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Information and Communications Technology, R&D, and Organizational Innovation

Exploring Complementarities in Investment and Production

Pierre Mohnen, Michael Polder, and George van Leeuwen

8.1 Introduction

In the eyes of most historians of science and technology, information and communications technology (ICT) can be classified among general purpose technologies (GPT) such as the wheel, steam power, the combustion engine, and electricity (Lipsey, Carlaw, and Bekhar 2005; Jovanovic and Rousseau 2005; Brynjolfsson and McAfee 2014). It took some time before ICT showed up in the productivity statistics, but by now it is common to distinguish between ICT and non-ICT capital in productivity analysis, and a great deal of economic and labor productivity growth in the last 30 years has been ascribed to ICT capital deepening (Jorgenson, Ho, and Stiroh 2008). Even skeptics have acknowledged the transformational power of digital technology, although some claim that the economic benefits are short-lived and that the impact of ICT does not stand up to that of earlier GPTs (e.g., Gordon 2016).

Another channel through which ICT affects labor productivity growth is through its potential impact on total factor productivity (TFP). One explana-

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tion for the differential success of ICT capital in fostering productivity has been the argument of complementarity between ICT investment and investment in intangible assets, such as organizational capital (Brynjolfsson and Saunders 2010; Bresnahan, Brynjolfsson, and Hitt 2002). Firms need to reorganize their way of operating to benefit from digital technology and vice versa.[1]

Beyond its contribution to TFP via organizational change, ICT can also increase the returns to R&D, generating a string of new technological innovations. It can also make R&D more effective in the sense that it facilitates the gathering, documenting, and sharing of knowledge and information. Finally, besides the potential to improve research effectiveness, these characteristics of ICT can also improve the possibility and quality of collaboration between researchers.

In this chapter, we look at the triangle between ICT, technological, and nontechnological innovation. In particular, we look at R&D as an instance of technological innovation and organizational change as a nontechnological innovation. Parts of this triangle and its relation to productivity have been covered extensively in the literature. Putting the pieces together in one framework is a novelty of our analysis. We shall reassess the contribution of ICT to TFP growth and reexamine the hypothesis of complementarity between organizational innovation and ICT. In addition, we shall explore whether the returns to ICT and R&D are mutually reinforcing, in the sense that innovation is ICT facilitated and, vice versa, that the returns from ICT stem in part from the generation of knowledge.

The chapter is structured as follows. In section 8.2, we briefly review the literature on the role of ICT and R&D for productivity, on the complementarity between ICT and organizational innovation, and on the GPT aspects of ICT. Section 8.3 is devoted to modeling aspects. In section 8.4, we describe the data and the main variables. In section 8.5, we present the estimation results, and in section 8.6, we conclude.

8.2 The Literature

A vast literature has documented evidence of different determinants of productivity both at the macro- and at the microlevel (see Syverson 2011). Among the determinants, investment in ICT and the generation of knowledge feature prominently.

One strand of the literature has estimated the returns (private and social) to R&D and the contribution of R&D to TFP or economic growth following the seminal work by Griliches (1979) and with some recent advances by Doraszelski and Jaumandreu (2013); see, e.g., Hall, Mairesse, and Mohnen (2010) for a review of the literature. Another branch has related R&D to innovation and innovation to productivity, the workhorse model being the

1. At the aggregate level, network and spillover effects can arise, and digital technology may improve the allocation of resources (Syverson 2011).

CDM model as proposed by Crépon, Duguet, and Mairesse (1998); see Mairesse and Mohnen (2010) for an overview. Neither line of research has considered the complementarity with ICT, although recently Polder et al. (2010) and Hall, Lotti, and Mairesse (2013) have modeled R&D and ICT investment as inputs into innovation, defined as product, process, and organizational innovation.

In parallel, many studies have investigated the effect of the adoption of ICT equipment on economic performance (see, e.g., Stiroh 2010) without an explicit role for R&D. Some studies have used aggregate or sectoral data; others have used firm data. The studies that use macro or sectoral data have mainly analyzed the effect of ICT or R&D on productivity within a growth accounting framework (see Draca, Sadun, and van Reenen 2007, and Biagi 2013 for reviews of the literature) but not so much the complementarity between ICT and R&D in raising productivity.

A substantial effort has been made to measure the stocks of intangibles—including R&D but also software, databases, and organizational capital—and to assess their importance in (intangible-adjusted) cross-country GDP growth (Corrado, Hulten, and Sichel 2009; Corrado et al. 2013). These industry-level data are beginning to be used to explore complementarities between different types of assets. Chen, Niebel, and Saam (2014) and Corrado, Haskel, and Jona-Lasinio (2017) find evidence of a positive direct effect of ICT on TFP, as well as a significant indirect effect through its interaction with intangibles. Using EU KLEMS data, Pieri, Vecchi, and Venturini (2017) explore complementarities between ICT and R&D in reducing technical inefficiencies.

By contrast, the empirical studies that have been conducted on the hypothesis of complementarity between ICT and organizational change are mainly based on microdata (Bresnahan, Brynjolfsson, and Hitt 2002; Black and Lynch, 2001; Caroli and Van Reenen, 2001; Crespi, Criscuolo, and Haskel 2007; Van Reenen et al. 2010; Riley and Vahterv 2013). The available econometric evidence shows that a combination of investment in ICT and changes in organization and work practices facilitated by these technologies contributes to firms' productivity growth. Case studies reveal that the introduction of information technology is combined with a transformation of the firm, including investment in intangible assets, and a change in the relation with suppliers and customers. Electronic procurement, for instance, increases control over inventories and decreases costs of coordinating with suppliers. In addition, ICT offers the possibility for flexible production, such as just-in-time inventory management, and enterprise resource planning.

Whereas there is a lot of empirical backing at the firm level for the complementarity between ICT and organizational innovation, there is less evidence of a complementarity between R&D and ICT or between ICT and technological innovations in the form of new products or processes. Hall, Lotti, and Mairesse (2013) on Italian data; Rybalka (2015) on Norwegian data;

and Aboal and Tacsir (2018) on Uruguyan data find no conclusive evidence in favor of either a complementarity or a substitutability between R&D and ICT. Many studies have investigated the role of ICT in fostering R&D or innovation, however. For German firm data, Cerquera and Klein (2008) find that ICT is associated with an increase in the variation of productivity across firms and that this process of creative destruction gives incentives for firms to invest in R&D. Also for Germany, Engelstätter (2012) finds that different types of software have a positive effect on product and process innovation and moreover that there is complementarity between software and organizational practices in their effect on innovative performance. Polder et al. (2010) find that ICT investment is important for all types of innovation in services, while it plays a limited role in manufacturing, and Kleis et al. (2012) find that investments in information technology increase innovation output as measured by the number of patents. Van Leeuwen and Farooqui (2008) show that e-sales and broadband use affect productivity significantly through their effect on innovation output. Finally, Forman and van Zeebroeck (2012) find that internet connections increase collaborative research but not the productivity of lone researchers or of researchers located close to each other. In contrast, Spiezia (2011) concludes from an Organisation for Economic Co-operation and Development (OECD)-led international comparison study on firm data that ICT usage does not increase the probability of coming up with a new innovation developed in-house.

