Endogenous Growth and Structural Change in a Dynamic Input-Output Model

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ABSTRACT

This paper introduces a simple dynamic input-output model, in which some of the most important properties of endogenous growth theory are included: innovation, knowledge spillovers, varying returns to scale and full employment. The wish to keep the hybrid model as tractable as possible (despite the industry detail), has caused some substantial simplifications: contrary to most new growth models, the model lacks an explicit microeconomic foundation and assumes production functions with fixed coefficients in the short run. After the constituent equations are presented, the long-run behavior of the model is studied by a number of computer simulations for a hypothetical economy. The paper concludes with some illustrations of the potential practical power of future interindustry endogenous growth models in integrating issues like technology, investment, trade and education.

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1. Objective and Setup

Since the mid-eighties, input-output (IO) analysis has no longer been contained in the core of mainstream economics. Leading journals like *Econometrica*, the *Review of Economics and Statistics* and the *Quarterly Journal of Economics* did not continue to publish IO papers and few top economists nowadays seem to show interest in developments in the field of IO analysis.[1] This is a sad state of affairs, since IO still could play the important role mentioned by its founding father Wassily Leontief in his foreword to the very first issue of the journal *Economic Systems Research*:

> *"Input-output analysis is a general methodological approach designed to reduce the steadily widening gap between factual observation and deductive theoretical reasoning that threatens to compromise the integrity of economics as an empirical science."* (Leontief, 1989, p.3)

Why did IO drift away from mainstream economics (or the other way round)? In my opinion, four major causes can be identified. First, from the mid-seventies onwards, faith in the ability of market mechanisms to yield 'socially optimal' solutions began to increase. Consequently, attention shifted away from government planning for which IO is seen as a useful instrument. Second, the belief grew stronger that macroeconomic theory should be rooted in microeconomic foundations. Since IO considers industries consisting of many firms as the smallest unit of analysis and the accompanying data material is also published at the industry level, IO did not fit into this development. Third, the vast majority of IO theories start from the (Post-Keynesian) notion that output and employment are mainly demand-constrained, whereas mainstream theory takes the opposite perspective that these variables are predominantly determined by supply-side factors. Fourth, and most important, mainstream economics got increasingly involved with explanations of long-run growth in which a major role is played by technological change, in particular after the emergence of the so-called endogenous growth theory. At the same time, IO is still generally judged to deal with situations in which production technologies are frozen. Hence, many hot topics in mainstream economics like changing trade patterns, changing skill compositions of workforces and changing environmental consequences of production could not be studied by IO methods.

Of course, the above-mentioned causes and consequences are somewhat overstated. For instance, there have been some attempts to give IO analysis a micro-economic foundation (see, e.g. Ten Raa & Mohnen, 1994, and Rose & Casler, 1996) and some work is going on to replace Ghosh's (1958) ultimately unsuccessful supply-side IO quantity model by more consistent methods to analyze effects of supply restrictions, for instance concerning agricultural production

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[1] This statement relates most strongly to 'traditional' IO analysis. Contributions on CGE-modeling and interindustry technology flows sometimes feature in top journals with an empirical flavor.

(see e.g. Papadas & Dahl, 1999).[2] Despite these examples of progress in the direction of mainstream economics, it is clear that it would take IO economists much effort to regain respect of the majority of mainstream economists.[3] Most importantly, they would have to monitor developments in mainstream economics quite closely, in order to note any opportunity for reducing the gap mentioned by Leontief in his above-cited remark. This contribution should be seen as a first result of explorations of what I think to be such an opportunity.

In this paper, I will try to indicate how the theory of endogenous growth in mainstream economics could be enriched by IO analysis. Since the publication of Paul Romer's (1986) article in the *Journal of Political Economy*, long-run growth and its potential determinants have become a paramount topic in mainstream economics. His ideas have been challenged, refined, and extended in numerous contributions to the literature. In most of these so-called endogenous growth models, Research & Development (R&D) and its accompanying positive externalities are the driving force of long-run productivity and output growth.[4] The externalities imply that governments could promote the long-run welfare of its citizens by pursuing active technology policies instead of laissez-faire.[5] This outcome naturally attracted a lot of attention from policy makers. Despite its impact, the practical usefulness of endogenous growth theory has been very limited until now, since it maintained the neoclassical assumption of economies consisting of perfectly identical, representative agents. In some contributions, distinctions were made between producers of capital goods, intermediates and consumption goods, but practically more relevant differences between, for example, buildings, computers, and transport equipment have not been introduced so far.

IO analysis explicitly focuses on differences between commodities themselves, as well as on the differences with respect to the inputs required for their production. In this strand of economics, though, issues of long-run economic growth and structural change have only scarcely been studied in a dynamic framework. After the construction and application of the well-known 'Leontief-Duchin-Szyld' model (Duchin & Szyld, 1985, and Leontief & Duchin, 1986) in the mid-eighties, the focus of the majority of empirical input-output studies seems to be on prediction of

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[2] Oosterhaven (1988) convincingly showed the flaws of the supply-driven model. Dietzenbacher (1997) recently demonstrated that this model should not be considered as a quantity model, but as a price model.

[3] It should be questioned whether it is worthwhile to pursue acceptance by mainstream economists if this would require IO researchers to change their attitudes towards the nature of economic phenomena. I suppose that most IO researchers would like to be accepted more widely, as long as the 'core' of their methods can be left unchanged. Of course, this raises the question what belongs to the core of IO analysis and what does not.

[4] The labels 'endogenous growth theory', 'new growth theory', 'R&D-driven growth theory' and 'Schumpeterian growth theory' are often used interchangeably in the literature. Each of these alternatives has its drawbacks. For convenience, I will stick as much as possible to the label 'endogenous growth theory'.

[5] Note that this conclusion could induce a small shift from liberal free market policies to a very gentle form of 'planning', which would be a move opposite to the one mentioned as one of the causes of waning interest in IO economics.

short-run developments and ex-post accounting for growth in a comparative statics framework (e.g. structural decomposition analyses).

As a first step towards a potentially fruitful bridge between endogenous growth theory and IO-analysis, I will introduce a very simple dynamic input-output model in which some of the most important properties of endogenous growth theories are included: innovation, knowledge spillovers, varying returns to scale and supply-side determination of production levels. From the IO perspective, the latter feature clearly is a deviation from standard practice. In exchange, the model lacks an explicit microeconomic foundation and assumes production functions with fixed coefficients in the short-run (no instantaneous substitution due to changes in relative prices) which is contrary to most endogenous growth models.

The paper is organized as follows. Section 2 is devoted to a brief review of the parts of endogenous growth theory which are relevant to the model. In Section 3, I will present and discuss the equations which together make up the model. The long-run behavior of the analytically complex model will be studied in Section 4 by a number of computer simulations for a hypothetical economy. In the presentation I will put emphasis on the identification of (industry-specific) 'optimal R&D investment levels', because it is the aspect of the endogenous growth theory which is most important for policy makers. Some illustrations of the potential power of future input-output endogenous growth models in integrating issues like technology, investment, trade and education are given in the concluding Section 5.

2. A Brief Overview of Endogenous Growth Theory

In this section, I will survey some of the main results which have emerged from the endogenous growth theory. It is not my intention to provide a complete review, since a number of surveys were published already (see e.g. Verspagen, 1992, Aghion & Howitt, 1998, and Los, 1999, Ch.2). In particular, I will not engage in detailed discussions of the microeconomic aspects, because these do not play a substantial role in the remainder of the paper. Instead I will focus on two issues characteristic of endogenous growth models which are important from an industry-level perspective: technological spillovers and scale effects.

