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The role of human capital in structural change and growth in an open economy: Innovative and absorptive capacity effects

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Abstract

Since the financial crisis in 2008, slow growth has riddled Europe and the COVID-19 pandemic is amplifying the challenge. Promoting economic growth and transforming to a more knowledge-based industrial structure will be high on the agenda for the coming decades. We study how more and better human capital can contribute to knowledge accumulation and structural change by means of a dynamic endogenous growth model, with Norway as a numerical case. Human capital has two main roles in productivity growth: to increase the *innovative capacity* by participating in research and development (R&D), and to increase the *absorptive capacity* in sectors that trade and can learn from abroad. We find that in a small, open economy, sectors where human capital, R&D and trade interact and enable absorption, tend to grow fastest.

KEYWORDS

absorptive capacity, computable general equilibrium model, endogenous growth, human capital, innovation, research and development

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1 | INTRODUCTION

European economies, like most other OECD economies, have experienced a slowdown in productivity growth over the last two decades. European countries were particularly hard hit by the financial crisis in 2008 and were still struggling to recover when COVID-19 struck. As a result, the promotion of economic growth and shifting to a more knowledge-based industrial structure have been key concerns in European policy documents and analysis, see, for example European Commission (2010, 2018), Foster-McGregor et al. (2014), Runiewicz-Wardyn (2013) and Varga and in t' Veld (2014). Moreover, productivity growth has been addressed in several national reviews including the Danish Productivity Commission (2014) and Norwegian Ministry of Finance (2015, 2016).

This paper studies the role of human capital, that is highly educated labour, in transforming the economy through knowledge accumulation, productivity growth and structural change. We develop a numerical, dynamic endogenous growth model for a small, open economy, Norway, where human capital contributes to growth via two main channels: enhancing *innovative capacity* and *absorptive capacity*. While it is well established that highly educated labour is a key input into innovation based on research and development (R&D), its role in increasing the ability to absorb knowledge transfer from abroad is less explored and constitutes the innovative part of the present model. For small, open economies, this growth channel stands out as relatively more important (Coe & Helpman, 1995; Keller, 2004).

According to the literature on *skill-biased* or *skill-directed technological change*, human capital is an important determinant of growth by directing technological progress into human-capital-intensive industries; see pioneering works by Acemoglu (1998), Berman et al. (1994), and Kiley (1999). This mechanism is also present in our model. However, contrary to these models, which describe closed economies, our perspective of the small, open economy adds nuance to their findings. We show that owing to the importance of human capital for the absorptive capacity mechanism, the productivity growth achieved by increasing human capital is not unambiguously oriented towards human-capital-intensive industries. A numerically calibrated, more detailed model than is usually seen in the literature indicates that for the small, open economy case, increased access to human capital not least benefits the industries that grow through the absorption channel.

This analysis of how human capital impacts the industrial structure can be instructive for Norway's growth prospects for the coming decades. A restructuring of the economy and of educational orientation is expected. Norway's challenge is special, in that fifty years of human-capital-intensive offshore petroleum extraction has influenced the industrial structure and contributed to the accumulation of technological knowledge and to steady economic growth. However, given peaking availability of profitable offshore resources and increased competition from renewables coupled with intensified action against climate change (IEA, 2017; Norwegian Ministry of Finance, 2017), a knowledge-driven restructuring of the economy can be expected. The present analysis studies how increased access to human capital affects productivity. The access may be the result of providing a larger share of the population with high skills or, of more relevance to the current Norwegian and other European economies, of adapting the educational system so that the labour force attains a more relevant and useful skills composition, that is enhanced quality (European Commission, 2018; Runiewicz-Wardyn, 2013). This may take place as a response to the sunsetting of a prominent industry like Norwegian offshore petroleum extraction. In this case, human capital would also become directly available for the mainland economy as demand contracts in the offshore sector.[1] Irrespective of the narrative behind the increased

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[1] This would be but one, though a significant one, of several channels through which restructuring would be driven and macroeconomic impacts would occur.

human capital access, the present analysis seeks to give guidance as to how and where human capital flows and impacts productivity and industry patterns in a small, open economy.

The innovation channel is modelled as R&D-based, as in the Romer tradition (Romer, 1990). A vast literature highlights the empirical relevance of human capital input in this process; see Alvarez-Pelaez and Groth (2005), Coe and Helpman (1995), Griliches (1995) and Jones and Williams (2000). Besides domestic innovation, R&D is also shown to have another impact—or a second face, as formulated by Cohen and Levinthal (1989)—by increasing the absorptive capacity of the economy. The importance of R&D activities for absorption means that human capital input in R&D has an *indirect* influence on the economy's absorptive capacity. In addition, the level of human capital may have a *direct* impact on absorptive capacity (Benhabib & Spiegel, 1994; Keller, 2004). Specifically, while firms' international interactions through importing, exporting, investing, networking etc. potentially give access to the international technological frontier, the ability to make use of the global knowledge pool is directly dependent on *both* the home country's own R&D *and* its human capital. Empirical research has lent convincing support to this hypothesis (Augier et al., 2013; Griffith et al., 2004; Kneller & Stevens, 2006; Montinari & Rochlitz, 2014). Obviously, the smaller and the more open the economy, the more important this source of productivity growth will be (Coe & Helpman, 1995; Keller, 2004). Traditional industries with large absorption potential attributable to high trade and R&D intensity may benefit the most.

Our model includes both the innovation and the absorption channels for knowledge dispersion. *Innovative capacity* is spurred by increased output in the R&D industry, which produces patents and high-tech capital varieties based on patents. The R&D-based capital varieties encapsulate the knowledge generated by R&D firms, so that the R&D can be used as input by final-goods industries.[2] We assume that the R&D input is universal and can be adopted by industries with various factor compositions. As in the literature on skill-directed technological change, increased access to human capital tends to spur the input of R&D in final-goods industries that are also human-capital-intensive at the expense of other final-goods industries. This mechanism is also present in our model.

However, while the pioneer models of skill-directed technological change were of closed economies, the small, open case opens another major channel whereby human capital can spur growth: the *absorptive capacity* channel. International trading is empirically found to be the main mechanism.[3] A vast literature, surveyed by Wagner (2007, 2012), among others, indicates that along with human-capital input, trade intensities and R&D also seem important for the absorption of knowledge and productivity growth from abroad. While earlier studies focussed primarily on the import channel (Coe & Helpman, 1995), we also include export as a channel for absorption, in accordance with relatively new empirical evidence; see surveys by Lopez (2005) and Silva et al. (2013); see also Dilling-Hansen and Smith (2015) for Danish evidence.

The innovation and absorption channels of the model both feature positive productivity externalities quantified and calibrated by using empirical estimates from the literature; see Section 2.3

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[2] See Demsetz (1988) for the use of the term encapsulated knowledge in this manner.

[3] Another potential channel for spillovers is foreign direct investment (FDI), e.g., via multinational corporations. Though the empirical foundation is mixed (Görg & Greenaway, 2004), support is most robust for developing, emerging and transitional economies; see, e.g., Damijan et al. (2004), Harding and Javorcik (2012) and Ozturk (2007). We exclude FDI as a channel for the Norwegian economy, in light of two Scandinavian studies (Braconier et al., 2001; Grünfeld, 2002) that find no significant spillover effects attributable to inward FDI. See also Bye et al. (2011) for a discussion of channels for absorption.

for details. The innovation channel is characterised by the *standing-on-shoulders effect* (Romer, 1990), that is dynamic productivity spillovers onto each firm's R&D from the accumulated R&D knowledge stock. Patent production in the R&D industry also generates an external *love-of-variety effect*: the productivity of R&D-based capital used in final-goods industries increases with the number of patents/varieties. Finally, the *endogenous absorption* of spillovers from abroad involves externalities, as improvements in absorbed productivity at firm level depend on the extent of foreign trade and the absorptive capacity of the entire industry (Falvey et al., 2004). The latter effect is especially important for small, open economies. According to evidence, productivity effects fade out in the long term due to diminishing returns to innovation as in Jones (1999) and to absorption in line with the productivity gap assumption (Acemoglu et al., 2006; Griffith et al., 2004; Vandenbussche et al., 2006).