Finally, a related line of research looks at complementarities between different types of innovation or different types of ICT. Miravete and Pernías (2006) and Martínez-Ros and Labeaga (2009), for instance, find complementarity between product and process innovation by looking at the adoption decision. This result is confirmed in Polder et al. (2010), who look at complementarity in the production function. This latter study also finds that product and organizational innovation are complements, while process and organizational innovation are found to be substitutes. For ICT, following an approach methodologically close to ours in the current chapter, Kretschmer, Miravete, and Pernías (2012) find that different types of software are substitutes in production. The results of Bartelsman, van Leeuwen, and Polder (2017), however, point to complementarity as well as substitutability, depending on the types of software considered.

In our chapter we will address the triangle of complementarity between ICT (hardware), R&D, and organizational change by looking at the joint firm-level binary investment decisions together with their productivity effects.

8.3 Model

While it is true that ICT and R&D can be considered as inputs in the innovation process, ICT and even R&D play a direct role in the production function besides affecting innovation. Therefore, in contrast to Polder et al. (2010); Hall, Lotti, and Mairesse (2012); and Rybalka (2015), we do not resort to a CDM type of model (Crépon, Duguet, and Mairesse 1998), with innovation inputs only affecting productivity through a knowledge production function. Instead, we shall model ICT, R&D, and organizational innovation as binary choices with simultaneous feedback effects—that is, when two strategies are complements in the sense that doing one increases the returns of doing the other (Milgrom and Roberts 1990), the returns from adoption (and therefore the adoption decisions) are mutually dependent.

In our model, firms choose combinations of investments (i.e., "investment profiles") based on their (ex-ante) expected returns in terms of productivity growth. When multiple investments are involved, there is a "complementarity bonus" (or "substitutability penalty") added to the return on the individual investment. Given the simultaneous modeling of the productivity equation, the ex-post effects of the investments on productivity growth will be consistent with the ex-ante expected returns that prompted the choice for that specific combination of investments.[2] We thus model complementarities in terms of an objective function where the strategy choices (or investments) are themselves endogenous, as in Kretschmer, Miravete, and Pernías (2012), who combined the adoption and production approach recommended by Athey and Stern (1998).

Modeling the direct effect of ICT and R&D on productivity also brings our analysis closer to the literature on intangibles and growth accounting using industry-level data (Corrado, Hulten, and Sichel 2009), where R&D and ICT are considered separate types of capital. Also in conformity with the introduction of stocks of intangibles in the production function as in Corrado, Hulten, and Sichel (2009), we consider it more appropriate that investment affects the growth rather than the level of total factor productivity. The productivity levels depend on the stocks of knowledge, organizational capital, and ICT capital. The productivity growth rates instead depend on the increases in these stocks. We do not model the choice of the investment levels, only the binary choices as to whether investments in ICT, R&D, and organizational innovations are made.

8.3.1 Investment Stage

In order to test for the presence of complementarity between innovation strategies (in particular, between investing in ICT, R&D, and organizational innovation), we first consider the adoption approach—that is, the detection of joint use of strategies for reasons other than correlations in unobserved determinants (Milgrom and Roberts 1990; Athey and Stern 1998).

2. It could be argued that the strategy choices are made on the basis of another objective function than total factor productivity growth and that therefore, as well as for reasons of limited managerial foresight or unforeseen developments, there may be a difference between ex-ante and ex-post complementarity.

This approach is close to that of Miravete and Pernías (2006) and was also applied by Bartelsman, van Leeuwen, and Polder (2017) and Van Leeuwen and Mohnen (2017).

Consider an objective function that depends on the realization of the combination of strategies, or states. The contribution to the objective function O_{it}^j achieved by the adoption of each individual strategy, $y_{it}^j \in \{0,1\}$, where j denotes ICT, R&D, and organizational innovation, is given by the following expression:

$$O_{it}^j = \left(\beta_j' x_{it}^j + \sum_{k \neq j} (\alpha_{jk}/2) y_{it}^k + \varepsilon_{it}^j\right) y_{it}^j. \tag{1}$$

For reasons of identification, $\alpha_{jk} = \alpha_{kj}$. The "return" from the adoption of strategy j depends on exogenous variables x_{it}^j, which may be strategy specific, the adoption of the other strategies y_{it}^k, and a random error term ε_{it}^j. The error terms are assumed to be jointly normally distributed with unitary variances (for reasons of identification) but nonzero covariances. The dependence on the adoption of other strategies makes this a simultaneous model, in which the choice of strategies is endogenously determined. This allows us to test for potential complementarity at the investment stage in the sense that firms adopt a combination of strategies that they think will be beneficial.

The total level of the objective, which will be left unspecified for now but modeled in section 3.2 as the contribution to TFP growth, is given by

$$TO_{it} = \sum_j O_{it}^j. \tag{2}$$

As shown by Lewbel (2007), this way of writing the objective function avoids any incoherency and incompleteness problem—that is, it guarantees the existence and uniqueness of the endogenous dummy variables for any given realization of the exogenous variables.

Let us illustrate the model by working with two strategies, denoted as $y^j \in \{0,1\}, j = 1, 2$. For example, if state (1,1) is chosen, where the first position refers to strategy y^1 and the second position to strategy y^2, then the contribution to TFP growth is given by[3]

$$TO_{it}(1,1) = \beta_1' x_{it}^1 + \alpha_{12} + \beta_2' x_{it}^2 + \varepsilon_{it}^1 + \varepsilon_{it}^2. \tag{3}$$

The coefficient α_{12} captures the complementarity (if positive) or substitutability (if negative) between the pair of strategies. For every combination of strategies, we can compute the value of the objective function. To estimate the parameters of the model, we write down the probability of every possible state. For instance, the probability that strategy 1 and strategy 2 are chosen, denoted as state (1,1), is derived from the upper and lower bounds of the

3. Notice that for notational convenience, $\alpha_{12} = \alpha_{21}$ in equation (3) corresponds to $\alpha_{12}/2 + \alpha_{21}/2$ in equation (1).

distribution of the error terms given that the value of the objective function under (1,1) must be higher than under any pair of strategies:

(4.1) $$TO_{it}(1,1) > TO_{it}(0,0) \Rightarrow \beta_1' x_{it}^1 + \alpha_{12} + \beta_2' x_{it}^2 + \varepsilon_{it}^1 + \varepsilon_{it}^2 > 0$$

(4.2) $$TO_{it}(1,1) > TO_{it}(1,0) \Rightarrow \beta_2' x_{it}^2 + \alpha_{12} + \varepsilon_{it}^2 > 0$$

(4.3) $$TO_{it}(1,1) > TO_{it}(0,1) \Rightarrow \beta_1' x_{it}^1 + \alpha_{12} + \varepsilon_{it}^1 > 0.$$

State (1,1) is therefore associated to the following area of the distribution of the error terms:

(5.1) $$\varepsilon_{it}^1 > -(\beta_1' x_{it}^1 + \alpha_{12})$$

(5.2) $$\varepsilon_{it}^2 > \max[-(\beta_2' x_{it}^2 + \alpha_{12}), -(\beta_1' x_{it}^1 + \alpha_{12} + \beta_2' x_{it}^2 + \varepsilon_{it}^1)],$$

where (5.1) follows directly from (4.3) and (5.2) follows from combining (4.1) and (4.2) while conditioning on ε_{it}^1. The same reasoning can be applied to derive the adoptions for the other states.