First of all, I should make clear which theories I would like to cover in this discussion of endogenous growth theory. For the present purpose, a theory or model should fulfil two criteria to be included: it should be 'Schumpeterian' and it has to assume that firms rationally optimize their profits. The first criterion implies that growth of output and productivity must be "generated through the introduction of new goods or processes, as opposed to physical or human capital accumulation" (Dinopoulos & Thompson, 1999, p. 159). It thus excludes the traditional neoclassical model in which long-run productivity growth equals the exogenous rate of technological progress, as well as Post-Keynesian growth theories in which the rate of export growth determines the rate of output growth.[6] Further, it prevents me from discussing the models in which the long-run growth rate is endogenized by letting it depend on investment in human capital (education). The second criterion implies that I will not deal with contributions to the so-called evolutionary growth theory. Authors in this tradition also see purposeful search for innovations (R&D) as the driving force of growth, but they argue that the intrinsic uncertainty with respect to the revenues of R&D prevents firms from maximizing their profits. Instead, they are modeled to follow routines which can be adopted in the course of time. I do not include evolutionary theories in this short survey simply because they do not belong to the mainstream I mentioned in the introduction. It should be born in mind, though, that the reduced form model which I will present in the next section can be brought in accordance with both models assuming rational optimization and models assuming routine-based behavior.

2.a Technology spillovers

The fundamental advantage of endogenous growth theories over the traditional exogenous neoclassical growth theory is that it provides explanations of why productivity levels have risen over time and why many firms devote substantial parts of their resources to the search for innovations. The notion that technology causes positive externalities (spillovers) has been crucial to the construction of all Schumpeterian endogenous growth theories.

In the famous paper leading to the first wave of endogenous growth theories (Romer, 1986), R&D variables entered the production function of firms as two additional inputs, next to labor and capital. First, the productivity of the rival inputs labor and capital could be increased by R&D paid for by the firm itself. Second, the public good characteristics of knowledge generated in R&D activities enable firms to benefit from knowledge produced elsewhere, too. In the empirical literature, this variable is sometimes called “the potential spillover pool” (Jaffe, 1986, p. 986). A fundamental problem connected to this class of models is their internal inconsistency with respect to incentives to invest in R&D. As technology is assumed to be completely public immediately, no firm would engage in R&D, because there are no opportunities to make a profit on its results.

In later new growth models, the traditional assumption of perfect competition was relaxed (see e.g. Grossman & Helpman, 1990, 1991, Romer, 1990, and Aghion & Howitt, 1992). Integrating insights from the field of industrial organization with the endogenous growth framework, these models assumed that technology is *not* completely public immediately and that markets in which firms sell their products are characterized by monopolistic competition. Given this market structure, firms have some freedom to set their own prices, due to the fact that they have some monopoly power in the segment of the market in which they sell their ‘version’ of the product. By setting their prices appropriately, firms will in principle be able to earn enough to

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[6] In a very recent paper, Kurz & Salvadori (2000) argue why the standard dynamic input-output model should also belong to the broad class of endogenous growth models. Clearly, this model does not belong to the Schumpeterian models, because output growth is solely caused by capital accumulation.

compensate for their R&D expenditures. In these second-wave new growth theories, at least two sectors are distinguished.[7] The R&D sector typically produces two goods, designs ('blueprints') for new goods, and general knowledge. The blueprints can be used in either the intermediate goods sector or the consumption goods sector, depending on the particular model. As blueprints provide 'recipes' for new products, positive profits can be secured for at least a short period by obtaining a patent or exploiting a time-lead. So specific blueprints are the driving force to engage in R&D projects, which yield general knowledge as a very important byproduct. Contrary to the blueprints, this general knowledge is assumed to be a public good: the entire research sector can use it too. The effects of these knowledge spillovers on the productivity of research have been modeled in several ways. Almost all recent endogenous models are constructed around either one of two broad classes of spillover mechanisms: 'increasing variety' and 'quality ladders'.

In Grossman & Helpman (1990) and Romer (1990) the output of the research sector (measured in blueprints) depends on its labor inputs and the availability of spilled general knowledge. The blueprints for new intermediate goods do not constitute quality increases. Instead, it is assumed that the expanding variety of intermediate inputs enhances productivity in the consumer goods sector, because more specialized inputs can be used. The positive knowledge spillovers in the 'increasing variety' models cause the equilibrium R&D expenditures to be lower than desirable from a social point of view: firms base their R&D decisions on the private returns to research which are lower than the social returns.

Aghion & Howitt (1992) assume that each new blueprint for each of a number of intermediate goods lowers the production costs of the unique consumption good. Knowledge spillovers are embodied in the previous blueprint, possibly invented by some other firm: when an innovation occurs the entire research sector is assumed to have obtained the underlying knowledge. Consequently, all other firms can use their R&D inputs to design new innovations that reduce production costs further. Grossman & Helpman (1991) exploit a similar idea, although they do not distinguish an intermediate goods producing sector. In their model, each innovation implies a step up the 'quality ladder' of one of various imperfectly substitutable consumer goods. Any R&D project is assumed to use the general knowledge associated with the consumer good with the highest quality so far. The length of the time period between two successive innovations (during which innovation rents can be earned) is a stochastic variable in both models, since innovations are assumed to arrive according to a Poisson process. The mean number of innovations per time period is assumed to be determined by the amount of labor (or

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[7] In many contributions to the IO-literature, the words 'sector' and 'industry' are more or less synonyms. The difference between the notions of 'sectors' and 'industries' in this paper should therefore be noted. I use the term 'sector' for those parts of the economy that produce outputs that serve a common goal throughout the economy, like blueprints and knowledge (the R&D sector) or consumption goods (the consumption goods sector). The term 'industry' refers to those parts of the economy that have certain similar intrinsic characteristics (or designs for such outputs), like chemical products or business services. Given these 'definitions', parts of several sectors could well be present within one industry, and the other way round.

human capital) employed in the R&D process. Although the 'quality ladder' models also contain positive knowledge spillovers, they do not yield conclusions identical to the 'increasing variety' models, due to the existence of a countervailing force. When a firm thinks of investing in an R&D project, it will 'calculate' whether its expected revenues will exceed its costs, without taking into account that the stream of revenues of the current best blueprint is immediately ceased. So R&D projects cause a negative externality too, and it depends on the relative magnitudes of this negative 'creative destruction' effect and the positive knowledge spillover effect whether the social returns are smaller or larger than the private returns.

From this discussion of the second wave of Schumpeterian new growth theory, three issues arise which will be important from the perspective of the IO growth model to be presented in the next section. First, knowledge spillovers can be modeled in two ways. In the first specification, all R&D processes become more productive when the stock of general knowledge (which is a byproduct of the search for profitable innovations) increases. Alternatively, the knowledge contained in a cheaper production process or a qualitatively superior consumption product is immediately accessed by other firms, who start their continued search for innovations at the newly established level of technology. Second, innovators can earn supernormal profits for a limited time span, due to legal protection (patents) or the ability to build a time-lead. Third, it is more or less accepted to model the occurrence of innovations as a Poisson process, the parameter of which is determined by R&D efforts.

2.b Scale effects

Ever since the introduction of the new growth models, the issue of scale effects has attracted much attention. Due to the above-mentioned positive externalities of R&D, returns to scale are no longer constant (like in the Solow-model), but increasing. This is exactly the reason why output growth can be sustained in new growth models, even when population does not grow. The evidence presented by Jones (1995a, 1995b) against the implications of scale effects has evoked a new wave of Schumpeterian growth theories, the properties of which have some important consequences for my IO growth model.

To clarify the discussion, I borrow heavily from the review article by Dinopoulos & Thompson (1999). They present a simple two-sector model which can be conceived as a reduced form of the models discussed earlier. Labor is assumed to be the only rival production factor:[8]

$$X[t] = \Lambda[t] L^{P}[t] \tag{1}$$

$$\frac{\dot{\Lambda}[t]}{\Lambda[t]} = \gamma L^{R}[t] \tag{2}$$

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[8] Note that my use of symbols is different from Dinopoulos & Thompson's (1999). The meanings of the symbols introduced here correspond as closely as possible to identical symbols in the interindustry model.

