. This empirical finding indicates that the incompatibility of technological components may have substantial implications for the spread of network technologies in general. Consequently, the issue of compatibility deserves specific attention in the practical technology and network policy decisions.

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7. Source: Eurostat Yearbook '95.

8. Source: Eurostat Yearbook '95.

9. Source: Eurostat 2 C. National Accounts ESA 1970-1993. Compensation of employees includes all payments in cash and kind by employers in remuneration for the work done by their employees during the relevant period (Eurostat Yearbook '95).

10. A Lagrange multiplier test is based on the OLS residuals. The hypothesis tested is: H_0: $\sigma_u^2 = 0,\ H_1 : \sigma_u^2 \neq 0$ and the LM test statistic is of the form:

$$LM = \frac{nT}{2(T-1)} \left[\frac{\sum_i \left(\sum_t e_{it} \right)^2}{\sum_i \sum_t e_{it}^2} \right]^2 .$$ (Greene 1993)

Annex 1

(i) Base technologies A and B are compatible substitutes

$$
\begin{aligned}
&[S(W)_1 - V(W)_1] - [S(A + C^1)_1 - V(A + C^1)_1] \\
&= \delta[\int_{E_0} (\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta)dG(\cdot) + \int_{E_0^c} (\tilde{\alpha}_2 + \tilde{c}_2^2 + \Delta)dG(\cdot) \\
&+ \int_{E_1^c} (\tilde{\alpha}_2 + \tilde{c}_2^2 + \Delta)dG(\cdot)] + c_1^1 \\
&= \delta \cdot \Delta + \delta[\int_{E_0} (\tilde{\alpha}_2 + \tilde{c}_2^1)dG(\cdot) + \int_{E_1 - E_0} (\tilde{\alpha}_2 + \tilde{c}_2^2)dG(\cdot) \\
&+ \int_{E_1^c} (\tilde{\alpha}_2 + \tilde{c}_2^2)dG(\cdot) - \int_{E_2 - E_1} (\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta)dG(\cdot) \\
&- \int_{E_2} (\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta)dG(\cdot) + \int_{E_2 - E_1} (2\tilde{\alpha}_2 + \tilde{c}_2^1 + \tilde{c}_2^2)dG(\cdot) \\
&+ \int_{E_1^c} (2\tilde{\alpha}_2 + \tilde{c}_2^1 + \tilde{c}_2^2)dG(\cdot) + \int_{E_1} (\tilde{\alpha}_2 + \tilde{c}_2^1 + \Delta)dG(\cdot) \\
&- \int_{E_1 - E_0} (\tilde{\alpha}_2 + \tilde{c}_2^1)dG(\cdot) + \int_{E_0^c} (\tilde{\alpha}_2 + \tilde{c}_2^1)dG(\cdot)] \\
&= \delta[\int_{E_1 - E_0} (\tilde{c}_2^2 - \tilde{c}_2^1)dG(\cdot) + \int_{E_2 - E_1} (\tilde{c}_2^2 - \tilde{c}_2^1 - \Delta)dG(\cdot) \\
&+ \int_{E_1^c} (\Delta)dG(\cdot)] + c_1^1 \geq 0.
\end{aligned}
$$

where $dG(\cdot) = dG(\tilde{\alpha}, \tilde{c}_2^1, \tilde{c}_2^2)$.