State (1,0) is adopted when

(6.1) $$TO_{it}(1,0) > TO_{it}(0,0) \Rightarrow \beta_1' x_{it}^1 + \varepsilon_{it}^1 > 0$$

(6.2) $$TO_{it}(1,0) > TO_{it}(0,1) \Rightarrow \beta_1' x_{it}^1 + \varepsilon_{it}^1 > \beta_2' x_{it}^2 + \varepsilon_{it}^2$$

(6.3) $$TO_{it}(1,0) > TO_{it}(1,1) \Rightarrow \beta_2' x_{it}^2 + \alpha_{12} + \varepsilon_{it}^2 < 0.$$

(7.1) In other words, when $\varepsilon_{it}^1 > -\beta_1' x_{it}^1$ and

(7.2) $$\varepsilon_{it}^2 < \min[-(\beta_2' x_{it}^2 + \alpha_{12}), (\beta_1' x_{it}^1 - \beta_2' x_{it}^2 + \varepsilon_{it}^1)].$$

State (0,1) is adopted when

(8.1) $$TO_{it}(0,1) > TO_{it}(0,0) \Rightarrow \beta_2' x_{it}^2 + \varepsilon_{it}^2 > 0$$

(8.2) $$TO_{it}(0,1) > TO_{it}(1,0) \Rightarrow \beta_2' x_{it}^2 + \varepsilon_{it}^2 > \beta_1' x_{it}^1 + \varepsilon_{it}^1$$

(8.3) $$TO_{it}(0,1) > TO_{it}(1,1) \Rightarrow \beta_1' x_{it}^1 + \alpha_{12} + \varepsilon_{it}^1 < 0.$$

(9.1) In other words, when $\varepsilon_{it}^1 < -(\beta_1' x_{it}^1 + \alpha_{12})$ and

(9.2) $$\varepsilon_{it}^2 > \max[-(\beta_2' x_{it}^2), \beta_1' x_{it}^1 - \beta_2' x_{it}^2 + \varepsilon_{it}^1].$$

State (0,0) is adopted when

(10.1) $$TO_{it}(0,0) > TO_{it}(1,0) \Rightarrow \beta_1' x_{it}^1 + \varepsilon_{it}^1 < 0$$

(10.2) $$TO_{it}(0,0) > TO_{it}(0,1) \Rightarrow \beta_2' x_{it}^2 + \varepsilon_{it}^2 < 0$$

(10.3) $$TO_{it}(0,0) > TO_{it}(1,1) \Rightarrow \beta_1' x_{it}^1 + \beta_2' x_{it}^2 + \alpha_{12} + \varepsilon_{it}^1 + \varepsilon_{it}^2 < 0.$$

(11.1) In other words, when $\varepsilon_{it}^1 < -\beta_1' x_{it}^1$ and

(11.2) $$\varepsilon_{it}^2 < \min[-\beta_2' x_{it}^2, -(\beta_1' x_{it}^1 + \beta_2' x_{it}^2 + \alpha_{12} + \varepsilon_{it}^1)].$$

As shown in Miravete and Pernías (2006), when $\alpha_{12} = 0$, the subdivision of the space of $(\varepsilon_{it}^1, \varepsilon_{it}^2)$ is the same as for the bivariate probit. When $\alpha_{12} > 0$, the states (1,1) and (0,0) are defined over a larger region of that error space, and if $\alpha_{12} < 0$, the states (1,0) and (0,1) are defined over a smaller region of that error space.

8.3.2 Productivity Growth Equation

Going one step further, the return from each investment profile can be measured in terms of productivity growth. The objective, which was left unspecified in equation (2), is then explicitly specified. In this way we integrate the strategy adoption equations with the productivity growth equation. This is what Kretschmer, Miravete, and Pernías (2012) have done in combining the "adoption approach" and the "productivity approach" of complementarity in the words of Athey and Stern (1998). Like them, we distinguish between observed and unobserved determinants of innovation; hence firms may adopt different strategies even if the observed determinants are the same. We differ from Kretschmer, Miravete, and Pernías (2012) in that we use not economic profits but productivity growth rates. Instead of combining dichotomous data on two types of software innovation with continuous variables on scale and profit, which depend on the innovation choices, we combine three dichotomous innovation indicators (ICT, R&D, and organizational innovation) with productivity growth rates that depend on the choice of investments. Another difference is that instead of maximizing a likelihood function with analytical conditional distributions, an expression that becomes more tedious to derive as the number of equations increases, we work with simulated conditional likelihoods.

To that effect, we shall estimate a total factor productivity growth equation, which depends on the chosen investment profiles. TFP growth is the portion of output growth that is not explained by the growth rates in the traditional inputs, labor and capital. In the case of two strategies, TFP growth would be given by the following expression:

$$(12)\quad \dot{TFP}_{it} = \gamma_t + TO_{it} = \gamma_t + (\beta_1' x_{it}^1 + \varepsilon_{it}^1) y_{it}^1 + (\beta_2' x_{it}^2 + \varepsilon_{it}^2) y_{it}^2 + \alpha_{12} y_{it}^1 y_{it}^2 + \varepsilon_{it}^3,$$

where γ_t represents disembodied technical change and ε_{it}^3 represents unobservable determinants of TFP growth.

$\dot{TFP}_{it}$ can take four values depending on the realizations of the error terms ε_{it}^1 and ε_{it}^2:

- State (1,1): $\gamma_t + \beta_1' x_{it}^1 + \alpha_{12} + \beta_2' x_{it}^2 + \varepsilon_{it}^1 + \varepsilon_{it}^2 + \varepsilon_{it}^3$ in the region defined by (5.1) and (5.2).
- State (1,0): $\gamma_t + \beta_1' x_{it}^1 + \varepsilon_{it}^1 + \varepsilon_{it}^3$ in the region defined by (7.1) and (7.2).
- State (0,1): $\gamma_t + \beta_2' x_{it}^2 + \varepsilon_{it}^2 + \varepsilon_{it}^3$ in the region defined by (9.1) and (9.2).
- State (0,0): $\gamma_t + \varepsilon_{it}^3$ in the region defined by (11.1) and (11.2).