The first equation states that output X of the of the commodity-producing sector depends on the prevailing labor productivity in production Λ and the amount of labor devoted to this sector L^P. Equation (2) implies that the proportional change of labor productivity is a linear function of the amount of labor allocated to R&D, L^R. The parameter γ is a measure of labor productivity in the R&D sector. The fact that this parameter is dependent neither on time nor on previously attained productivity improvements reflects the effects of knowledge spillovers. The full employment condition, which the new growth literature assumes to be fulfilled automatically, ensures that labor supply L equals the sum of L^P and L^R. Now, keeping in mind that steady states in this one-factor model must be characterized by a constant proportion L^R/L, the steady state growth rate of output per capita x can be shown to equal

$$\frac{\dot{x}[t]}{x[t]} = \frac{\dot{\Lambda}[t]}{\Lambda[t]} = \gamma\left(\frac{L^R[t]}{L[t]}\right)L[t] \qquad , \tag{3}$$

At least three important hypotheses concerning scale effects in the simple model can be extracted from equations (2) and (3). First, the output of an economy will grow twice as fast as output of another economy with an identical productivity of R&D and an equal fraction of the workforce employed in the R&D sector, if its workforce is twice as large. Second, if an economy has a constant population and its productivity in R&D activities remains stable, its steady state productivity growth rate will remain equal only if the fraction of the labor force allocated to R&D remains stable. Third, if R&D productivity remains stable and the proportion of labor in R&D remains equal, population growth yields accelerating productivity growth.

The first hypothesis can be tested by confronting it to cross-country data. The most-cited study which reports results of a related test is Backus *et al.* (1992), who do not find a relation between per capita GDP growth and the logarithm of initial GDP for aggregate economies, but a significant positive link if only manufacturing output growth rates and initial levels are considered.[9] The second and third hypotheses are of a time series nature. Jones (1995a) presents evidence that the second hypothesis is untenable, at least when tested on data for the period 1950-1990: in four major industrialized countries productivity growth did not change dramatically, while the numbers of scientists and engineers employed in R&D departments rose considerably. In fact, this is also evidence against the third hypothesis (since population rose as well), but investigations on extremely long time series by Kremer (1993) yield results favorable to this hypothesis. All in all, the empirical evidence regarding scale effects is unclear, especially since

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[9] It should be noted, however, that Backus *et al.* (1992) offers only circumstantial evidence regarding the first hypothesis, since the *ceteris paribus* conditions (e.g. equal ratios of R&D labor tot total labor) are certainly not fulfilled in their sample of 67 countries. Further, GDP is not an ideal measure of scale for testing the simple model, because cross-country GDP differences could also be caused by different capital-labor ratios.

all kinds of measurement problems emerge, short-run and long-run effects cannot be disentangled or international effects of technology creation cannot be taken into account. Nevertheless, many authors feel very awkward about the scale effect results of models which are similar to the model of equations (1) and (2) and have constructed alternative Schumpeterian growth models in which scale effects are either absent or play a less prominent role. One of them will offer the basis for the most important equation in the IO growth model to be developed in the next section.

In fact, the theories which try to remove scale effects can be represented by a modified form of equation (3):

$$\frac{\dot{x}[t]}{x[t]} = \frac{\dot{\Lambda}[t]}{\Lambda[t]} = \frac{\gamma_0}{\gamma[t]}\left(\frac{L^R[t]}{L[t]}\right)L[t] \tag{4}$$

Now, the productivity of labor employed in R&D (in terms of productivity gains) is no longer constant. The equation shows that absence of scale effects is ensured if and only if this productivity $\gamma_0/\gamma[t]$ declines in the steady state at a rate exactly equal to the steady state growth rate of labor supply L. As Jones (1999) emphasizes, equation (4) offers the opportunity to classify theories of R&D-driven growth into three groups. First, if $\gamma[t]$ is constant or grows slower than L (like in the model discussed above), the theory is an 'endogenous growth theory with scale effects'. Second, if $\gamma[t]$ grows faster than L, the model could be called a 'semi-endogenous growth theory'. Finally, if $\gamma[t]$ grows exactly as fast as L, the theory could be called an 'endogenous growth model without scale effects'. It should be mentioned, however, that these group names are subject to debate.[10]

The first semi-endogenous model was formulated by Jones (1995b), followed by Kortum (1997) and Segerstrom (1998). Their models are based on the notion that opportunities for innovation diminish (the 'pool of productivity-enhancing innovations' gets fished out), which implies that more resources have to be allocated to R&D activities in order to maintain a constant productivity growth rate. These models boil down to equivalents of the following productivity growth equation:

$$\frac{\dot{x}[t]}{x[t]} = \frac{\dot{\Lambda}[t]}{\Lambda[t]} = \frac{\gamma_0}{\Lambda[t]^{(1-\varphi)}}\left(\frac{L^R[t]}{L[t]}\right)L[t] \quad , \tag{5}$$

in which 1-φ is a measure of the speed at which R&D becomes less productive as technology advances. In the steady state, productivity grows according to

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[10] Dinopoulos & Thompson (1999), for example, prefer to denote models belonging to the second group by 'exogenous growth models'. Moreover, Jones (1999) argues that the phrase 'without scale effects' is mistaken with respect to the third group of models.

$$\frac{\dot{\Lambda}}{\Lambda}=\frac{\nu}{1-\varphi}, \tag{6}$$

with ν indicating both the population growth rate and the growth rate of labor employed in R&D. The steady state productivity *growth rate* is thus proportional to the population growth rate.[11] Nevertheless, the productivity and output *levels* which correspond to the growth path are positively related to upward changes in the fraction of labor devoted to R&D.

Contributors to the endogenous growth theories without scale effects (for example, Peretto & Smulders, 1998, Young, 1998, and Howitt, 1999) found mechanisms which could save the conclusion of R&D-dependent long-run growth rates without running into scale effect problems. The central idea is that R&D is becoming less productive in an aggregate sense, because it is assumed to generate variety-specific knowledge and quality increases, as well as an ever-increasing number of varieties. So, in comparison to increasing variety models in the 'second wave' (e.g. Romer, 1990), there are increasingly less useful knowledge spillovers between firms producing different varieties. Hence, each R&D worker produces less and less relevant (from a societal perspective) knowledge as the economy grows, although his productivity with respect to his 'own' variety does not change. Assuming standard profit maximization assumptions under monopolistic competition it can be shown that in the steady state firms allocate their R&D workers in such a way that the number of varieties increases at the same pace as population.[12] Dinopoulos and Thompson (1999, p. 174) show that (at least some) 'endogenous growth models without scale effects' boil down to the productivity growth equation:

$$\frac{\dot{\Lambda}}{\Lambda}=\kappa\gamma_0\frac{L^R[t]}{L[t]}, \tag{7}$$

where κ is the constant ratio between population and the number of varieties. Hence, labor productivity growth can be written as a linear function of the proportion of the workforce devoted to R&D: aggregate productivity keeps growing at a steady pace when a constant fraction of an expanding population is devoted to R&D. Consequently, governmental policies which attempt to increase this fraction will be successful in promoting long-run growth, contrary to the prediction of the 'semi-endogenous' models. Further, scale effects do not apply to growth rates, but are only reflected in the result that larger economies produce more varieties than small countries as long as they are technologically independent.

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[11] Note that endogenous growth models with scale effects assume $\varphi=1$. This implies that these models do not have a steady state growth rate if population grows: more and more people can be allocated to R&D activities without diminishing returns.

[12] This is due to the fact that the returns to developing a new variety depend on the extent of the market, which is partly determined by population size.