We find that increased availability of human capital benefits the productivity-enhancing sectors, including those with both innovation and absorption potential. For the small, open Norwegian economy, the absorptive capacity improvements attributable to human capital seem to be the dominant explanation for the structural changes taking place. Industries with a large absorption potential owing to high intensities of trade and R&D-based capital experience the strongest productivity growth and attract a larger share of the economic resources, including human capital, in the transitional phase. In the long run, economy-wide welfare improves because of the positive productivity externalities involved in the growth processes.

2 | AN ENDOGENOUS GROWTH MODEL WITH INNOVATION AND ABSORPTION

The description of the computable general equilibrium (CGE) model with endogenous growth focusses on the two represented productivity growth channels of the economy. The domestic *innovation* processes that are driven by the production and use of R&D-based capital is presented in Section 2.1. Thorough documentation of these features is provided in Bye et al. (2006). Section 2.2 explains the *absorption* processes in the final-goods industries and how they depend on the industries' input of human capital and R&D-based capital, as well as international trade relations. Section 2.3 is devoted to the empirical basis for the quantification of these mechanisms. The rest of the CGE model is briefly described in Section 2.4. Appendices A–C provide additional details on the formal model structure, parameter values, calibration and solution procedures.[4]

2.1 | Productivity growth through domestic innovation

Following the pioneering work by Romer (1990), domestic innovation in the model takes place within the R&D industry, which then provides R&D-based technologies. The process involves two distinct activities within each firm: (i) R&D that develops a patent and (ii) production of an R&D-based capital variety that is based on the patent. The industry output of patents, benefits from endogenous domestic productivity spillovers due to an accumulated stock of knowledge (the *standing-on-shoulders effect*), R, and that is freely accessible, thus

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[4] Transfers, and tax and subsidy wedges are suppressed in the expositions.

$$X_R = R^{s_1} \tau_R^* VF_R^s \tag{1}$$

and $R = R_{-1} + X_R$. The parameter s_1 denotes the elasticity with respect to domestic spillovers. Following Jones (1995), we assume decreasing returns to scale in R&D production so that s_1 is less than unity. The productivity growth dynamics generated by the accumulated stock of R&D knowledge, R, is external to the individual patent producer, which is too small to take into account the effect of its own output on the accumulated stock of patented knowledge. This implies a market imperfection. $s < 1$ is the scale elasticity of the variable input factors, VF_R, used for production of R&D. The R&D industry also benefits from spillovers from abroad through interactions with researchers internationally, journal articles, patents, etc. These spillovers are considered exogenous and are represented by τ_R^*.

The development of a patent represents a fixed establishment cost for a new firm in the R&D industry before the firm enters the market for R&D-based capital goods with a new and distinct variety, K_i^V.[5] Based on the assumption of value maximisation for the representative firm and that profit is equal for all firms, R&D firms enter until the shadow price of developing a patent (the entry cost) is equal to the discounted net profit of the marginal firm.

R&D-based capital varieties are partly exported and partly delivered to domestic final-goods industries. The input of R&D knowledge that is encapsulated in the capital varieties (henceforth *R&D input*) varies in intensity across final-goods industries.[6] An R&D firm exhibits its market power in the domestic market for its variety and obtains a monopoly price in its niche. Apart from producing different capital varieties, the R&D firms are equal. The export price is exogenous.

The R&D input in final-goods industries is represented by a Spence-Dixit-Stiglitz (love-of-variety) preference for a composite of varieties, K^V:

$$K^V = \left[\sum_{i=1}^{R} \left(K_i^V\right)^{\frac{(\sigma_{KV}-1)}{\sigma_{KV}}} \right]^{\frac{\sigma_{KV}}{(\sigma_{KV}-1)}} . \tag{2}$$

The accumulated stock of R&D knowledge, R, also represents the number of firms in the R&D industry and of available capital varieties. Love of variety implies that the larger the number of varieties, the more productive is K^V, the R&D input of the final-goods firms. σ_{KV} is the uniform elasticity of substitution that is applied to all pairs of capital varieties. It is common to all final-goods industries. The more varieties there are, the higher the productivity of the R&D input (K^V) within the final-goods industries. We refer to this as a quality rise of the R&D input. This *love-of-variety effect* represents a second external productivity growth mechanism stemming from R&D that benefits the final-goods firms, particularly those in industries with intensive the R&D input. Again, the R&D-producing firms are too small for their impact on the productivity of the use of the aggregated composite, K^V, in final-goods industries to be taken into account. The input intensity of R&D within a final-goods industry j, $\frac{K_j^V}{VF_j}$, varies with j and determines the R&D influence on absorptive capacity, which is presented in more detail in the next section.

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[5] The scale elasticity, s, is common to all sectors and also applies to R&D-based capital production.

[6] In the R&D industry, the input of K^V is per definition zero in both patent production and R&D-based capital production to avoid cumulative love-of-variety multiplicators. Note that there are, thus, no absorptive capacity effects through R&D-based capital investment in the R&D industry; see Section 2.2.

2.2 | Productivity growth in firms through absorption of international knowledge

In general terms, the production technology of firm *i*, irrespective of final-goods industry, can be represented by

$$X_i\left(X_i^H, X_i^W\right) = g_i\left(VF_i\right) \tag{3}$$

where X_i^H, X_i^W represent production for domestic and export deliveries, respectively, and VF_i is a nested constant-elasticities-of-substitution (CES) function containing a number of variable inputs (see Figure B.1 in Appendix B). The simplified version of VF_i can be represented by

$$VF_i = \tau \cdot f_i\left(H_i, L_i, K_i^V, K_i^M, V_i\right) \tag{4}$$

where H_i, L_i, K_i^V, K_i^M, and V_i represent the firm's input of human capital, other labour, R&D, other capital than R&D and intermediates respectively. The elasticity of substitution between human capital and other labour is 2 which is in the upper part of the range for Norwegian estimates (Bjørnstad & Skjerpen, 2006).[7] The productivity effect on the firms of domestic innovation is channelled through input of the aggregated composite of R&D-based capital varieties, K^V. Factor inputs also depend on a factor-neutral, endogenous productivity level τ, which is common to all firms in the industry and, as such, has no subscript. We assume, see Equation (5), that the growth in τ is partly exogenous and partly dependent on the endogenous industry-specific capacity to absorb spillovers from abroad, following, for example Griffith et al. (2004).

$$\dot{\tau} = \dot{\tau}* + \left(\lambda_1 A + \lambda_2 B\right)\Delta. \tag{5}$$

Most studies of small, open economies take into account an exogenous growth driver. The first term, $\dot{\tau}*$, represents this productivity 'flowing in' from abroad. The second term accounts for the absorptive capacity effects. Productivity growth also depends on endogenous export and import impetuses, represented by the terms A and B, as well as on the productivity gap, Δ, from the exogenous frontier, τ^F; i.e., $\Delta = \frac{(\tau^F - \tau)}{\tau^F}$; that is; see, for example Griffith et al. (2004). The productivity-gap effect hypothesises that productivity growth diminishes as the exogenous frontier is approached.

Our modelling of trade channels is supported by empirical findings of the relationship between domestic productivity impetuses and trade (see, e.g. Harris & Moffat, 2015). Earlier studies focussed on the learning by importing in domestic firms acquired through competing with foreign, more advanced products. The import channel is empirically supported by a number of studies; see, for example Keller (2010) for an overview of the literature. We also include export as a channel for absorption in accordance with relatively convincing empirical evidence; see surveys by Lopez (2005) and Silva et al. (2012); see also Dilling-Hansen and Smith (2015) for Scandinavian evidence in the case of a small, open economy. There are still unsettled disputes on the causality between productivity and export. The focus has gradually shifted from causality going from high productivity to export, that is a self-selection effect

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[7] Sensitivity tests indicate that an elasticity of substitution of <2 implies price/wage rates for human capital that are close to and in some cases even lower than for other labour in the first years of the simulation period. The model is also quite sensitive to changes in the supply of human capital.

(Bernhard & Jensen, 1999; Clerides et al., 1998), to emphasis also on the opposite relationship. Recent studies show that exporting serves as an important learning channel, particularly for small, open economies (Aw et al., 2011; Baldwin & Gu, 2003; Girma et al., 2008; Salomon & Shaver, 2005). These two causality theories are not mutually exclusive: not only do innovators export more; exporters also innovate more (Andersson & Lööf, 2009). In other words, self-reinforcing effects occur: the more productive an industry becomes, the more export and learning results.