If we assume the random vector $[\varepsilon^1_{it}, \varepsilon^2_{it}, \varepsilon^3_{it}]'$ to be normally distributed with mean 0 and variance-covariance matrix Ω, then the likelihood function associated with the observed choices of strategies and the observed values of TFP growth is given by

$$(13)\quad \mathcal{L} = \prod_{i,t} f_1\{\dot{TFP}_{it} - [\gamma_t + (\beta_1' x^1_{it} + \varepsilon^1_{it}) y^1_{it} + (\beta_2' x^2_{it} + \varepsilon^2_{it}) y^2_{it} + \alpha_{12} y^1_{it} y^2_{it}] \mid \varepsilon^1_{it}, \varepsilon^2_{it}\} \times F_2(\varepsilon^1_{it}, \varepsilon^2_{it})$$

where $f_1(. \mid \varepsilon^1_{it}, \varepsilon^2_{it})$ is the (conditional) univariate normal density function of ε^3_{it} conditional on values of ε^1_{it} and ε^2_{it}, and $F_2(\varepsilon^1_{it}, \varepsilon^2_{it})$ is the bivariate normal distribution of ε^1_{it} and ε^2_{it}. If we define the four regions of $(\varepsilon^1_{it}, \varepsilon^2_{it})$ as R(1,1), R(1,0), R(0,1), and R(0,0), respectively, and the corresponding truncated distributions as $F_2(\varepsilon^1_{it}, \varepsilon^2_{it}) \mid R(1,1)$ and so on, then the likelihood function can also be written as

$$(14)\quad \mathcal{L} = \prod_{i,t} f_1[\dot{TFP}_{it} - (\gamma_t + \beta_1' x^1_{it} + \alpha_{12} + \beta_2' x^2_{it} + \varepsilon^1_{it} + \varepsilon^2_{it}) \mid R(1,1)]$$
$$\times F_2[\varepsilon^1_{it}, \varepsilon^2_{it} \mid R(1,1)] f_1[\dot{TFP}_{it} - (\gamma_t + \beta_1' x^1_{it} + \varepsilon^1_{it}) \mid R(1,0)]$$
$$\times F_2[\varepsilon^1_{it}, \varepsilon^2_{it} \mid R(1,0)] f_1[\dot{TFP}_{it} - (\gamma_t + \beta_2' x^2_{it} + \varepsilon^2_{it}) \mid R(0,1)]$$
$$\times F_2[\varepsilon^1_{it}, \varepsilon^2_{it} \mid R(0,1)] f_1[\dot{TFP}_{it} - \gamma_t \mid R(0,0)] F_2[\varepsilon^1_{it}, \varepsilon^2_{it} \mid R(0,0)]$$

In practice, the variance-covariance matrix must be imposed to be positive definite. This can be done by using a Cholesky factorization of Ω. In the appendix, we indicate the various steps taken to calculate the maximum simulated likelihood using the Geweke-Hajivassiliou-Keane (GHK) procedure (see Train 2003; Cappellari and Jenkins 2006).

We measure TFP growth using the index approach—that is, we assume constant returns to scale, equilibrium factor holdings, and perfectly competitive markets such that the output elasticities can be measured by the observed factor shares, which we allow to vary over time and to be industry-specific. We are interested in differences in the contributions to TFP growth for firms adopting different investment profiles: (0,0), (1,0), (0,1), and (1,1). These differences can be estimated by drawing values for ε^1_{it} and ε^2_{it} from their respective domains of definition and then averaging over the different draws. We are also interested in finding out whether those different investments reinforce each other. This indication of complementarity (or substitutability) is given by the sign of coefficient α_{12}.

The model we have just presented can be generalized to more than two strategies. In the remainder of the chapter, we shall work with three strategies: investment in ICT, R&D, and organizational innovation. To determine the optimal investment profile—that is, the combination of strategies—each combination needs to be compared with seven other combinations. We shall estimate pairwise complementarities and returns from investing in ICT only, R&D only, organizational innovation only, pairs of investments, all three of them, or none at all.

8.4 Data

The data used in this exercise are sourced from the Business Register and different surveys at Statistics Netherlands, which are linked at the firm level. The sample includes firms in the manufacturing sector (NACE Rev. 2 10 to 33) as well as the services sector (NACE Rev. 2 50 to 93).[4] Production data (value added, capital depreciation costs, and employment) are taken from the Production Statistics (PS). Capital services are proxied by depreciation costs (observed at the firm level). Value added and depreciation cost are deflated using industry-level price information from the Dutch National Accounts. Information on the age of a firm and whether it is foreign-owned are derived from the Business Register.

Information on R&D and organizational innovation, as well as the export status, is sourced from the Community Innovation Survey (CIS). Organizational innovations include the introduction of new business practices, knowledge management systems, methods of workplace organization (i.e., system of decision-making), and management of external relations. The CIS provides information on whether a firm is stated to have performed such an innovation in the three-year period ending in the year preceding the survey (e.g., the CIS 2010 is carried out in 2011 and concerns innovation in the period 2008–10). R&D investment is the sum of internal and external R&D and, unlike organizational innovation, refers only to the last year of the survey.

Information on ICT investment comes from the investment survey and concerns hardware only.[5] We have decided to treat the three investment types in the same way, and therefore we work with binary data for ICT and R&D, which is the only type of information we have for organizational innovation. In our analysis, a firm classifies as investing in ICT and R&D when the investment is positive, but the investment should also have some substance. This is to improve the identification of any effects of investment on TFP, where really small investments can be expected not to make any difference, and we need to distinguish between those and more substantial investment efforts. By way of threshold, we therefore exploited industry-specific data on depreciation cost by type of investment. The investment dummies then

4. The commercial R&D sector, NACE Rev 2 code 72, is excluded from the analysis, as well as oil and petroleum, NACE Rev 2 code 19.

5. From 2012 onward, the Dutch Investment Survey includes information on investment in software. We therefore focus on hardware, as including software would have substantially reduced the number of observations in our analysis.

Table 8.1 **Summary statistics for the estimation sample (2008–12, even years)**

		Manufacturing		Services		Total	
		Mean	SD	Mean	SD	Mean	SD
ICT investment	share of firms	0.42	0.49	0.40	0.49	0.41	0.49
R&D investment	share of firms	0.27	0.44	0.19	0.39	0.22	0.41
organizational innovation*	share of firms	0.45	0.50	0.35	0.48	0.39	0.49
TFP growth**	%	−0.05	0.31	−0.04	0.29	−0.04	0.30
Employment	Fte	257.31	436.03	241.01	526.86	247.21	494.33
Age	Years	24.31	15.18	20.13	15.05	21.72	15.24
Export status	share of firms	0.82	0.39	0.56	0.50	0.66	0.47
Foreign owned	share of firms	0.34	0.47	0.26	0.44	0.29	0.46

* Organizational innovation refers to the period $t - 2$ to t.
** TFP growth refers to growth from t to $t + 1$.

equal 1 when the ratio of the firm's investment to its value added exceeds the share of the depreciation cost for that capital good in value added in the firm's industry. Table 8.A1 reports the annual average of these thresholds by industry. Thus the investment dummies can be loosely interpreted as capturing whether a firm has expansionary investments or not over and above the average industry replacement rate.

Our data span the period from 2008 to 2012. We assume that R&D and ICT in period t and ORG (organizational innovation) in period $t - 2$ to t affect TFP growth between year t and year $t + 1$. Because CIS only covers even years, the eventual estimation sample refers to 2008, 2010, and 2012, where TFP growth concerns growth from 2008 to 2009 and so on. A sensitivity analysis, where the timing of the ICT and R&D investment dummies refers to $t - 2$ rather than t, gave more or less similar results as those reported in the results section of this chapter.