From this necessarily superficial overview of the scale effects issue in the endogenous growth theory, the main conclusion should be that the outcomes of these models are extremely sensitive to the specification of the equation linking output and productivity growth to one or more R&D variables. Of course, this will also apply with regard to my IO growth model. In my personal view, the recent 'endogenous growth models without scale effects' do a good job in the sense that they explicitly consider the growth-inhibiting effects of the increasing complexity caused by labor force growth. It should be realized that an important part of the results hinge on my choice for a specification which make the model belong to the class of 'endogenous growth models without scale effects'. The next section's discussion of the model equation will make clear how I exactly incorporated the above-discussed technology spillovers and scale effects issues in an interindustry context.

3. The Model

The IO growth model which I propose is a very simple example of a 'sequential' or 'two-stage dynamic' (Dervis *et al.*, 1982) model. At the beginning of each period, the industries have to decide on a number of issues, given a set of variables which are assumed to be beyond their range of influence at that stage. For example, industries decide on their current period R&D inputs on the basis of their previous sales levels, previous relative prices and the prevailing production functions in their R&D sector. The complete set of these short-run equations yields current output, R&D, employment and consumption levels. In fact, output determination just involves the solution of a kind of static input-output model in each period. The dynamics are introduced in the second stage, in which the consequences of the current decisions on the values which are assumed to be exogenous at the beginning of the next period(s) are modeled. For example, current decisions with respect to R&D expenditures shape future production functions. Consequently, new values of the variables which are exogenous to the short-run decision process can be fed to the system and long-run effects of parameter changes can be studied.[13]

The model deals with a closed economy, in which *n* industries each producing a single, homogeneous commodity are specified. Each industry consists of two sectors, like in the endogenous growth models. In the production sector, the relation between output and inputs (labor and *n* intermediate inputs) is given by an industry-specific Leontief production function,

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[13] Note that this type of model is not dynamic in the sense that industries are assumed to solve some kind of dynamic optimization process, as is the case in some recent Walrasian computable general equilibrium models. Instead, the dynamics are of a type similar to the dynamics of the 'Leontief-Duchin-Szyld' IO-model (Duchin & Szyld, 1985, Leontief & Duchin, 1986), where current decisions on investment in capital goods determine the capacity levels in future periods.

the parameters of which indicate the requirements per unit of gross output.[14] In the R&D sector, inputs are used in fixed industry-specific proportions as well. The output of this sector consists of blueprints for new production processes. These blueprints are represented by industry-specific Leontief production functions with lower input coefficients than the one currently in use. The allocation of inputs to the R&D process thus enlarges future output levels at the cost of decreasing the current capacity to produce commodities for consumption purposes.

Below I will introduce the equations making up the model. For brevity, they are written in matrix notation whenever convenient. Bold capitals refer to matrices, bold lowercase symbols represent column vectors and italic symbols relate to scalars. Diagonal matrices are denoted by a hat and primes indicate transposed matrices or vectors. Further, superindices P and R relate to inputs for production and R&D, respectively, whereas subindices c and s indicate coefficient matrices and flow matrices. Tildes are used to indicate variables in money terms, and bars denote (weighted) sums or (weighted) averages.

3.a R&D-driven technological progress

Since one of the main differences between recent dynamic input-output models (Duchin & Szyld, 1985, Leontief & Duchin, 1986, Kalmbach & Kurz, 1990 and Edler & Ribakova, 1993) and the present model is the explicit endogenous nature of technological progress, I will start the exposition of the equations with those describing the link between R&D and productivity growth. The specification of this equation is inspired by the aggregate models belonging to the 'endogenous growth without scale effects' category. Throughout the paper, I will denote the (nx1)-vector of labor quantities (required for production purposes) per unit of gross output as effective in the period starting at t and ending at t+1 by $\mathbf{l}^{\mathbf{P}}_{\mathbf{c}}[t+1]$. Its elements are assumed to change according to the difference equation

$$l_j^P[t+1] = \left(\frac{1}{1+\sigma_j \cdot Inn_j[t]} \right) l_j^P[t] \tag{8}$$

with Inn denoting the industry-specific number of process innovations occurring at t and σ indicating the fixed proportional increase in labor productivity implied by each innovation (their 'size').[15] Following Aghion & Howitt (1992), innovations arrive at stochastic intervals:

$$Inn_j[t] \sim \text{Poisson}(\lambda_j[t]), \tag{9}$$

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[14] In a model aimed at providing a tool for policy evaluation, capital goods inputs might not be excluded. The inclusion of these goods, however, would yield short-run adjustment processes which would complicate the model to an unwarranted extent. I will come back to this issue in the concluding section.

[15] Labor productivity (in terms of real value added per unit of labor) is inversely related to the labor requirements per unit of output. This relationship will be discussed below.

in which λ_j is an industry-specific variable the value of which is given by

$$\lambda_j[t+1]=\gamma_j\left[\left(1+\sum_{i\neq j}\eta_{ij}\left(\frac{l_{s,i}^{R}[t]+\sum_{k=1}^{n}z_{s,ki}^{R}[t]}{\sqrt{x_i[t]x_j[t]}}\right)^{\alpha_i}\right)\cdot\frac{l_{s,j}^{R}[t]+\sum_{k=1}^{n}z_{s,kj}^{R}[t]}{x_j[t]}\right]^{\alpha_j} \qquad (10)$$

This expression seems more complicated than it is, but it requires a number of comments.

First, setting aside the factor in parentheses, the equation almost resembles a multi-input version of equation (7): l_s^R denotes the labor inputs, z_s^R indicates the inputs of materials in the R&D process and x reflects the total inputs, aggregated over the production and the R&D sector (all measured in constant prices). The only difference is in the exponent α ($0<\alpha<1$). If this parameter would equal 1 (as in equation (7)), this would yield serious problems in the specification of interindustry differences in innovation arrival rates. The empirical evidence shows that the ratio of R&D intensities in the 'average' low-tech industry and the 'average' high-tech industry is often roughly 1:20, whereas the corresponding labor productivity growth rates ratio is often in the order of 1:5.[16] This would imply that γ for low-tech industries should be about four times as high as for high-tech industries. The obvious drawback of that solution would be that the low-tech industry would produce four times as much innovations as the high-tech industry if it would spend the same fraction of its inputs on R&D! The specification of equation (10), however, reflects diminishing returns to R&D intensity. A given arrival rate λ can be attained for a given R&D intensity by an infinite number of (α,γ)-pairs. For pairs with relatively low γ-values, diminishing returns prevent the industry to gain much more from allocating more of its inputs to R&D.

Second, it should be noted that the specification of equation (10) implicitly supposes that all firms *within* an industry have immediate access to the process technology related to the innovation and can direct their R&D towards further improvements, like in the quality ladder models discussed earlier. This kind of spillovers does not occur *between* industries, however.

Interindustry knowledge spillovers are modeled in a way which is in line with the increasing variety models: a given R&D expenditure is assumed to be more productive if new ideas are brought forward by R&D undertaken in other industries (see the second factor of the right hand-side of equation (10)). It should be borne in mind, however, that knowledge generated by other industries is very heterogeneous with respect to its relevance for a given industry's own R&D. Griliches (1979, p. 104), in his seminal contribution to the literature on technology spillover measurement, mentions that "the photographic equipment industry and the scientific instruments industry (...) may be, in a sense, working on similar things and hence benefiting much from each

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[16] See e.g. Los (1999, Ch.1) for empirical comparisons of high-tech, med-tech and low-tech industries in OECD countries.

other's research". Nobody, though, would argue that such an argument would have empirical content for the photographic equipment industry and, for example, the leather products industry. To capture such differences in relevance, I included the nonnegative parameters η.[17]

To avoid systematic economy-wide scale effects on growth rates due to interindustry knowledge spillovers, I also express the spillover factor as a ratio of R&D inputs to total inputs. I decided to include not only the size of the 'sending' industry but also the size of the 'receiving' industry in the denominator, to reflect the notion that the spread of new knowledge may be limited to a diminishing fraction of the firms in both industries when they grow in size. As a consequence of this particular specification, spillover effects for the economy as a whole partly depend on changes in the industry structure in terms of output composition.