The export and import channels for absorption are modelled as follows:

$$A = \Omega^H \cdot \Omega^R \cdot \frac{X^W}{X}, \tag{6}$$

$$B = \Omega^H \cdot \Omega^R \cdot \frac{I}{X^H}. \tag{7}$$

The term A accounts for the absorbed productivity's dependence on industry exports, X^W, as a share of total output, X. The term B describes the corresponding dependence on industry imports, I, measured relative to domestic deliveries of similar products from domestic firms within the industry, X^H. We denote the absorptive capacity effects of R&D intensity (κ^R) and human capital (H) in the industry as $\Omega^R\left(\kappa^R\right)$ and $\Omega^H(H)$, respectively, both functions increasing but with decreasing returns. All firms are symmetric, and we assume that they do not consider the strategic effects of adjusting their trade, R&D intensity or input of human capital on their absorbed productivity, that is there are external knowledge spillovers among firms. Despite methodological challenges and great uncertainty (Lopez, 2005; Silva et al., 2013), such externalities are empirically supported by several studies; see, for example Aw (2002), Alvarez and Lopez (2008), Falvey et al. (2004) and Greenaway and Kneller (2008).

2.3 | Quantifying the two productivity growth channels

The domestic spillover elasticity s_1 is set as 0.5 to ensure that the spillover effects of the knowledge base decrease, as supported by both theoretical and empirical findings (see Jones, 1995; Jones & Williams, 1998; Leahy & Neary, 1999). The elasticity of substitution between capital varieties σ_{KV} is 3.0. The higher the elasticity, the smaller the productivity effect the users of the R&D input attain from another capital variety. We have chosen a relatively high elasticity to ensure a conservative estimate of the love-of-variety effect. The scale parameter, s, is quantified based on Norwegian estimates (Heide et al., 2004).[8]

We use an estimated 1 percent average future total factor productivity (TFP) as a benchmark for calibrating the productivity growth in Equation (5) in the reference path (see Appendix C for more details of the reference path). This is based on the historical average annual TFP growth rates for Norway and is in line with the long-term projections for the Norwegian economy. To split the growth depending on whether it stems from domestic innovation or absorption, we rely

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[8] We have previously tested the growth model's performance for variations in central parameters, including the spillover parameter and the substitution elasticity between R&D-based capital varieties. Increases and decreases of these parameters have symmetric effects and the sensitivities appear fairly similar irrespective of scenarios; Bye et al. (2009).

on Coe and Helpman (1995) and Keller (2004). We calibrate 10 percent of domestic growth as stemming from domestic innovation. This lies in the lower range of the existing estimates for small, open economies and is based on the fact that several endogenous mechanisms believed to drive domestic innovation are excluded from the model, such as basic governmental research, endogenous education and learning by doing.

The elasticities given above and the rest of the parameters in the model (see Appendices B and C), along with the domestic innovation contribution to growth, calibrated as described, form a basis for calibrating the base level of accumulated knowledge, R_0.

The growth in absorbed productivity, τ in Equation (5), constitutes the remaining 90% of the productivity growth. The values of λ_1, λ_2, φ^R and φ^H determine the contributions of the absorptive capacity factors, human capital and R&D intensity, on the import and export channels respectively. Estimates of absorptive capacity effects through the import channel for Norwegian industries are found in Grünfeld (2002), who reports an elasticity of total productivity growth with respect to the R&D content of imports of 0.05. These results are broadly in line with Griffith et al. (2004) and with the import channel impact in Coe and Helpman (1995) when we take into account that they have not specified the influence of absorptive capacity. Export effects are found in Alvarez and Lopez (2008), Delgado et al. (2002), Baldwin and Gu (2003) and Falvey et al. (2004). The evidence as to which channel dominates is mixed, and we ascribe identical impetuses to them: that is $\lambda_1 = \lambda_2 = 0.05$.

It remains to quantify the relative contributions to absorptive capacity of R&D intensity and human capital. We do this by specifying the Ω^R and Ω^H functions:

$$\Omega^R = \frac{\varphi^R \kappa^R}{\frac{\varphi^R}{2} + \kappa^R},\ \Omega^{R'} > 0,\ \Omega^{R''} < 0,\ \varphi^R > 0, \tag{8a}$$

$$\Omega^H = \frac{\varphi^H H}{\frac{\varphi^H}{2} + H},\ \Omega^{H'} > 0,\ \Omega^{H''} < 0,\ \varphi^H > 0, \tag{8b}$$

where $\kappa^R = \frac{K^V}{VF}$ and H are both indices normalised to base-year level. These functional forms ensure that industries engaging in foreign trade increase their capacity to learn from this interplay with foreign agents if the availability of human capital or the intensity of R&D input within the industry increases, though with decreasing returns.[9] The positive signs of the parameters φ^R and φ^H ensure these features. The empirical literature on their relative strength is both sparse and mixed, and only a few contributions see them in in relation to one another. Following Griffith et al. (2004), we assign similar strengths to the two factors, that is $\varphi^R = \varphi^H = \varphi$. Figure 1 shows the sensitivity of the absorptive capacity function, $\Omega^i (i = R, H)$, to different values of the absorptive capacity parameter, φ, and to the levels of the indices.

As φ determines the diminishing returns to absorptive capacity, we have calibrated it to 4 to ensure balanced growth in the long run (see Section 2.4 and Appendix C). The absorptive capacity effects are uncertain, and we present some sensitivity scenarios in Section 3. Once all other growth impetuses have been quantified, the exogenous growth in τ^* can be calibrated to account for the remaining growth in absorbed productivity.

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[9] Formulating trade and R&D in intensity terms in Equations (6), (7) and (8a) while introducing human capital in level terms in Equation (8b), is in accordance with the formulations in Griffith et al. (2004). Note that both are measured as indices with value 1 in the base year.

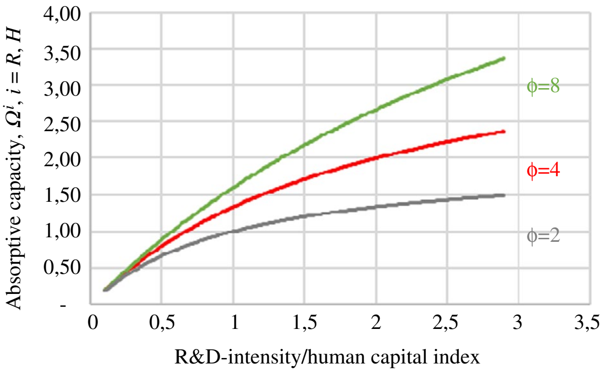

FIGURE 1 The absorptive capacity function for different R&D-intensity/human-capital indices and absorptive capacity parameters

2.4 | Other market behaviour, equilibrium and balanced growth

We have grouped the economic production activities into eight sectors; see Appendix A. Final-goods industries deliver to final-goods markets and produce intermediates for each other according to an empirical input–output structure based on the Norwegian National Accounts. Each firm has perfect foresight and maximises the present value of the after-tax cash flow. For final-goods industries, we assume perfect competition among numerous firms within each industry, and the first-order conditions equate prices with marginal costs for deliveries to both the foreign and the domestic markets. Foreign and domestic markets are segmented due to the transformation costs involved in switching between the markets, and this is represented by a constant elasticity of transformation (CET) technology.

Production technologies for all industries are represented by nested CES structures (see Figure B1 in Appendix B). All industries differ in their use of the main factors of production. The factor *human capital* is characterised by having more than four years of university or equivalent education. *Other labour* represents the rest of the labour force. These two factors are perfectly mobile within the country, but immobile across borders, and they are imperfect substitutes. In addition, industries use two types of capital. *R&D* is capital goods that encapsulate R&D knowledge generated in the R&D industry. One patent is developed in each R&D firm, and the firm produces one capital variety based on the patent. *Other capital* constitutes ordinary, less high-tech goods.

Final goods and other capital are importable, and imported and homemade varieties are imperfect substitutes (Armington, 1969), implying that for each good the ratio of imports to home deliveries is determined by the ratio of the domestic price to the import price. International prices are determined by the world market, as is the interest rate, all exogenous to domestic firms.