Table 8.1 gives the summary statistics by sector for the key variables used in the estimation separately for manufacturing and services. Firms in both sectors are on average of a similar size, whereas manufacturing firms are slightly older than their counterparts in services. Moreover, manufacturing firms are more often foreign-owned and are more likely to export. Overall, the share of exporting firms is relatively high, which is probably due to the fact that we observe mainly larger firms.

Average TFP growth is negative in both sectors, with a similar magnitude of, respectively, minus 5 percent in manufacturing and minus 4 percent in services. The fact that our data period includes the financial crisis of 2008/2009 explains these substantial negative growth figures, where average (median) TFP growth was minus 10 (minus 5) percent in these years. In the other years, the crisis aftermath, TFP growth is roughly around 0. Table 8.2 also shows that for

Table 8.2 Combinations of investment strategies (estimation sample, 2008–12, even years)

	Manufacturing		TFP growth*			
Profile	N	%	Mean	Median	Q1	Q3
000	802	0.29	−0.067	−0.029	−0.186	0.095
001	430	0.15	−0.062	−0.014	−0.170	0.094
010	123	0.04	−0.062	−0.009	−0.224	0.081
011	266	0.09	−0.023	−0.014	−0.146	0.097
100	484	0.17	−0.039	−0.018	−0.158	0.092
101	335	0.12	−0.054	−0.039	−0.192	0.106
110	140	0.05	−0.088	−0.021	−0.211	0.127
111	227	0.08	−0.008	0.018	−0.124	0.128
	2,807					

	Services		TFP growth*			
Profile	N	%	Mean	Median	Q1	Q3
000	1,665	0.36	−0.048	−0.020	−0.159	0.094
001	659	0.14	−0.059	−0.018	−0.156	0.077
010	181	0.04	−0.024	0.020	−0.158	0.112
011	259	0.06	−0.041	0.001	−0.149	0.097
100	948	0.21	−0.038	−0.014	−0.147	0.094
101	450	0.10	−0.030	−0.006	−0.130	0.105
110	162	0.04	−0.019	−0.008	−0.156	0.138
111	252	0.06	0.001	0.006	−0.126	0.128
	4,576					

Notes: Q1 and Q3 are the first and third quartile of the distribution. Combinations of ICT, R&D, and organizational innovation, where 0 = no investment and 1 = positive (net) investment. Organizational innovation refers to the period $t - 2$ to t. * TFP growth refers to growth from t to $t + 1$.

each investment profile, there are firms reporting negative as well as positive growth and that the third quartile of the TFP growth distribution is always positive. Interestingly, the distribution of TFP growth seems to roughly move to the right with the number of investments—that is, average and median TFP growth, as well as the first and third quartile of the distribution, are larger for those profiles where multiple investments are combined. This is an indication of complementarity between these investments, which will be tested more formally in our econometric model. Nevertheless, firms do not often combine these investments; witness the frequency distribution of the profiles. In manufacturing, about two-thirds of the observations concern cases where a firm does not invest at all or in a single strategy only. In services, this share is even higher, with about three-quarters of the sample.

Table 8.3 reports the summary statistics of the variables that are input to the TFP growth calculation. Using a Laspeyres index, TFP-growth was calculated as the ratio of the volume changes in value added and the total

Table 8.3 Summary statistics for the production variables (by industry, estimation sample, 2008−12, even years)

	Industry variables *Averages across years*		Firm variables *averages across industry and years*			
	Capital share	Labor share	Value added	Employment	Capital services	TFP growth
Manufacturing						
10–12 Food and beverages	0.35	0.65	22,468	265	3,400	−0.050
13–15 Textile, leather products	0.27	0.73	9,898	115	741	0.017
16–18 Wood and paper, printing	0.32	0.68	13,527	162	2,092	0.012
20 Chemicals	0.50	0.50	42,740	195	6,386	−0.092
21 Pharmaceuticals	0.52	0.48	69,118	433	5,176	0.283
22–23 Plastics, construction products	0.28	0.72	12,611	192	1,943	0.037
24–25 Basic metals and –products	0.24	0.76	11,222	144	1,113	−0.002
26 Electronic products	0.40	0.60	23,626	239	1,497	0.137
27 Electric equipment	0.50	0.50	31,100	410	4,059	−0.047
28 Machinery n.e.c.	0.28	0.72	22,889	233	2,486	−0.025
29–30 Transport equipment	0.33	0.67	37,808	398	4,730	0.039
31–33 Other manufacturing, repair	0.15	0.85	19,807	482	1,069	−0.005
Services						
58–60 Publishing, movie, radio and TV	0.16	0.84	22,784	247	4,405	−0.040
61 Telecommunications	0.62	0.38	57,741	275	25,460	0.073
62–63 IT and information services	0.12	0.88	15,288	170	1,497	0.036
69–71 Management, tech. consultancy	0.10	0.90	20,151	253	1,100	−0.032
73–75 Advertising, design and other	0.11	0.88	8,622	126	627	0.023
G Wholesale and retail trade	0.20	0.80	15,598	218	1,460	−0.023
H Transportation and storage	0.32	0.68	25,648	309	3,430	−0.006
I Accommodation and food serving	0.17	0.83	10,424	213	1,894	−0.030

Notes: Value added and depreciation cost in prices of 2008. Employment in full-time equivalents.

of inputs, where the capital and labor changes have been weighted by their lagged factor shares at the industry level. This approach takes into account differences in the nature of the production process between industries. Clearly, the average TFP growth differs across industries, with the pharmaceutical industry being a clear outlier.

8.5 Results

In this section, we report the estimation results of the integrated model with three types of investment, the returns for each investment profile, and

Table 8.4 **Estimation results of the investment plus productivity equations (based on maximum simulated likelihood)**

		Manufacturing (N = 2,807)			Services (N = 4,576)		
		Coeff.	SE	*p*-value	Coeff.	SE	*p*-value
ICT	log employment	−0.079***	0.017	0.000	0.060***	0.013	0.000
	export status	−0.121***	0.045	0.008	−0.014	0.029	0.637
	log age	0.012	0.016	0.452	0.000	0.012	0.996
	foreign ownership	−0.086**	0.038	0.024	−0.091**	0.033	0.006
R&D	log employment	−0.005	0.024	0.838	−0.068***	0.016	0.000
	export status	0.524***	0.074	0.000	0.289***	0.041	0.000
	log age	−0.004	0.027	0.869	−0.002	0.019	0.930
	foreign ownership	0.019	0.050	0.704	−0.104**	0.044	0.019
ORG	log employment	0.147***	0.021	0.000	0.108***	0.015	0.000
	export status	−0.004	0.054	0.942	−0.044	0.034	0.195
	log age	0.011	0.021	0.605	0.008	0.015	0.574
	foreign ownership	0.116**	0.044	0.008	0.070*	0.038	0.064
TFP growth	Year 2010	0.164***	0.018	0.000	0.101***	0.014	0.000
	Year 2012	0.118***	0.023	0.000	0.071***	0.017	0.000
	intercept	−0.653***	0.021	0.000	−0.498***	0.014	0.000
complementarities	ICT-R&D	0.251***	0.027	0.000	0.175***	0.025	0.000
	ICT-ORG	−0.044	0.038	0.245	0.046**	0.019	0.018
	R&D-ORG	1.279***	0.072	0.000	1.129***	0.020	0.000
Correlations	ρ_{12}	−0.229***	0.034	0.000	0.173***	0.024	0.000
	ρ_{13}	0.166***	0.044	0.000	0.045**	0.019	0.018
	ρ_{14}	−0.742***	0.021	0.000	0.811***	0.007	0.000
	ρ_{23}	−0.771***	0.036	0.000	−0.061*	0.035	0.079
	ρ_{24}	0.254***	0.049	0.000	0.011	0.032	0.733
	ρ_{34}	−0.517***	0.028	0.000	−0.695***	0.015	0.000
	σ_4	0.553***	0.015	0.000	0.503***	0.010	0.000
	Log-likelihood		−6,561.12			−9,912.21	