For simplicity I assume that technological progress is purely labor-saving. This implies that the requirements (in quantities) of intermediate inputs per unit of gross output (also in quantities) remain constant over time.[18] This assumption could easily be replaced by some other assumption for empirical reasons, but is in line with the well-known macroeconomic stylized facts of steadily increasing capital-labor ratios and virtually constant capital-output ratios.[19]

Equations (8)-(10) distinguish the model from existing dynamic input-output models, in the sense that technological change is explicitly modeled as the result of the search for innovation. These equations do not indicate, however, how industries decide between allocating resources to the production sector and the R&D sector. This is the main topic of what follows in the next subsections, in which I try to relate the equations as much as possible to the endogenous growth models discussed in the previous section.

3.b R&D investment

In the endogenous growth literature, firms are assumed to base the size of their R&D budgets on a maximization of their profit stream. Roughly speaking, this implies that a higher chance of discovering a profit-increasing innovation given some R&D effort (i.e. more favorable

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[17] The measurement of the parameters η has given rise to a whole literature, which I will not review here. In my opinion, the most original contributions are Terleckyj (1974), Griliches (1979), Scherer (1982), Jaffe (1986), Wolff & Nadiri (1993) and Verspagen (1997). See e.g. Van Meijl (1995, Ch. 6) or Los (1999, Ch. 3) for surveys. These studies estimate econometrically convenient specifications in which knowledge from 'own' R&D and knowledge obtained through spillovers are substitutes. In equation (10), these are treated as complements, which is more in line with endogenous growth theory and the empirical results reported in Cohen & Levinthal (1989).

[18] This also implies that value added per unit of gross output (both in constant prices) remains constant over time and that percentage changes in the labor requirements per unit of output are equal to percentage changes in real value added per unit of labor.

[19] Alternative assumptions concerning input coefficient change can be found in the models presented by Los (1999), Los & Verspagen (1999) and Verspagen (1999). The empirical studies by Leontief & Duchin (1986) and Kalmbach & Kurz (1990) explicitly aim to predict changes of particular input coefficients and their effects on the economy. See e.g. Sawyer (1992) for a study which specifically aims at investigating whether intermediate inputs requirements change systematically over time or not.

technological opportunities) will lead to more resources being devoted to R&D activities. This relationship is empirically supported indeed, but it is well-recognized in the more institutional literature on industrial innovation (e.g. Freeman, 1983) that R&D managers have to rely on relatively simple rules of thumb, since even the probabilities of innovational success and the magnitude of its possibly associated revenues are highly uncertain. In the model I will use a very simple rule of thumb, which says that each industry invests a fixed fraction θ_j of its sales (in current prices) of the previous period in R&D activities:

$$\tilde{\mathbf{i}}^{\mathbf{R}}[t+1] = \hat{\mathbf{\Theta}}\hat{\mathbf{P}}[t]\mathbf{x}[t] \tag{11}$$

Since I assume that R&D activities are characterized by industry-specific Leontief production functions (which change over time, due to innovations caused by R&D itself), relative prices of the inputs in these processes must be taken into account to determine how much of the various inputs are bought. I assume that the industries base their decisions on the prices and the Leontief production functions (with parameters $\mathbf{Z}_{\mathbf{c}}^{\mathbf{R}}$ representing the physical amounts of materials required per unit of labor, which change over time inversely to the rate of labor productivity growth in the production sector of the corresponding industry) which prevailed in the preceding period, so that the optimal allocation of research funds $\tilde{\mathbf{i}}^{\mathbf{R}}$ can be specified.[20]

$$\mathbf{l}_{\mathbf{s}}^{\mathbf{R}}[t+1] = \left(\hat{\bar{\mathbf{p}}}^{\mathbf{R}}[t]\right)^{-1} \cdot \tilde{\mathbf{i}}^{\mathbf{R}}[t+1], \tag{12}$$

in which the diagonalized vector in the first right hand side factor can be considered as a vector of 'R&D costs per unit of labor employed in the R&D processes':

$$\bar{\mathbf{p}}^{\mathbf{R}}[t] = w[t] \cdot \mathbf{e} + \left(\mathbf{p}'[t]\mathbf{Z}_{\mathbf{c}}^{\mathbf{R}}[t]\right)'$$

Now, the physical amounts of materials for R&D purposes are given by

$$\mathbf{Z}_{\mathbf{s}}^{\mathbf{R}}[t+1] = \mathbf{Z}_{\mathbf{c}}^{\mathbf{R}}[t] \cdot \hat{\mathbf{L}}_{\mathbf{s}}^{\mathbf{R}}[t+1] \tag{13}$$

3.c Wages, prices and profits

In the IO literature, prices are often completely determined by supply-side factors. In models without capital goods, prices are assumed to be a function of the nominal wage rate (which is

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[20] In most CGE-models, prices and quantities are determined simultaneously. In the present model, industries are assumed to be extremely backward-looking: most quantities are assumed to be set taking only previous prices into account, while prices are set according to previous technological standards. A model with more forward-looking expectations should be regarded as more realistic, but would introduce all kinds of complexities, which would probably not add to the understanding of the growth process in an interindustry context.

assumed to be equal across industries) and the set of input coefficients. I also adopt this procedure, but have to make an additional assumption with regard to the way in which R&D investment is financed. As discussed in Section 2, modern endogenous growth theories assume that innovation enables firms to earn back their R&D costs by imposing a positive mark-up over their production costs. In the price equation, I represent this micro-economic mechanism in a rough way, by simply assuming that industries include their R&D costs in their production costs. This implies that output prices are higher than would have been the case if no R&D costs had been incurred.[21] Introducing **A** as the matrix of input coefficients, commodity prices are then given by

$$\mathbf{p}'[t+1] = w[t]\left(\mathbf{l}_{\mathbf{c}}'^{\mathbf{P}}[t] + \mathbf{l}_{\mathbf{s}}'^{\mathbf{R}}[t+1]\hat{\mathbf{X}}^{-1}[t]\right)\left(\mathbf{E} - \mathbf{A}[t] - \mathbf{Z}_{\mathbf{s}}^{\mathbf{R}}[t+1]\hat{\mathbf{X}}^{-1}[t]\right)^{-1}, \tag{14}$$

in which it is implicitly supposed that industries are also backward-looking with respect to their expectations that their sales levels will remain unchanged. I will assume that the nominal wage rate is stable and treat it as a numéraire. Since prices fall over time (due to decreasing labor requirements in production per unit of output), the real wage rate increases at a pace which is about similar to the aggregate labor productivity growth rate. Generally small deviations from this rate are due to differences in labor requirements between the production and the R&D sector, and changes in the composition of the consumption bundle, to which I turn now.

3.d Consumption and output

In most IO models, output levels are obtained as the product of the Leontief inverse (calculated from the intermediate input requirements per unit of output) and the vector of final demands. For the closed economy I consider, final demand is the sum of materials demand for R&D purposes and consumption demand by households. Materials demand for R&D purposes has been dealt with in subsection 3.a, now I will turn to consumption demand.

Contrary to standard IO models, I will not let employment be dependent on total final demand, but the other way round. In order to stay as close as possible to endogenous growth theory, I will assume that output levels are determined by supply conditions. In the model, output levels are bound by a single condition: the maximum aggregate labor supply is completely employed. Part of the labor supply is already occupied by the demands for R&D materials and their consequent indirect effects on output. My supply-side perspective in this paper implies that I assume that the remaining labor supply is used to produce consumption demand and its indirect requirements. So, given labor supply conditions at the beginning of a period and the input requirements per unit of output, 'the economy' can choose for a particular combination of investment in R&D and current consumption. This important trade-off also characterizes the endogenous growth theories discussed in Section 2, but is now extended to the industry-level.