Consumption and savings result from the decision of a representative consumer with infinite life and perfect foresight that maximises the intertemporal utility of total consumption. The consumer chooses a consumption path subject to an intertemporal budget constraint that requires the present value of consumption not to exceed total wealth (current non-human wealth plus the present value of labour income and net transfers). Consumption is distributed across 10 different goods and services according to a nested CES structure (see Figure B.2 in Appendix B). The representative consumer supplies human capital and other labour in exogenous amounts. One public sector collects taxes, distributes transfers and purchases goods and services from domestic industries and from abroad in fixed quantities. Welfare effects can be measured by changes in discounted consumer utility.

The model is characterised by equilibrium in each period in all product and labour markets. Intertemporal equilibrium requires the fulfilment of two transversality conditions: the limit values of the total discounted values of net foreign debt and real capital must be zero. The model is characterised by a path-dependent, balanced growth path solution (or steady-state solution); see Sen and Turnovsky (1989). This model implies that both the path and the long run stationary solution differ across simulated scenarios.

To ensure a long run, *balanced growth path*, the following conditions must be fulfilled: (1) the rate of technological change for each input factor in each industry must converge to the same rate, *g*, such that each industry grows at the same rate, (2) growth in per capita consumption equals g, and (3) the population growth rate is constant. For technical reasons, we have set all exogenous and endogenous growth drivers to zero in the far future (after approximately 100 years) to ensure that a balanced growth path is reached within a limited number of periods. This is consistent with decreasing returns to scale in both innovation and absorption. The growth rate may vary along the transitional path. Bye et al. (2006) and Appendix C provide further details.

3 | ANALYSIS: GROWTH AND STRUCTURAL EFFECTS OF HUMAN CAPITAL

We simulate a positive shift in the level or quality of human capital available for productivity-enhancing sectors and track how Norway's mainland economy is affected in terms of long-term economic structure and productivity. The shift represents a 20 percent increase in the first simulation period of available human capital resources, defined as personnel with more than four years of university education or equivalent and a corresponding reduction in the number of low-skilled personnel. As already indicated, there may be several underlying reasons for this change. The intention of this analysis is to understand the channels through which human capital will flow in an open economy with a realistic industrial composition, calibrated to the Norwegian economy.[10] We concentrate on long run impacts, and we omit cost aspects of improving or reorienting the educational system to obtain the increase in human capital, as well as administrative costs and cost of raising public funds to cover increased public spending.

Our findings prove to be particularly reliant on quantification of the absorptive capacity mechanisms. To better understand and interpret the implications of the main novelties of this model, the impact of human capital on absorption of knowledge from abroad, we have simulated two sensitivity scenarios in addition to the main scenario. *Sensitivity 1* totally excludes the absorptive capacity effect of human capital, while *Sensitivity 2* reinforces this effect. See also the discussion related to Figure 1 on impacts of alternative parameter values for the absorptive capacity equations in Section 2.3.

3.1 | Numerical results

The immediate effects of the positive shift, according to the Rybczynski theorem (Rybczynski, 1955), are that human capital will substitute for other labour and other input factors in all industries and that human-capital-intensive industries will expand in relative terms. The relative factor intensities for the most relevant and influential industries, calculated as their share of

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[10] The simultaneous reduction of low-skilled workers makes the shift a better fit for illustrating higher or improved education than for interpreting it as an inflow of human capital to the mainland economy from the offshore sector.

TABLE 1 Base-year factor intensities of selected private industries, measured as factor expenses relative to value-added

	Factor intensities			
Industry	**Human capital**	**(Other) labour**	**R&D**	**(Other) capital**
R&D	0.33	0.53	—	0.14
Consumer goods and services—CGS	0.04	0.79	0.02	0.15
Export-oriented manufacturing—EOM	0.04	0.55	0.05	0.36

Source: National Accounts, Statistics Norway.

base-year value-added according to the Norwegian National Accounts, are reported in Table 1. The most human-capital-intensive sector is the R&D industry, indicating that increased availability of human capital will increase the innovative capacity of the economy. More R&D output will initiate a productivity improvement by stimulating investment of R&D-based capital in final-goods industries. The most pronounced example of an industry intensively using R&D-based capital as input is export-oriented manufacturing (EOM). The simultaneous incidence of enhanced production of R&D and increased availability of human capital implies that technological improvements tend to be biased towards final-goods industries that combine R&D intensity with human-capital intensity, as EOM does. Labour-intensive industries, in Table 1 exemplified by consumer goods and services (CGS), have considerably lower growth potential due to less intensive use of R&D and other capital. In addition to the innovative capacity improvements attributable to human capital, the absorptive capacity of knowledge spillovers through trade will improve as a result of an increased supply of R&D and of human capital. This also affects the ways in which technological progress occurs and contributes to overall economic growth.

Besides GDP and welfare impacts, Table 2 reports effects on output, resource flows and productivity for the same selected, representative industries shown above: the R&D industry (human-capital-intensive), the CGS industry (labour-intensive) and the EOM (R&D and capital-intensive). This last is also trade-intensive: trade intensity measured as gross trade relative to gross product amounts to more than 2.[11] The effects in all scenarios are measured as percentage changes from a benchmark scenario (see Section 2.3 and Appendix C).

As observed in Table 2, the Rybczynski effect is evident as a result of a considerable up-scaling of the human-capital-intensive R&D industry. It leads to a 15.5 percent increase in the production of patents and a 5.3 percent increase in of R&D-based capital. In addition to the favourable effect of the increased availability of human capital, the R&D industry benefits from positive productivity externalities from standing on the shoulders of previous R&D efforts, as a result of an 8.6 percent increase in the number of R&D firms/patents.

The relative expansion of the human-capital-intensive industries following the increased availability of human capital is mirrored by a fall in the price of human capital relative to the wage rate for labour. The industries most adversely affected by the wage changes are the relatively labour-intensive industries, represented in Table 2 by the CGS industry with an increase in production of only 1.7 percent.[12]

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[11] Gross trade of good *i* is the sum of gross exports and gross imports of good *i*.

[12] Table 1 presents direct factor intensities. The input-output-modified intensities are more relevant in explaining the Rybczynski and reallocation effects. These, however, are not easily quantified in a complex CGE model.

TABLE 2 Industrial output and resources in main scenario, percentage changes from benchmark, long run

R&D industry (human-capital-intensive)	
Number of firms/patents/varieties	8.6
Patent production	15.5
R&D-based capital production (domestic deliveries)	5.3 (7.9)
Human capital input in patent production	20.7
Human capital input in R&D-based capital production	21.9
Absorbed productivity	1.0
Consumer goods and services—CGS (labour-intensive)	
Production	1.7
Human capital input	18.3
R&D-based capital input	5.4
Absorbed productivity	2.1
Export-oriented manufacturing—EOM (R&D and capital-intensive)	
Production	6.9
Human capital input	23.7
R&D-based capital input	10.5
Absorbed productivity	2.8
Economy-wide effects	
GDP	3.9
Welfare[a]	1.7

[a] Percentage change in discounted value of consumption.

As input of R&D encapsulated in patent-based capital is universally applicable, the combination of increased R&D and increased human capital availability may potentially lead to a human-capital-biased technological change in the final-goods sector, as demonstrated in the theoretical models of Acemoglu (1998) and Kiley (1999). However, the final-goods sector in this empirically based model is far more complex. The differences in R&D intensity across industries are empirically more decisive for technological direction than the much smaller variation in their human-capital intensity. We find that productivity growth first and foremost takes place in industries that are relatively R&D-intensive, as shown by the expansion of the EOM industry. This industry benefits from technological progress through the higher quantity *and* quality (the love-of variety effect) of its R&D input, which rises by 10.5 percent; the average rise in the domestic market is 7.9 percent. The love-of-variety effect gives rise to a quality increase, which causes the price per efficiency unit of R&D-based capital to drop by 3.3 percent in the long run. The EOM industry is not particularly human-capital-intensive in this economy, as Table 1 indicates. Hence, our finding for this small, open economy deviates from the skill-biased technological change demonstrated in closed economy models (Acemoglu, 1998; Kiley, 1999). The EOM industry increases its production by 6.9 percent. This is partly explained by the absorbed productivity effect catalysed by human capital. Note that the absorption process is self-reinforcing, as higher productivity increases export, which further increases absorbed productivity. Industries that are R&D-intensive therefore enjoy both innovation and absorption-based productivity growth, which explains the 6.9 percent increase of output in EOM. Table 2 shows that significant absorbed productivity effects are also seen for the other industries, though weaker than for EOM.