Notes: Significance at 10 percent (*); 5 percent (**); 1 percent (***). Intercepts in the probit equations and sector dummies for services are not reported. ρ_{ij} is the correlation between the error terms of equations *i* and *j*. The equations are numbered as follows: 1 = ICT, 2 = R&D, 3 = ORG, 4 = TFP growth.

the individual returns of each investment, both on average and as a contribution to the return of each investment profile. Anticipating that the patterns differ across industries, we present the estimation results separately for manufacturing and services.

8.5.1 Complementarities

In table 8.4, we report the results for the integrated model with simultaneous discrete-choice investment equations for ICT, R&D, and organizational innovation, mutual dependence among the three types of investment, and controlling for firm size, export status, age, and foreign ownership and for four industry subsectors in services.[6] Firm size can be seen to be positively associated with investing in our sample, except for investments in ICT for firms in manufacturing and in R&D for firms in services. Exporting firms are more frequently observed to invest in R&D and less frequently in ICT and are found to be not particularly different from nonexporting firms in terms of the frequency of organizational innovation.[7] Age is not found to be significant in any of the three equations. Foreign ownership is positively correlated to organizational innovation and negatively, whenever significant, to ICT and R&D investments. As already mentioned before, aggregate TFP growth in the Netherlands was negative just after the crisis of 2008 but then recovered in the following years, which is reflected in the year dummy pattern. The correlations between the error terms are significant, attesting to the existence of unobservables that are correlated in the adoption and the productivity equations, which justifies our estimation approach.

The three types of investment turn out to be complementary in the sense that they reinforce each other in increasing TFP growth and hence that the probability of investing in one increases the probability of investing in the other one. It is only for ICT and organizational innovation that we do not obtain a positive and significant interaction term. In the logic of our model, two investments are carried out simultaneously if they yield a larger contribution to TFP growth than if they are carried out separately or not at all. Three investments are carried out simultaneously if together they increase TFP growth by more than any pair of investments, individual investment, or no investment at all. The coefficient for the combination of ICT and organizational innovation is significantly smaller than the other α coefficients in both sectors. This is surprising because given the existing evidence in the literature, one would expect this relation to be relatively strong. A possible explanation for this finding is that we consider investment in hardware only, while the complementarity with organizational innovation could lie more in the use of software and specific types of telecommunication equipment.

By contrast, the R&D and organizational innovation combination is significant and has the highest coefficient in both sectors. This suggests that firms that invest in R&D benefit from a simultaneous organizational change. Such a complementarity could be related to the introduction of knowledge management systems or the management of external relations (such as information flows or coordination of collaborative innovation efforts), which are seen as an organizational innovation and clearly could improve the effectiveness of R&D. To our knowledge, there is not much evidence in the literature on this relation, and our finding suggests that it could be explored

6. We report in table 8.4 the estimated coefficients and not the marginal effects. However, the qualitative conclusions about patterns of significance remain the same.

7. Clearly, the causality can run both ways. Including export status is meant to control for the degree of international activities here.

Table 8.5 **Average returns of individual investments depending on the investment profile**

Profile		Manufacturing					Services				
		Obs	Mean	St. dev	Min	Max	Obs	Mean	St. dev	Min	Max
(0,0,1)	*ORG only*	*430*	*0.107*	*0.035*	*0.033*	*0.238*	*659*	*0.090*	*0.025*	*0.039*	*0.205*
	ORG		0.107	0.035	0.033	0.238	659	0.090	0.025	0.039	0.205
(0,1,0)	*R&D only*	*123*	*0.034*	*0.009*	*0.010*	*0.053*	*181*	*0.024*	*0.009*	*0.006*	*0.047*
	R&D		0.034	0.009	0.010	0.053	181	0.024	0.009	0.006	0.047
(0,1,1)	*R&D and ORG*	*266*	*0.057*	*0.031*	*0.003*	*0.195*	*259*	*0.033*	*0.011*	*0.010*	*0.061*
	R&D		0.021	0.012	−0.001	0.088	259	0.012	0.006	−0.001	0.030
	ORG		0.036	0.025	0.002	0.159	259	0.021	0.008	0.007	0.041
(1,0,0)	*ICT only*	*484*	*0.145*	*0.052*	*0.035*	*0.335*	*948*	*0.143*	*0.027*	*0.071*	*0.231*
	ICT		0.145	0.052	0.035	0.335	948	0.143	0.027	0.071	0.231
(1,0,1)	*ICT and ORG*	*335*	*0.164*	*0.027*	*0.105*	*0.266*	*450*	*0.121*	*0.036*	*0.053*	*0.298*
	ICT		0.083	0.016	0.052	0.140	450	0.062	0.019	0.027	0.159
	ORG		0.081	0.016	0.039	0.129	450	0.058	0.019	0.024	0.146
(1,1,0)	*ICT and R&D*	*140*	*0.044*	*0.014*	*0.012*	*0.075*	*162*	*0.037*	*0.013*	*0.012*	*0.082*
	ICT		0.025	0.008	0.006	0.044	162	0.021	0.007	0.007	0.043
	R&D		0.020	0.007	0.004	0.039	162	0.016	0.006	0.005	0.038
(1,1,1)	*all investments*	*227*	*0.102*	*0.023*	*0.017*	*0.174*	*252*	*0.064*	*0.024*	*0.023*	*0.165*
	ICT		0.059	0.011	0.013	0.082	252	0.036	0.013	0.014	0.091
	R&D		0.004	0.007	−0.019	0.023	252	0.008	0.006	−0.003	0.028
	ORG		0.039	0.014	0.005	0.091	252	0.020	0.009	0.005	0.062

in further detail. While the magnitude of the coefficient seems quite large here, our analysis of the implied average returns in the next section shows that these are plausible.

Finally, investing in ICT and investing in R&D are found to be complementary decisions, in the sense that investing in one increases the productivity of investing in the other one. This lends supports to the idea that ICT is a general-purpose technology that facilitates innovation and increases the output and productivity of R&D (Jovanovic and Rousseau 2005). Vice versa, investing in R&D increases the returns to ICT by generating knowledge that can be shared and diffused through new technology.

In sum, our results suggest that firms consider investment in ICT, R&D, and organizational innovation simultaneously and that they believe that simultaneous investment can be beneficial. In the next section, we shall examine the implied average returns of investing in certain profiles and from individual investments.