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[21] See Dietzenbacher & Los (2000) for an empirical account of the price effects of R&D expenditures.

A major problem connected to this approach is the composition of the consumption vector. Many different consumption vectors fulfill the full-employment condition. In principle one could adopt a linear programming approach (see e.g. Dervis *et al.*, 1982, Ch. 3), in which aggregate consumption is composed in such a way that the value of total consumption (measured either in constant prices or in current prices) is maximized. I do not choose this solution, however, mainly because this approach is likely to yield strongly discontinuous consumption compositions in periods in which many innovations take place in a few industries. Instead, I follow an approach recently put forward by Verspagen (1999) and extended in Los & Verspagen (1999), which starts from the assumption that the composition of consumption is given at the beginning of each period. For example, one can assume that the shares of the n commodities depend on the consumption level in the previous period, which allows for modeling commodity-specific Engel curves. Given that the composition of the consumption bundle is known, its size is obtained as the maximum attainable given the full employment condition. This is the case if the solution for the consumption level $c[t+1]$ as given by the equation

$$l^{\max}[t+1]-l_s^G[t+1]=\mathbf{l}_{\mathbf{c}}^{\mathbf{P}}[t]'(\mathbf{E}-\mathbf{A}[t])^{-1}\mathbf{b}[t+1]c[t+1] \tag{15}$$

The left hand side denotes the difference between the maximum labor supply ($l^{\max}$) and the part of this labor supply which is 'absorbed' by the production of the materials for R&D and the intermediate inputs required for this production and the labor itself employed in R&D. That is, $l_s^G[t+1]\equiv\mathbf{l}_{\mathbf{c}}^{\mathbf{P}}[t]'(\mathbf{E}-\mathbf{A}[t+1])^{-1}\mathbf{Z}_{\mathbf{s}}^{\mathbf{R}}[t+1]\mathbf{e}+\mathbf{e}'\mathbf{l}_{\mathbf{s}}^{\mathbf{R}}[t+1]$.[22] For the maximum labor supply, a simple exponential growth pattern is modeled:

$$l^{\max}[t+1]=(1+\nu)l^{\max}[t] \tag{16}$$

The evolution of consumption shares **b** (equation (15)) is governed by commodity-specific Engel curves, which were introduced in growth theory by Pasinetti (1981). To model these, I borrow an elegant specification from Verspagen (1993), which ensures that consumption shares always add up to one:

$$\mathbf{b}[t+1]=\mathbf{b}[t]+\left[\hat{\mathbf{B}}[t]\mathbf{T}\left(\mathbf{b}[t]-\mathbf{b}^*\right)-\left(\hat{\mathbf{B}}[t]-\hat{\mathbf{B}}^*\right)\mathbf{T}'\mathbf{b}\right]\cdot\left(c[t]-c[t-1]\right) \tag{17}$$

In this specification, $\mathbf{b}^*$ represents the consumption shares which prevail at an infinite consumption level. The elements τ of matrix $\mathbf{T}$ indicate how quick current consumption levels adapt to $\mathbf{b}^*$. If T is chosen to have zeroes on the main diagonal and sufficiently small

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[22] In theory, the left hand side of equation (15) might become negative. If reasonable values are chosen for the R&D to output ratios θ and the input coefficients in **A**, this problem (yielding negative consumption levels) will not occur.

nonnegative values elsewhere, negative shares will not occur and actual shares will converge monotonically to their asymptotic values if c grows (no overshooting).

Given the solution for $c[t+1]$ in equation (15), the vector of output levels $\mathbf{x}$ is determined using the standard static open Leontief model:

$$\mathbf{x}[t+1] = \left(\mathbf{E} - \mathbf{A}[t]\right)^{-1}\left(\mathbf{b}[t+1]c[t+1] + \mathbf{Z}_{\mathbf{s}}^{\mathbf{P}}[t+1]\mathbf{e}\right) \tag{18}$$

Together, the equations (8)-(18) constitute the IO model of R&D-driven growth. Due to its industry detail and its stochastic nature it seems impossible to study the long-run behavior of the model by analytical means. Instead, the next section is devoted to a set of simulation experiments for a hypothetical economy.

4. Simulation Results

Having specified a model and turning to simulation experiments to analyze its properties, it is often tempting to report on as many experiments as possible. In this section, I have chosen to highlight just a few experiments, which either give basic insights into the interaction of the equations making up the model or provide indications of the potential policy-related value added of IO endogenous growth models relative to aggregate endogenous models.

With regard to the specification of the initial variable configuration and the calibration of the parameters, I could have chosen to let the economy resemble an actual economy as well as possible. I did not do this, because it would have involved a very rich but intractable industry structure, whereas I would have had to adapt the empirical data to an unwarranted extent in order to get rid of international trade flows and capital goods stocks and flows. Instead, I present simulation results for a completely hypothetical economy, which consists of only five homogeneous industries. The initial values of the variables and the parameters can be found in the Appendix. It should be noted that the initial values and the parameters are chosen such that the economy is almost in equilibrium. Sensitivity analysis in this section, though, will show that the long-run behavior of the model is not affected qualitatively by non-equilibrium initial values, as long as these are in a rather large range around equilibrium.

4.a A typical simulation run

A quick glance at the Appendix shows that the five specified industries are initially equally large in terms of gross output levels. The initial labor productivity levels do not deviate much (apart from the small price effects of R&D materials costs, real value added levels initially equal labor inputs), but the industries mainly differ with respect to the average innovation arrival rates. Industry 2 represents a high-tech industry, since it attains a mean productivity growth rate of more than 6%, which is partly due to its high R&D intensity (10%). Further, its R&D yields relatively important knowledge spillovers to the other industries. Without spillover effects (the magnitude of which depends on the industry structure), industry 2's productivity growth rate would average slightly more than 3%, while spending 2% of its previous sales on R&D. This industry can be considered a medium-tech industry, in terms of the often-used OECD classification. The other three industries have R&D intensities of only 0.5%, and differ with respect to their opportunities to benefit from spillovers. Setting aside these spillover effects, their labor productivity figures grow at 1.2% (industry 1), 2.1% (4) and 1.7%(5), respectively.

Figure 1

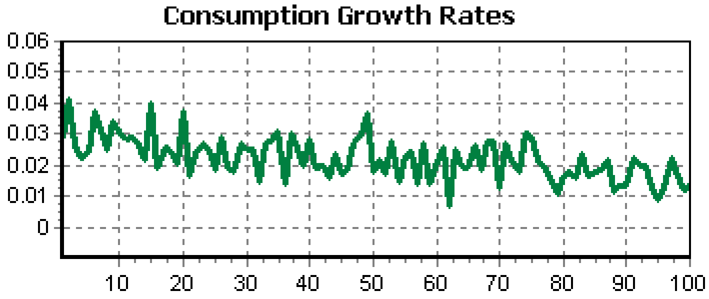
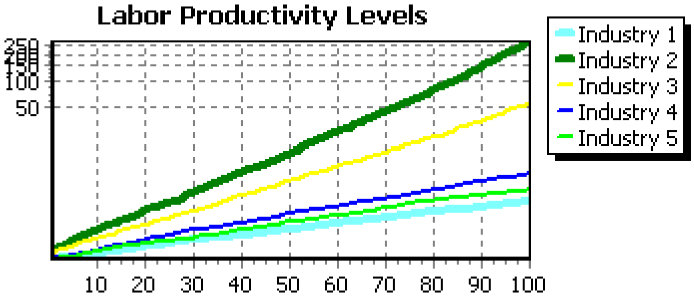


Figure 1 shows how R&D driven productivity growth translates into consumption growth. It fluctuates to some extent, due to the specified random character of the innovation processes. The 'amplitude' of the fluctuations is, of course, affected by the exogenous size of the innovations. Clearly, the model yields long run consumption growth, although its average rate seems to be slowing down over time. This could basically be due to two underlying sources: productivity growth slowdown at the industry level and/or a growth-hampering employment shift towards industries with lower productivity levels. Figures 2 and 3 show that the second explanation is the right one.[23] In Figure 2 (with a logarithmic vertical axis), the almost straight lines indicate that industry-level labor productivity growth rates do not slow down.