To sum up, the result of more human capital is partly to expand the human-capital-intensive R&D industry and partly to stimulate the EOM industry. Thus, growth is partly R&D-driven and partly a result of spillovers from abroad. GDP raises by 3.9 percent in the long run, when growth effects have faded out. The welfare gain of 1.7 percent, computed as the discounted value of real consumption, originates from external standing-on-shoulders effects among R&D firms, love-of-variety effects of R&D utilised by final-goods industries and external spillovers absorbed from abroad. Our model analysis illustrates that the economy becomes more productive both through domestic R&D-based innovation and through absorbing productivity spillovers from abroad, and human capital has a key part in both these processes. The sensitivity scenarios below elaborate more on the absorptive capacity effect of human capital.

3.2 | Sensitivities of the absorptive capacity effect of human capital

In *Sensitivity 1*, we assume no absorptive capacity effects of human capital[13] to illustrate its importance as a driver behind the increase in absorptive capacity. In this case, the economy gains less from cross-border productivity spillovers. The result is an industrial pattern less biased towards the EOM industry than in the main scenario. As Table 3 shows, a smaller amount of human capital now flows to EOM and more is kept in the relatively more human-capital-intensive R&D industry, leading to a relative increase in the production of patents when compared with the main scenario. More patents imply a larger productivity gain for R&D firms from standing on the shoulders of previous R&D efforts and a larger love-of-variety improvement in the quality of R&D enjoyed by final-goods industries. The absorption processes in this alternative scenario are fuelled only by increased R&D and do not directly benefit from an increased availability of human capital. Nevertheless, we find a significant, but smaller, increase in absorbed productivity from abroad for the EOM industry. Growth is slower, and the long run GDP ends up only 2.1 percent above the benchmark scenario in *Sensitivity 1*.

Eliminating the direct absorptive capacity effect of human capital in this sensitivity test serves to decompose the result of the main scenario. It reveals that this direct absorptive capacity effect has a significant crowding-out effect on domestic innovation and that this benefits growth.

In Sensitivity 2, we triple the initial absorptive capacity effect of human capital in EOM to explore the crowding-out effect further.[14] The most striking effect is that human capital is attracted by the EOM industry, and in the long run, EOM increases its production by 7.5 percent. More human capital does not stimulate R&D activity: rather, production of patents falls by 24.7 percent, while R&D-based capital production falls by 14.7 percent. The results for this sensitivity illustrate that increasing the availability of human capital does not necessarily increase R&D activity. With a sufficiently strong absorptive capacity channel, R&D activity is totally crowded out by productivity growth in EOM. In this sensitivity scenario, we are left with endogenous domestic technological progress entirely dominated by international knowledge spillovers, and the lack of innovation stimulus implies that GDP growth is lower than in *Sensitivity 1* and in the main scenario.

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[13] $\Omega^H = 0$, see Equations (6), (7) and (8b) in Section 2.

[14] In eq. (8b), Ω^{H} is initially three times larger for a given H. Along the path, the difference weakens according to the assumed diminishing absorptive capacity effects. In the long run, the difference is only 10 percent.

TABLE 3 Sensitivities, percentage changes from relevant benchmark, long run

	Sensitivity 1	Sensitivity 2
R&D industry		
Patent production	19.3	−24.7
R&D-based capital production	6.1	−17.7
Human capital input in patent production	23.8	−14.7
Human capital input in R&D-based capital production	24.5	0.2
Export-oriented manufacturing		
Production	3.6	7.5
Human capital input	21.5	30.2
R&D-based capital input	9.4	−5.7
Absorbed productivity	1.5	2.3
Economy-wide effects		
GDP	2.1	1.0

4 | CONCLUDING REMARKS

The efforts of most European governments to stimulate productivity growth in the aftermath of the financial crisis in 2008 have become even more critical now in the recovery after the COVID-19 pandemic that hit the world economy in 2020. Improving education and adapting knowledge to become more relevant and future-oriented is part of these efforts. Increased availability of human capital tends to favour the human-capital-intensive parts of the economy. This point is familiar from the large, closed economy models of Acemoglu (1998) and Kiley (1999). In the small, open economy case of the present study, productivity spillovers from abroad are stimulated by greater access to human capital. This absorption channel proves to be the dominant explanation for the structural changes taking place. Industries with a high absorption potential because of extensive international trading and intensive use of R&D have the highest productivity growth and attract relatively more of the economic resources, including human capital. Recently, free trade has faced rising political resistance in large economies and some of Norway's key trading partners such as the United States and the UK. This unrest adds uncertainty with respect to the potential of the absorption channel as a means of recovering from the pandemic.

Some features of our model and results deserve critical discussion and further examination in future research. First, in our model, the increased abundance of human capital turns out to have little impact on the direction of technological change. Rather, trade intensity is the major determinant of its direction. If productivity spillovers were internalised, not made external as in our model, the bias towards human capital would be more pronounced. Firms would then strategically invest in absorptive capacity, and investment in human capital would intensify to a larger extent in response to the human capital increase.

Second, our model of innovation and absorption relies on the assumption that human capital is crucial to both processes. However, Acemoglu et al. (2006) and Vandenbussche et al. (2006) model qualitatively different key resources in the two processes; they assume that innovation requires more selected, specific human capital resources than does absorption. Their model and empirical findings indicate that more diversification of human capital would affect the bias of technological change, a point we cannot capture in a model with generic human capital.

As we have indicated, the studied shift in the amount or quality of human capital can have different backgrounds and take place in very different contexts. The most obvious interpretation is that the provision of increased or reoriented education increases access to human capital or quality at the expense of other labour. However, it is pivotal to stress that several aspects of such a reform are omitted from our simulations. Access to human capital will not come in isolation. The alternative costs of strengthening the education system, including the public spending that would have to be funded, are not part of the computation. Other factor reallocations that would take place simultaneously are not accounted for. For instance, improving the educational system would require investment in teaching capacity, buildings and laboratories that would crowd out other human and real capital use.

The intention of the present study is merely to identify human capital flows and not to indicate the multifaceted implications of any particular context. While it is easy to acknowledge that this is a limitation, the modelling of complex economies and trends will always need to simplify and exclude; this is the very nature of modelling exercises. It cannot be claimed that the magnitude or timing of the simulated effects have direct relevance for policy. Realistically, the process will be slower and more irregular, and the available human capital will not necessarily be of immediate use to the economy. The mechanisms and interplays we identify may nevertheless inform policies for structural change, growth and human capital generation.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX A

SECTORS

- R&D industry (producing patents and R&D-based capital)
- Consumer Goods and Services industry
- Export-Oriented Manufacturing industry
- Intermediate Services
- Production and Distribution of Energy
- Ordinary Machinery Production
- Exogenous Offshore Sector
- Public sector

APPENDIX B

THE MODEL STRUCTURE AND CALIBRATION OF FIRM AND HOUSEHOLD BEHAVIOUR

When firm notation *i* is suppressed, all variables in the equation apply to firm *i*. Subscripts denoting industry are also suppressed for most variables. Subscript 0, −1 or *t* denotes period. When period specification is absent, all variables apply to the same period. In contrast to the exposition in Section 2, we disregard inputs of intermediate goods. In consumption, *i* denotes good *i* and *j* denotes CES composite *j*. For the sake of simplicity, other policy variables in the CGE model are disregarded.