8.5.2 Returns on Investments

In our model, the expected return from a given investment profile is the same as the ex-post return in terms of TFP growth. If a certain profile is chosen, it is because its realized return is higher than the return on any other investment profile. In table 8.5, we present the average and the standard deviation of the returns earned on the seven investment profiles in manufacturing and in services.[8] In the example of two strategies given above, the return to adopting investment profile (1,1) would be given by

$$[(\beta_1' x_{it}^1 + \alpha_{12} + \beta_2' x_{it}^2 + \varepsilon_{it}^1 + \varepsilon_{it}^2) \mid R(1,1)] F_2[\varepsilon_{it}^1, \varepsilon_{it}^2 \mid R(1,1)],$$

where R(1,1) are all values of ε_{it}^1 and ε_{it}^2 defined by restrictions (5.1) and (5.2).

These returns are to be understood as above-normal rates of return, since R&D and ICT are not subtracted from the traditional inputs (labor and capital) in the calculation of TFP growth. In part, these returns are random in the sense that they depend on unobservables that lie in a truncated part of their distribution, which is determined by the observed investment profile, and are to be understood as the returns conditional on having chosen that investment profile multiplied by the probability of choosing that investment profile. They are calculated via simulation using the same draws as in the estimation procedure. They are also conditional on the values taken by the vector of explanatory variables x_{it}^1 and x_{it}^2. According to our model, for each observation, the alternative investment profiles yield a return lower than the observed profile. In the case of pairs or triplets of investment, the joint returns are subdivided in the table into the return contributions made by the individual investments.

It is remarkable that the ranking of the returns per investment profile and even the magnitudes of those returns are very similar for firms in manufacturing and in services. The highest average return is earned by firms that invest at the same time in ICT and organizational innovation followed by firms that invest in ICT only. While this may seem surprising recalling the result of no complementarity for this combination, as reported above, it should be noted that we are not comparing the same firms under alternative investment profiles. The differences in return could be due to different characteristics of the firms, such as size, age, or export status. Likewise, the returns for firms that invest in all three strategies are smaller than the returns for firms that invest only in ORG, only in ICT, or in both ORG and ICT, whereas according to the complementarities, we would expect the highest returns for firms that invest in all strategies. That would only be true when comparing the same firm under different scenarios, while in our case, the composition of the sample of firms choosing any of the profiles differs.[9]

Finally, table 8.6 presents the average returns to each individual investment conditional on the firms' characteristics. These returns are calculated as follows. The average rate of return on R&D, for instance, is the return a firm gets if it belongs to the set of investment profiles (0,1,0), (1,1,0), (0,1,1),

8. Note that the returns in the (0,0,0) case, where no investment takes place, is 0 by definition and is not reported.

9. In most cases, the alternative (counterfactual) returns (not shown) are negative, although they only need to be lower than the returns earned on the chosen investment profile.

Table 8.6 **Average returns to individual investments conditional on firms' characteristics**

	Obs	Mean	Std. dev.	Min	Max
Manufacturing					
ICT	1,186	0.097	0.055	0.006	0.335
R&D	756	0.018	0.014	−0.019	0.088
ORG	1,258	0.073	0.040	0.002	0.238
Services					
ICT	1,812	0.097	0.054	0.007	0.231
R&D	854	0.014	0.009	−0.003	0.047
ORG	1,620	0.059	0.035	0.005	0.205

and (1,1,1) multiplied by the respective probabilities of choosing each of those profiles. Since a firm can be in eight zones of the space spanned by $(\varepsilon^1_{it}, \varepsilon^2_{it}, \varepsilon^3_{it})$, which are themselves determined by the firm's characteristics, and since it makes a positive return on a particular investment only if it actually invests in it, the average rate of return is a weighted average of the returns in the four profiles in which it is active regarding that investment.

It is interesting to notice that the returns are again very similar in manufacturing and in services. Investing in ICT yields on average an implied rate of return close to 10 percent, which can go as high as 33.5 percent in manufacturing and 23.1 percent in services. R&D earns on average only 1.8 percent in manufacturing and 1.4 percent in services, with at most 8.8 percent in manufacturing and 4.7 percent in services. This is definitely lower than the average rates of return on R&D reported in Hall, Mairesse, and Mohnen (2010) and those reported for the Netherlands by Bartelsman et al. (1989). The implied rate of return on organizational innovation lies in between the rate on R&D and ICT, with an average of 7.3 percent in manufacturing and 5.9 percent in services and a maximum that exceeds 20 percent.

8.6 Conclusions and Further Research

This chapter has investigated the relation between investments in ICT, R&D, and organizational innovation and the contributions of different investment profiles on TFP growth at the firm level in Dutch manufacturing and services. We find that, overall, the investment decisions are complementary in the sense that investing in one strategy increases the probability of investing in another because joint investments lead to higher TFP growth than do individual investments. We find a relatively strong complementarity between R&D and organizational innovation, which could be related to new ways of managing knowledge systems and external relations improving the productivity of R&D. To our knowledge, this relation has not been explored intensively in the literature. The fact that the magnitude of the complementarity between ICT and organizational innovation is lower than the other complementarities also merits some further investigation, in particular considering software investments in addition to those in hardware only. There is clear evidence that ICT and R&D complement each other. This implies that R&D policies could stimulate investments in ICT, and conversely, policies designed to stimulate ICT also increase the demand for R&D. Our results imply that ICT earns on average a rate of return of 9.7 percent, followed by 6 percent to 7 percent on organizational innovation and a modest 1.4 percent to 1.8 percent on R&D.

The research could be extended in a number of directions. First, information on the separate types of organizational innovation available in our data could be exploited (business practices, knowledge systems, and external relations), as those types could relate differently to ICT and R&D. Second, as mentioned above, it will be good to consider software investment next to hardware investment, even though for the Netherlands, we only have data from 2012 onward for this type of asset. Third, we could estimate the elasticities of labor and capital simultaneously with the returns to ICT, R&D, and organizational innovation. A fourth extension would be to use the intensities of R&D and ICT in the productivity growth equation instead of, or in addition to, just the binary information.

Appendix

Calculation of the Maximum Simulated Likelihood

This part is based on Train (2003) and Cappellari and Jenkins (2006). For simplicity, we take the case of two strategies and one performance equation. The example can easily be generalized to three strategies and one performance equation. We start by using a Cholesky factorization of Ω:

$$\begin{bmatrix} \varepsilon_{\iota\tau}^1 \\ \varepsilon_{\iota\tau}^2 \\ \varepsilon_{\iota\tau}^3 \end{bmatrix} = C \begin{bmatrix} \eta_{it}^1 \\ \eta_{it}^2 \\ \eta_{it}^3 \end{bmatrix} = \begin{bmatrix} c_{11} & 0 & 0 \\ c_{21} & c_{22} & 0 \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} \eta_{it}^1 \\ \eta_{it}^2 \\ \eta_{it}^3 \end{bmatrix}$$

with

$$\Omega = C * C' = \begin{bmatrix} 1 & \rho_{21} & \rho_{31}\sigma_3 \\ \rho_{21} & 1 & \rho_{32}\sigma_3 \\ \rho_{31}\sigma_3 & \rho_{32}\sigma_3 & \sigma_3^2 \end{bmatrix},$$