Figure 2



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[23] Inspection of a diagram similar to Figure 1 for an extended period (not documented here) also shows that the aggregate labor productivity growth rate asymptotically settles at a constant value.

Figure 3 shows that an increasing part of the labor force gets active in the low-productivity growth industries 1, 4 and 5. As such, the model results are opposite to but reconcilable with the 'agricultural reserve army of labor'-explanation of growth proposed by some development economists (Lewis, 1954). This theory ascribes large parts of high productivity growth rates experienced by former underdeveloped countries to shifts from labor from low-productivity agriculture to high-productivity manufacturing.

The result that labor inputs in the high-tech and medium-tech industries 2 and 3 almost vanish is clearly not in line with observed facts. This is due to the fact that the model regards all productivity increases as process innovations, whereas 'real' high-tech industries (e.g. 'computer manufacturing' and 'instruments manufacturing') are characterized by product innovations which lower labor requirements in downstream industries. The incorporation of product innovations should therefore be one of the first model improvements to be sought for.

Figure 3

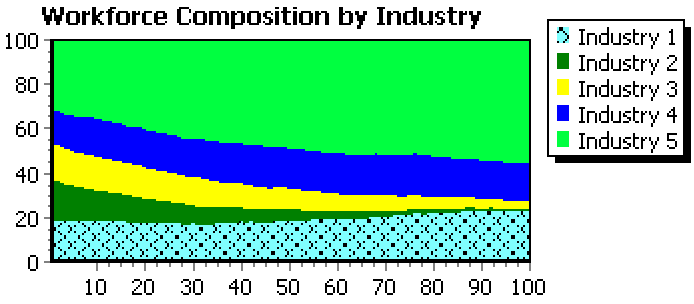
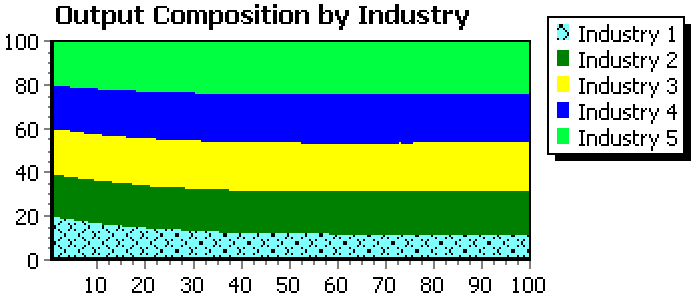


Figure 4 considers the composition of gross output. The differences between the initial consumption shares and the 'shares at infinite consumption' lead to an adjustment process of about 40 periods. During this period, the consumption shares of industries 1 and 2 decrease to the benefit of the three remaining industries. For industry 2, however, the output share appears to remain stable over time. This is mainly due the fact that the large majority of R&D materials is assumed to be delivered by industry 2, a mechanism which is not effective for industry 2. This is a first result which indicates that interindustry linkages may be very important for long-run growth and structural change.

Figure 4



4.b Some sensitivity analysis

The simulation results presented so far sketch only a far from complete picture, in the sense that they do not give any clues to which variables or parameters cause the observed positive long-run growth rates. It might even be the case that these are not related to the choice for particular R&D-intensities. Further, it remains to be seen whether similar results are found if different realizations of the stochastic process are considered. Before I turn to a discussion of some industry-specific simulation experiments, I will deal with some results which are obtained when R&D decisions and/or their consequences are assumed to vary in the entire economy to the same extent. In the presentation, I focus on two variables which are generally seen as important measures of 'welfare in the long run', the net present value (NPV) of consumption and the average real GDP growth rate. The former was calculated according to $\Sigma(1-\delta)^t c[t]$, with δ the rate of time preference (discount rate), for a 100-period interval. I ran 20 simulations for each of five scenarios. These scenarios do not differ with respect to the initial variable configuration, the changes are due to changes in the set of parameter values. The summary results, for δ=0.05, are in Table 1.

Table 1: Economywide effects of economywide changes.

	Mean NPV consumption*	std.dev.	Mean annual GDP growth	std.dev.
Benchmark configuration	46585.2	982.2	0.0230	0.00047
Permanent R&D increase	48227.1	1049.9	0.0246	0.00045
Temporary R&D increase	47934.2	854.4	0.0230	0.00056
No Spillovers	41497.4	847.1	0.0192	0.00056
No R&D investment	28580.3	86.1	0.0008	0.00003

*NPV: net present value.

The first row ('benchmark configuration') is obtained for the parameter values given in the appendix. Actually, the first of the twenty runs for this scenario was the one for which diagrams were presented in the previous subsection. The variation in GDP growth rates as evidenced by the standard deviation in the rightmost column appears to be relatively small. The second scenario ('permanent R&D increase') supposes that each of the five industries increases its R&D intensity (θ) by 25% for the entire time span of 100 periods. Apparently, the initial sacrifice of consumption to release labor for additional R&D and the production of the required materials in order to attain a higher growth rate (approximately 0.15% per year) is worthwhile, since the NPV of consumption is higher than in the benchmark. The most important conclusion, however, is that the model is a true endogenous growth model, since a permanent change in the fraction of resources devoted to R&D affects the long-run growth rate.

The third scenario ('temporary R&D increase') is defined to see whether temporary changes in R&D intensities have permanent effects or not. This scenario is identical to the benchmark except for the first five periods, in which R&D efforts are doubled by every industry. From the reported mean annual growth rate (for this scenario calculated excluding the first five observations) can be concluded that a temporary change has no permanent effect on growth. Simultaneously, a permanent level effect is present, like in the Jones (1995b) model. This level effect (growth to a higher consumption level during the shock and equal growth rates afterwards) yields a NPV of consumption higher than in the benchmark case.[24]

Scenario four ('no spillovers') assumes that the industries invest as much in R&D as in the benchmark case and experience the same productivity effects of their own R&D, but cannot benefit from knowledge spillovers from other industries (all ηs are set to zero). This has a significant negative effect on the long-run growth rate. Further, the NPV of consumption is considerably lower. This does not come as a surprise as spillover-induced productivity growth comes does not require any sacrifice of current consumption.

The final scenario ('no R&D') simply assumes that no R&D is undertaken at all. The results are clear: the economy is caught in a stationary situation without growth. The very low NPV of future consumption is generated by a stable series of consumption levels.[25]

4.c Optimal R&D intensities

One of the most important issues emerging from endogenous growth theory is that R&D investment may be too low, due to the fact that profit-maximizing firms do not take positive effects of spillovers into account (see Section 2). In the present model, industries are not maximizing their profits, but determine their R&D expenditures according to a very simple rule of thumb. This assumption creates the possibility that too much resources are devoted to R&D, irrespective of any creative destruction processes at the micro-economic level. In the framework of the IO growth model, overinvestment is caused by too large a sacrifice of current consumption. In this section, I want to stress the importance of both differences and linkages between industries for the issue of optimal investment in R&D. Along the way, the influence of chance on the outcomes of possible (policy-induced or not) will be pointed at.