Final-goods industries

$$PV_0 = \int_0^\infty e^{-rt}\left(\pi_t - P_t^J J_t\right) \mathrm{d}t = \int_0^\infty e^{-rt}\left(\pi_t - P_t^K K_t\right) \mathrm{d}t + P_0^J K_0 \tag{B.1}$$

$$\pi = P^H X^H + P^W X^W - w\tilde{L} \tag{B.2}$$

$$\left[\left(X^H\right)^\rho + \left(X^W\right)^\rho\right]^{\frac{1}{\rho}} = \left[f\left(\%\tilde{L}\tau, K\tau\right)\right]^s \tag{B.3}$$

$$\dot{\tau} = \dot{\tau}* + \left(\lambda_1 A + \lambda_2 B\right)\Delta = \left(\lambda_0 + \lambda_1 A + \lambda_2 B\right)\Delta \tag{B.4}$$

$$A = \Omega^H \cdot \Omega^R \cdot \frac{X^W}{X}, \tag{B.5}$$

$$B = \Omega^H \cdot \Omega^R \cdot \frac{I}{X^H} \tag{B.6}$$

$$\Omega^R = \frac{\phi\left(\frac{K^V/VF}{K_0^V/VF_0}\right)}{\frac{\phi}{2} + \frac{K^V/VF}{K_0^V/VF_0}},\ \Omega^{R'} > 0,\ \Omega^{R''} < 0 \tag{B.7a}$$

$$\Omega^H = \frac{\phi\frac{H}{H_0}}{\frac{\phi}{2} + \frac{H}{H_0}},\ \Omega^{H'} > 0,\ \Omega^{H''} < 0 \tag{B.7b}$$

$$C = c\left[\left(X^W\right)^{\frac{1}{s}} + \left(X^H\right)^{\frac{1}{s}}\right] \tag{B.8}$$

$$\overline{\pi} = P^H X^H - c\left(X^H\right)^{\frac{1}{s}} + P^W\left(1+\alpha_2\right)X^W - c\left(X^W\right)^{\frac{1}{s}} \tag{B.9}$$

$$P^H = \frac{c}{s}\left(X^H\right)^{\frac{1-s}{s}} \tag{B.10}$$

$$P^W = \frac{c}{\left(1+\alpha_2\right)s}\left(X^W\right)^{\frac{1-s}{s}} \tag{B.11}$$

$$s = 1/\rho \tag{B.12}$$

$$w = \left[\delta_L\left(w_L\right)^{\left(1-\sigma_L\right)} + \left(1-\delta_L\right)\left(w_H\right)^{\left(1-\sigma_{HL}\right)}\right]^{\frac{1}{1-\sigma_{HL}}} \tag{B.13}$$

$$H = \left(1-\delta_H\right)\left(\frac{w_H}{w}\right)^{-\sigma_L}\tilde{L} \tag{B.14}$$

$$L = \delta_L\left(\frac{w_L}{w}\right)^{-\sigma_{HL}}\tilde{L} \tag{B.15}$$

$$K = \left[\delta_{KM}\left(\frac{K^M}{\delta_{KM}}\right)^{\left(\frac{(\sigma_K-1)}{\sigma_K}\right)} + \left(1-\delta_{KM}\right)\left(\frac{K^V}{\left(1-\delta_{KM}\right)}\right)^{\left(\frac{(\sigma_K-1)}{\sigma_K}\right)}\right]^{\left(\frac{\sigma_K}{(\sigma_K-1)}\right)} \tag{B.16}$$

$$K^{V} = \left[\sum_{i=1}^{R} \left(K_i^{V}\right)^{\frac{(\sigma_{KV}-1)}{\sigma_{KV}}} \right]^{\frac{\sigma_{KV}}{(\sigma_{KV}-1)}} \tag{B.17}$$

$$P^{KV} = \left[\sum_{i=1}^{R} \left(P_i^{KV}\right)^{(1-\sigma_{KV})} \right]^{\frac{1}{(1-\sigma_{KV})}} \tag{B.18}$$

$$J^{KM} = \dot{K}^{M} + \mu^{KM} K^{M} \tag{B.19}$$

$$P^{KM} = (r + \mu^{KM}) P^{JM} - \dot{P}^{JM} \tag{B.20}$$

$$J^{KV_i} = \dot{K}_i^{V} + \mu^{KV} K_i^{V} \tag{B.21}$$

$$P^{KV_i} = (r + \mu^{KV}) P_{K_i}^{H} - \dot{P}_{K_i}^{H} \tag{B.22}$$

R&D industry

Equation (B.1) applies to R&D activity. In addition, the following structure describes R&D (patent) production:

$$\pi = P_R X_R - w\tilde{L} \tag{B.2$'$}$$

$$X_R = R^{s_1} \tau_R^{*} V F_R^{s} \tag{B.3$'$}$$

$$C = \frac{c}{(R)^{s\frac{1}{s}}} \left[X_R\right]^{\frac{1}{s}} \tag{B.8$'$}$$

$$R = R_{-1} + X_R \tag{B.20}$$

$$\overline{\pi} = P_R (1 + \beta) X_R - \frac{c}{(R)^{s\frac{1}{s}}} \left(X_R\right)^{\frac{1}{s}} \tag{B.9$'$}$$

$$P_R = \frac{c}{(1 + \beta)\, s (R)^{s\frac{1}{s}}} \left(X_R\right)^{\frac{1-s}{s}} \tag{B.10$'$}$$

Each high-tech capital variety is delivered both to the home and export market in quantities X_{Ki}^{H} and X_{Ki}^{W}, respectively, during each period. For each variety, Equations (B.2) and (B.12) apply, in addition to the following:

$$PV_{i0} = \int_0^\infty e^{-rt}\left(\pi_{it} - P_t^K K_{it}\right)\mathrm{d}t - P_{R0} + P_0^J K_{i0} \tag{B.1''}$$

$$\left[\left(X_{Ki}^H\right)^\rho + \left(X_{Ki}^W\right)^\rho\right]^{\frac{1}{\rho}} = \left[f\left(\%\overline{L}_i\tau, K_i^M\tau\right)\right]^s \tag{B.3''}$$

$$C_i = c\left[\left(X_{Ki}^W\right)^{\frac{1}{s}} + \left(X_{Ki}^H\right)^{\frac{1}{s}}\right] \tag{B.8''}$$

$$\overline{\pi}_i = P_{Ki}^H\left(X_{Ki}^H\right)X_{Ki}^H - c\cdot\left(X_{Ki}^H\right)^{\frac{1}{s}} + P_K^W\left(1+\alpha_3\right)X_{Ki}^W - c\cdot\left(X_{Ki}^W\right)^{\frac{1}{s}} \tag{B.9''}$$

$$P_{Ki}^H = m_{Ki}\frac{c}{s}\left(X_{Ki}^H\right)^{\frac{1-s}{s}} \tag{B.10''}$$

$$\varepsilon_{Ki} = -\frac{\partial X_{Ki}^H}{\partial P_{Ki}^H}\frac{P_{Ki}^H}{X_{Ki}^H} \tag{B.23}$$

$$m_{Ki} = \frac{\varepsilon_{Ki}}{\varepsilon_{Ki} - 1} = \frac{\sigma_{KV}}{\sigma_{KV} - 1} \tag{B.24}$$

$$P_K^W = \frac{c}{(1+\alpha)s}\left(X_{Ki}^W\right)^{\frac{1-s}{s}} \tag{B.11''}$$

$$(1+\beta)P_{R0} = \int_0^\infty e^{-rt}\left(\overline{\pi}_i\right)\mathrm{d}t \tag{B.25}$$

Consumer behaviour

$$U_0 = \int_0^\infty u\left(d_t\right)e^{-\theta t}\mathrm{d}t \tag{B.26}$$

$$u(d_t) = \frac{\sigma_d}{\sigma_d - 1}d^{\left(\frac{\sigma_d - 1}{\sigma_d}\right)} \tag{B.27}$$

$$W_0 = \int_0^\infty P_t^D d_t e^{-rt}\mathrm{d}t \tag{B.28}$$

$$d_t = \left[\mu \cdot P_t^D\right]^{-\sigma_d} \tag{B.29}$$

$$D_t = d_t(1+n)^t \tag{B.30}$$

$$D_{it} = \omega_{i.0}\left(\frac{P_{jt}^D}{P_{it}^D}\right)^{\sigma_j}\frac{VD_{jt}}{P_{jt}^D} \tag{B.31}$$

$$P_i^D = \left(\left(1-\upsilon_i\right)(P_i^H)^{(1-\sigma_{HI})} + \upsilon_i(P_i^I)^{(1-\sigma_{HI})}\right)^{\frac{1}{1-\sigma_{HI}}} \tag{B.32}$$

$$\frac{D_{t+1}}{D_t} = (1+n)(1+g) \tag{B.33}$$

Variables

PV_0	The present value of the representative firm
π	Operating profit
P^J	Price index of the investment good composite
J	Gross investment
P^K	User cost index of capital composite
	Capital composite
X^H	Output of final-good firm delivered to the domestic market
X^W	Output of final-good firm delivered to the export market
X	Total output of the final-good firm
P^H	Domestic market price index of final good
P^W	World market price index of final good
W	Composite cost index of labour and human capital
	Composite of human capital and other labour
H	Human capital (subscript *0* denotes the base-year value)
L	Other labour (subscript *0* denotes the base-year value)
w^H	Price (wage) index, human capital
w^L	Price (wage) index, other labour
τ	Endogenous factor productivity change through absorption of international spillovers
	Composite of R&D-based capital
	Other capital
J^{KM}	Gross investment, other capital
P^{JM}	Price of investment good, other capital