(ii) Base technologies A and B are incompatible substitutes

$$
\begin{aligned}
&\delta^{-1}[S(W)-V(W)]-[S(A+C^1)-V(A+C^1)]\\
&= \delta\cdot\Delta+\delta[\int\limits_{E_0}(\tilde{\alpha}_2+\tilde{c}_2^1)dG(\cdot)+\int\limits_{E_1-E_0}(\tilde{\beta}_2+\tilde{c}_2^2)dG(\cdot)+\int\limits_{E_1^c}(\tilde{\beta}_2+\tilde{c}_2^2)dG(\cdot)\\
&- \int\limits_{E_2-E_1}(\tilde{\alpha}_2+\tilde{c}_2^1+\Delta)dG(\cdot)-\int\limits_{E_2}(\tilde{\alpha}_2+\tilde{c}_2^1+\Delta)dG(\cdot)\\
&+ \int\limits_{E_2-E_1}(\tilde{\alpha}_2+\tilde{c}_2^1+\tilde{\beta}_2+\tilde{c}_2^2)dG(\cdot)+\int\limits_{E_1^c}(\tilde{\alpha}_2+\tilde{c}_2^1+\tilde{\beta}_2+\tilde{c}_2^2)dG(\cdot)\\
&+\int\limits_{E_1}(\tilde{\alpha}_2+\tilde{c}_2^1+\Delta)dG(\cdot)-\int\limits_{E_1-E_0}(\tilde{\alpha}_2+\tilde{c}_2^1)dG(\cdot)+\int\limits_{E_0^c}(\tilde{\alpha}_2+\tilde{c}_2^1)dG(\cdot)]\\
&\int\limits_{E_2-E_1}(\tilde{\beta}_2+\tilde{\alpha}_2+\tilde{c}_2^2-\tilde{c}_2^1-\Delta)dG(\cdot)+\int\limits_{E_0}(\tilde{\alpha}_2+\tilde{c}_2^1-\tilde{\beta}_2-\tilde{c}_2^2)dG(\cdot)\\
&+\int\limits_{E_1}(\tilde{\beta}_2+\tilde{c}_2^2)dG(\cdot)+\int\limits_{E_2^c}(\Delta)dG(\cdot).
\end{aligned}
$$

References

Antonelli, C. (1990). Induced adoption and externalities in the regional diffusion of information technology. *Regional Studies* 24, 31-40.

Antonelli, C. (1993). Externalities and complementarities in telecommunication dynamics. *International Journal of Industrial Organization* 11, 437-447.

Bertuglia, C.S., Fischer, M.M. and Preto, G. (Eds.) (1995). *Technological Change, Economic Development and Space.* Springer-Verlag.

Besen, S.M. and Farrell, J. (1994). Choosing how to compete: Strategies and tactics in standardization. *Journal of Economic Perspectives* 8, 117-131.

Capello, R. (1994). *Spatial Economic Analysis of Telecommunications Network Externalities.* Avebury, Aldershot.

Choi, J.P. (1994). Irreversible choice of uncertain technologies with network externalities. *Rand Journal of Economics* 1994, 25, 382-400.

Church, J. and Gandal, N. (1993). Complementary network externalities and technological adoption. *International Journal of Industrial Organization* 11, 239-260.

Economides, N. and White, L.J. (1994). One-way networks, two-way networks, compatibility, and public policy. Discussion papers EC-. Stern School of Business.

Farrell, J. and Saloner, G. (1985). Standardisation, compatibility and innovation. *Rand Journal of Economics,* 16, 70-83.

Farrell, J. and Saloner, G. (1986). Installed base and compatibility: Innovation, product preannouncements, and predation. *American Economic Review* 76, 940-955.

Gandal, N. (1994). Hedonic price indexes for spreadsheets and an empirical test for network externalities. *Rand Journal of Economics* 25, 160-170.

Gandal, N., Greenstein, S. and Salant, D. (1995). Adoptions and orphans in the early microcomputer market. Working Paper No. 2-95, Tel-Aviv University, Israel.

Greene, W.H. (1993). *Econometric Analysis.* Macmillan Publishing Company.

Hägerstrand, T. (1967). *Innovation diffusion as a spatial process.* University of Chicago Press.

Katz, M. and Shapiro, C. (1985). Network Externalities, competition and compatibility. *American Economic Review* 75, 424-440.

Katz, M. and Shapiro, C. (1986). Technology adoption in the presence of network externalities. *Journal of Political Economy* 94, 822-841.

Koski, H. and Nijkamp, P. (1996). Timing of adoption of new communications technology.

Saloner, G. and Shepard, A. (1995). Adoption of technologies with network effects: an empirical examination of the adoption of automated teller machines. *Rand Journal of Economics* 26, 479-501.

Shurmer, M. (1993). An investigation into sources of network externalities in the packaged PC software market. *Information Economics and Policy* 5, 231-251.

Stoneman, P. (1995), (ed.). *Handbook of the economics of innovation and technological change.* Blackwell.