and each $\eta_{it}^j (j = 1,2,3)$ follows a standard normal distribution. We set the variances of ε_{it}^1 and ε_{it}^2 equal to 1 for reasons of identification. In order to have this Ω matrix, elements of C are as follows: $c_{11} = 1$, $c_{21} = \rho_{21}$, $c_{31} = \rho_{31}\sigma_3$, $c_{22} = \sqrt{(1 - c_{21}{}^2)}$, $c_{32} = (\rho_{32}\sigma_3 - c_{31} * c_{21}) / c_{22}$, $c_{33} = \sqrt{(\sigma_3^2 - c_{31}{}^2 - c_{32}{}^2}$. The ρ_{ij} coefficients are imposed to stay between -1 and 1 by using the following reparameterization:

$$\rho_{ij} = \frac{\exp(2\widetilde{\rho_{ij}}) - 1}{\exp(2\widetilde{\rho_{ij}}) + 1}.$$

$$\text{We can rewrite} \begin{bmatrix} \varepsilon_{it}^1 \\ \varepsilon_{it}^2 \\ \varepsilon_{it}^3 \end{bmatrix} = \begin{bmatrix} c_{11}\eta_{it}^1 \\ c_{21}\eta_{it}^1 + c_{22}\eta_{it}^2 \\ c_{31}\eta_{it}^1 + c_{32}\eta_{it}^2 + c_{33}\eta_{it}^3 \end{bmatrix}.$$

Inequalities (5.1), (7.1), (9.1), and (11.1) can be rewritten as

$$(5.1') \qquad \eta_{it}^1 > -(\beta_1' x_{it}^1 + \alpha_{12})$$

$$(7.1') \qquad \eta_{it}^1 > -(\beta_1' x_{it}^1)$$

$$(9.1') \qquad \eta_{it}^1 < -(\beta_1' x_{it}^1 + \alpha_{12})$$

$$(11.1') \qquad \eta_{it}^1 < -\beta_1' x_{it}^1.$$

The first step of the maximum simulated likelihood algorithm consists in drawing for each alternative a value from the corresponding truncated standard normal distribution of η_{it}^1 using initial values of the parameters. Let us denote this value as d_{it}^1.

Inequalities (5.2), (7.2), (9.2), and (11.2) can be rewritten as

$$(5.2') \qquad \eta_{it}^2 > \max[-(a_{2it} + \alpha_{12}) / c_{22}, -(a_{1it} + a_{2it} + \alpha_{12}) / c_{22}]$$

$$(7.2') \qquad \eta_{it}^2 < \min[-(a_{2it} + \alpha_{12}) / c_{22}, (a_{1it} - a_{2it}) / c_{22}]$$

$$(9.2') \qquad \eta_{it}^2 > \max(-a_{2it} / c_{22}, (a_{1it} - a_{2it}) / c_{22})$$

$$(11.2') \qquad \eta_{it}^2 < \min(-a_{2it} / c_{22}, -(a_{1it} + a_{2it} + \alpha_{12}) / c_{22})$$

where $a_{1it} = \beta_1' x_{it}^1 + d_{it}^1$, $a_{2it} = \beta_2' x_{it}^2 + c_{21} d_{it}^1$.

The second step consists in drawing for each alternative a value from the corresponding truncated standard normal distribution of η_{it}^2 using initial values of the parameters. Let us denote this value as d_{it}^2.

The third step consists in changing from ε_{it}^3 to η_{it}^3 so that the final likelihood function becomes

$$(14') \quad \mathcal{L} = \prod_{i,t} \left(\frac{1}{c_{33}}\right) \varphi((T\dot{F}P_{it} - [\gamma_t + \beta_1' x_{it}^1 + \alpha_{12} + \beta_2' x_{it}^2 + (1 + c_{21}) d_{it}^1$$

$$+ c_{22} d_{it}^2) - c_{31} d_{it}^1 - c_{32} d_{it}^2 (/ c_{33}) \Phi_2 (d_{it}^1, d_{it}^2) | R(1,1)$$

$$\times \left(\frac{1}{c_{33}}\right) \varphi((T\dot{F}P_{it} - (\gamma_t + \beta_1' x_{it}^1 + d_{it}^1) - c_{31} d_{it}^1 - c_{32} d_{it}^2) / c_{33}) \Phi_2 (d_{it}^1, d_{it}^2) | R(1,0)$$

$$\times \left(\frac{1}{c_{33}}\right) \varphi((T\dot{F}P_{it} - (\gamma_t + \beta_2' x_{it}^2 + c_{21} d_{it}^1 + c_{22} d_{it}^2) - c_{31} d_{it}^1 - c_{32} d_{it}^2) / c_{33})$$

$$\times \Phi_2 (d_{it}^1, d_{it}^2) | R(0,1) \times \left(\frac{1}{c_{33}}\right) \varphi((T\dot{F}P_{it} - \gamma_t - c_{31} d_{it}^1 - c_{32} d_{it}^2) / c_{33})$$

$$\times \Phi_2 (d_{it}^1, d_{it}^2) | R(0,0),$$

Table 8.A1 **Depreciation shares in value added by industry (average across years)**

	ICT	R&D
10–12 Food and beverages	0.002	0.018
13–15 Textile, leather products	0.003	0.008
16–18 Wood and paper, printing	0.004	0.006
20 Chemicals	0.002	0.091
21 Pharmaceuticals	0.002	0.195
22–23 Plastics, construction products	0.002	0.027
24–25 Basic metals and –products	0.002	0.017
26 Electronic products	0.002	0.182
27 Electric equipment	0.003	0.211
28 Machinery n.e.c.	0.004	0.085
29–30 Transport equipment	0.002	0.073
31–33 Other manufacturing, repair	0.003	0.016
58–60 Publishing, movie, radio and TV	0.007	0.004
61 Telecommunications	0.016	0.005
62–63 IT and information services	0.016	0.023
69–71 Management, tech. consultancy	0.007	0.011
73–75 Advertising, design and other	0.008	0.010
G Wholesale and retail trade	0.005	0.005
H Transportation and storage	0.006	0.006
I Accommodation and food serving	0.002	0.002

Source: Statistics Netherlands, Growth accounts.

where d_{it}^1 and d_{it}^2 are draws from each of the truncated bivariate normal distributions $\Phi_2(d_{it}^1, d_{it}^2) \mid R(.)$ defined over the region $R(.)$, itself defined by the boundaries of η_{it}^1 and η_{it}^2, and where $\varphi(.)$ is the univariate standard normal density function and Φ_2 the bivariate normal cumulative distribution function. It is important here to account for the Jacobian of the variable transformation $(1/c_{33})$.

In our application, the model has four equations, and a step is added between the second and third step above. The logic is the same, but there are eight inequalities to take into account and eight elements in the likelihood function. The steps are repeated 50 times, and then an average is taken of the corresponding values of the likelihood function.[10] The parameters of the likelihood function are then estimated using a numerical maximization algorithm at each iteration repeating the simulation-based computation of the likelihood function starting from the updated values of the estimated parameters.

10. Experiments with up to 200 draws did not produce very different results.

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