P^{KM}	User cost of capital, other capital
C	The variable cost function
c	Price index of the CES aggregate of production factors
	Modified profit (the period-internal maximand of firms)
R	Accumulated number of patents/R&D-based capital varieties/R&D firms/accumulated stock of knowledge (subscript *0* denotes the base-year value)
X_R	Production of patents
P_R	Shadow price of patents
	R&D-based capital variety *i*
	User cost of R&D-based capital variety *i*
	Gross investment, R&D-based capital variety *i*
	Domestic market price index of R&D-based capital variety *i*
	World market price index of R&D-based capital varieties
P^{KV}	User cost index of the R&D-based capital composite
	Discounted period utilities of a representative consumer
	Consumption of the representative consumer
P^D	Consumer price index
R	Nominal interest rate
W_0	Consumer's current non-human wealth + present value of labour income + net transfers
μ	Marginal utility of wealth
D	Aggregate consumption
N	Annual population growth rate
D_i	Demand for consumer good *i*
VD_j	Aggregate expenditure on CES aggregate *j*
G	Growth rate
I	Import
P^I	Import price
P_i^D	Price of Armington composite good
A	The export channel of absorption
B	The import channel of absorption
Ω^H	The absorptive capacity effect of human capital
Ω^R	The absorptive capacity effect of R&D-based capital intensity
	Exogenous contribution to absorbed productivity growth
Δ	Productivity gap from the (exogenous) technology frontier
VF	Composite of variable input factors

Estimates and calibration

Model technology is calibrated to the 2002 Norwegian National Accounts.

Parameters

		Value
S	Scale elasticity	0.83
ρ	Transformation parameter between deliveries to the domestic and the foreign market	1.2
	Elasticity of substitution between variety-capital and ordinary capital	1.5
	Calibrated share of other ordinary capital in the capital composite	Industry-specific
	Uniform elasticity of substitution applying to all pairs of capital varieties	3.0
	Elasticity of substitution between human capital and labour	2.0
	Calibrated share of labour in the composite of human capital and labour	Industry-specific
s_1	Elasticity of domestic knowledge spillovers	0.5
	Domestic demand elasticity for capital variety *i*	3.0
	Mark-up factor for variety firm *i*	1.5
	Consumer's rate of time preferences	0.04
	Intertemporal elasticity of substitution	0.3
	Calibrated budget share of good *i* in CES aggregate *j* in period 0	Good-specific
	Elasticity of substitution between the two consumer goods in CES aggregate *j*	0.5 for all *j*
	Armington elasticity between imported and domestic produced varieties	4.0
	Initial import share in the Armington aggregate	Good and user-specific
λ_1	Strength of the export channel of absorption	0.05
λ_2	Strength of the import channel of absorption	0.05
	Parameter in the absorptive capacity functions	4.0
β	R&D subsidy	Scenario-specific
α_2	General subsidy to final-goods export deliveries	Scenario-specific
α	Subsidy to export deliveries of high-tech capital	Scenario-specific
μ^{KV}	Depreciation rate, R&D-based capital	Good and user-specific
μ^{KM}	Depreciation rate, other capital	Good and user-specific

The elasticities of substitution in production technology range from 0.15 in the upper part of the nested tree to 0.5 in the lower part of the nested tree structure (see Figure B.1 in Appendix B) and are in the range of empirical findings (Andreassen & Bjertnæs, 2006). We have less of an empirical foundation for substitution possibilities within the composites of R&D-based and other capital. We assume a relatively high substitution elasticity of 1.5, while the elasticity between

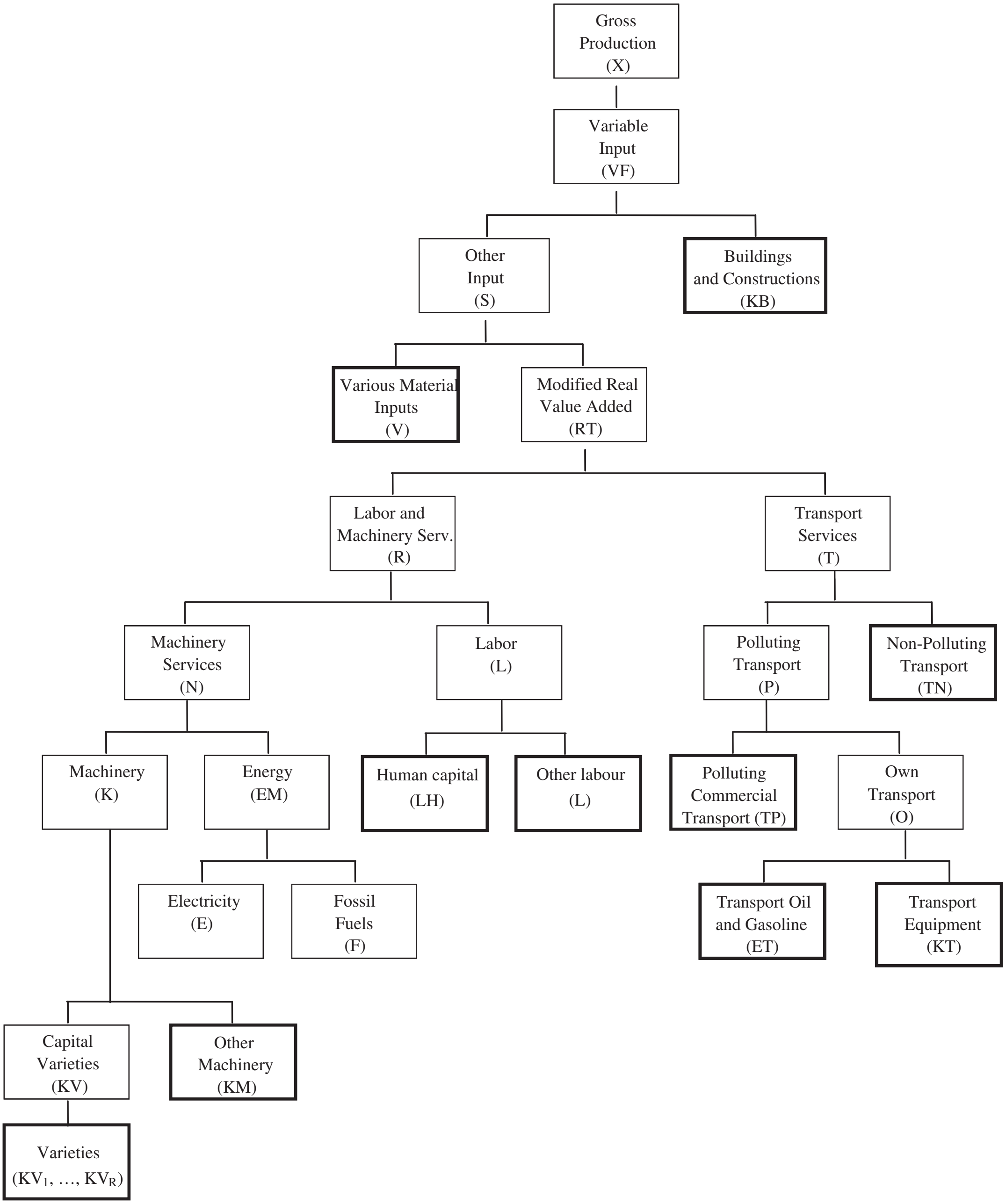

FIGURE B1 The nested structure of the production technology

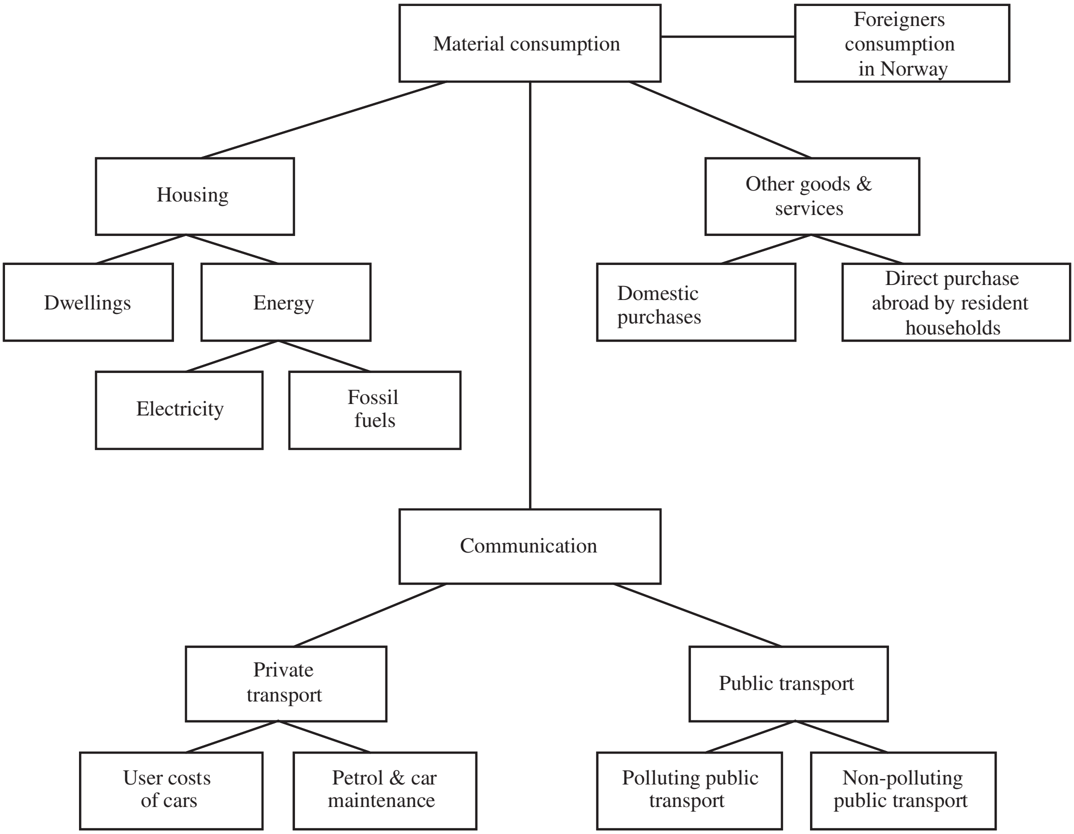

FIGURE B2 The nested structure of consumption activities

different R&D-based capital varieties is expected to be even higher and is set at 3.0, giving a mark-up factor of 1.5 in the domestic price of R&D-based capital varieties.[15]

The elasticity of scale is equal to 0.83 in all industries and fits econometric findings of moderately decreasing returns to scale in Norwegian firms (Klette, 1999). The scale elasticity is at the lower end of the estimates of Klette (1999) but has been chosen to avoid unrealistic industrial specialisation patterns.[16] This implies that the elasticity of transformation between domestic and foreign deliveries is equal to 4.9. The elasticity of substitution between domestic products and imported goods is assumed to be equal to 4. The elasticity of scale related to

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[15] This result is in line with the Jones and Williams' (2000) computations, which exclude creative destruction (similar to our model). Numerical specifications of Romer's Cobb Douglas production functions, as in Diao et al. (1999), Lin and Russo (2002), and Steger (2005), result in far larger mark-ups. Mark-ups of 1.5 are nevertheless in the upper range of econometric estimates (Basu, 1996; Norrbin, 1993). Our main motivation for staying in the upper range area is that we model industrial R&D as outsourced to a separate industry. Thus, R&D costs are ascribed to this industry, whereas the marginal costs of final-goods industries exclude this part of the costs. This finding deviates from typical regressions of mark-ups, where marginal costs include all observed costs, including industrial R&D costs.

[16] Because $\rho = 1/s$, a larger elasticity of scale will imply a larger elasticity of transformation between domestic and foreign deliveries, $1/(1-\rho)$. If the elasticity of scale is close to 1 (constant returns to scale), the elasticity of transformation will be very high, implying practically no transformation costs of shifting between domestic and foreign deliveries.

previous knowledge is set equal to 0.5, to ensure decreasing spillover effects of the knowledge base, and is supported by both theoretical and empirical findings (see Jones, 1995, 1999; Leahy & Neary, 1999).

The composite of human capital and other labour is a CES aggregate, where human capital consists of personnel with more than four years of university or equivalent education, and other labour constitutes the rest. The share of human capital in each industry in the base-year calibration is based on calculations from Norwegian R&D statistics and Bjørnstad et al. (2002). The elasticity of substitution between human capital and other labour is 2. Empirical estimates range from 0.5 to 5 (Bjørnstad & Skjerpen, 2006). The base-year wage differential between human capital and other labour is 30 percent, according to Bjørnstad and Skjerpen (2006). We calibrate the base-year wage levels from a homogenous labour model in which we assume that the wage rate is a weighted average of human capital and other labour in the industry. The human capital weight is 0.05.

APPENDIX C

THE REFERENCE PATH: CALIBRATION AND GROWTH DYNAMICS

In the transition path, the exogenous growth factors are assumed to grow at constant rates. In most cases, rates are set in accordance with the average annual growth estimates of the government projection of the Norwegian economy up to 2050 (Norwegian Ministry of Finance, 2004). Population growth is set at 0.4 percent annually. Total factor productivity (TFP) growth rates are entirely exogenous and valued, on average, at 1 percent annually. Public consumption and output (both exogenous activities) grow at constant rates. The offshore sector is treated as exogenous in this model, as we concentrate on the mainland economy; exogenous offshore investment and oil and gas exports result from a smoothing of their expected present values to account for the economic significance of Norwegian oil and gas resources without introducing another source of dynamics into the growth path. The model is calibrated to the National Accounts, using 2002 as base year.

World market prices increase by 1.4 percent annually and are chosen so that the exogenous inflationary impulses are in line with internal impulses, which are dampened by the consumption smoothing features of the model. The delivery ratios between the export and domestic markets are in line with those of the government projection. The international nominal interest rate is 4 percent. The exchange rate serves as numeraire.

Some of our sources report industry-specific productivity impetuses and parameters (domestic and through trade—more details are given in Section 2), but we have assumed common elasticities for all. In the last part of the reference transition path, that is 60–80 years from now, the stable GDP growth rate amounts to 1.5–1.7 percent annually, while the annual average along the path is somewhat lower, at 1.4 percent, and in line with the Norwegian Ministry of Finance's long run projections.

To obtain a balanced long run growth path for the economy, the following equation must also be fulfilled:

$$\left[\frac{(1+\theta)}{\frac{(1+r)}{(1+p)}}\right] = (1+g)^{\frac{-1}{\sigma_d}} \tag{C.1}$$

θ is the rate of time preferences, r is the nominal interest rate, p is the rise in the consumer price index, and σ_d is the intertemporal elasticity of substitution; see also Appendix B. In an infinite time horizon, growth in our model will only depend on exogenous drivers. For technical reasons, we have set all exogenous, and subsequently also endogenous, growth drivers at zero in the distant future (after approximately 100 years) to ensure that a balanced growth path is reached within a limited number of periods. Sensitivity tests show that the growth rates within the stable part of the transition period appear to be independent of this timing; only the durability of the stable period is affected. This setting ensures that the economy eventually follows a balanced growth path and that this growth path, with zero growth in both consumption and the consumer price index, satisfies the transversality conditions; the limit values of the total discounted values of net foreign debt and real capital must be zero. In particular, Equation (C.1) then implies that $r = \theta$ at all points in time. See also Section 2.4 for more details of the balanced growth path.