In Figure 5, a large number of simulations are summarized. The benchmark parameter configuration was maintained, except for the R&D intensity of the high-tech industry 2. For each of the 31 values ranging from θ_2=0.0 to θ_2=0.3, twenty simulation runs were done for 100 periods. The resulting net present values of consumption were computed and averaged over the twenty runs for ten discount rates, ranging from δ=0.03 to δ=0.10. All average NVPs were

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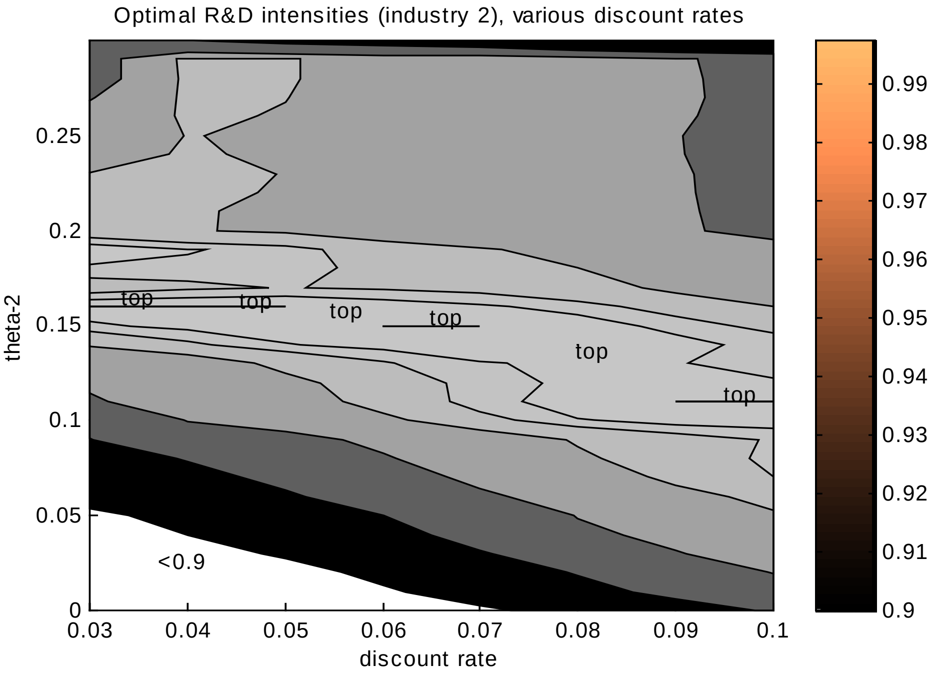
[24] Of course, this welfare improvement is strongly dependent on the supposed discount rate. This issue will be dealt with below.

[25] The very small average growth rates and the positive standard deviations appear to have been caused by innovations in the very first period, due to an error in the initialization values. This will be corrected in the next version.

divided by the maximum NVP found for the corresponding discount rate, to see which R&D intensity is optimal.

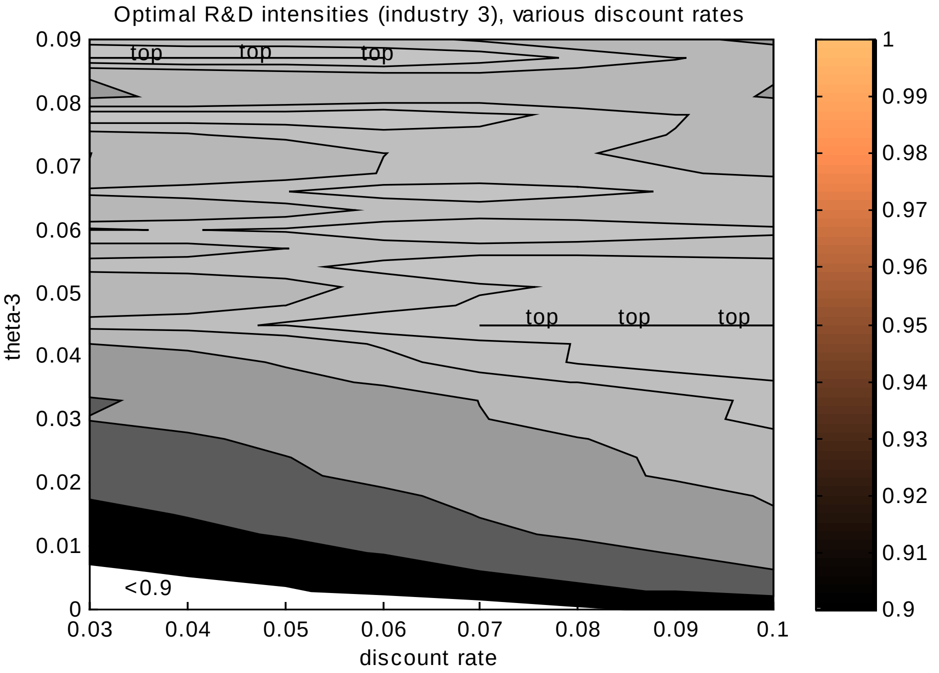
Figure 5



The maximum NVPs are marked by 'top', to indicate that the diagram is a projection of a three-dimensional graph on a two-dimensional plane. A first conclusion is that the optimal R&D intensity is sensitive to the discount rate indeed. For low discount rates, the optimal θ_2 is about 0.16, for high discount rates it is reduced to about 0.11. This indicates that the hypothetical economy considered could improve on the benchmark configuration by keeping all parameters constant and increasing industry 2's R&D intensity from 0.10 to a slightly higher value. The loss of sticking to the current intensity would not be so large, though, seeing that the gradients to the top (from below and above) are not extremely steep: even at low discount rates, the NPV corresponding to θ_2=0.1 exceeds 95% of the maximum attainable level.

To indicate the effects of differences between industries, I present a similar diagram for medium-tech industry 3 in Figure 6. It should be noted that the 31 simulation values for industry 3's R&D intensity vary over a much smaller range (0.00-0.09) than for industry 2 in Figure 5 (0.0-0.3). In a relative sense, however, the range in Figure 6 is larger: θ_3 is allowed to get 4.5 times as large as in the benchmark compared to 3.0 for θ_2. The pattern of optimal R&D intensities diminishing with the discount rate is confirmed. The gradients to the optimal values, however, are much flatter than for industry 2. For large ranges of θ_3, there is not even monotonicity. This may seem strange at first sight, but it is a reflection of the potential effects of chance on the eventual success of changes in issues related to stochastic R&D processes: runs for the various θ_2s were fed with different random seeds. Consequently, relatively many runs with 'early' consumption-enhancing innovations in a series of twenty runs could yield a higher discounted value of consumption than for another series with a θ closer to the optimum. The most important conclusion to be drawn from Figure 6, however, is that the loss of choosing (or inducing by policy measures) a suboptimal R&D intensity is much smaller for industry 3 than for industry 2. This is due to the fact that increasing θ_3 by a given percentage involves much less opportunity costs than increasing θ_3 by the same percentage. The introduction of more industry-specific inputs than homogeneous labor would probably diminish this difference. What remains, though, is the result that industry-specific technological opportunities (reflected in the industry-specific parameters α and γ) yield substantially different optimal R&D intensities.

Figure 6



The IO growth model also provides opportunities to see how sensitive the optimal R&D intensities are to the productivity-enhancing effects of knowledge spillovers from one or more specific industries. It could be expected that stronger positive effects should lead to higher optimal intensities for the industry which generates the spillovers, since the rest of the economy would benefit more from a given sacrifice of current consumption. The effects for the optimal intensities of spillover receiving industries is less clear. To investigate these issues, I multiplied the productivity effects of the spillovers generated by high-tech industry 2 (η_{2j}, j=1..5) by the values 0.0, 0.25, 0.5, 1, 2, 4 and 8 and again ran twenty simulations for varying R&D intensities. The NPVs of future consumption relative to their maximum value (δ=0.05) are plotted in Figures 7 (for the spillover-generating industry 2) and 8 (for the spillover-receiving industry 3).

Figure 7

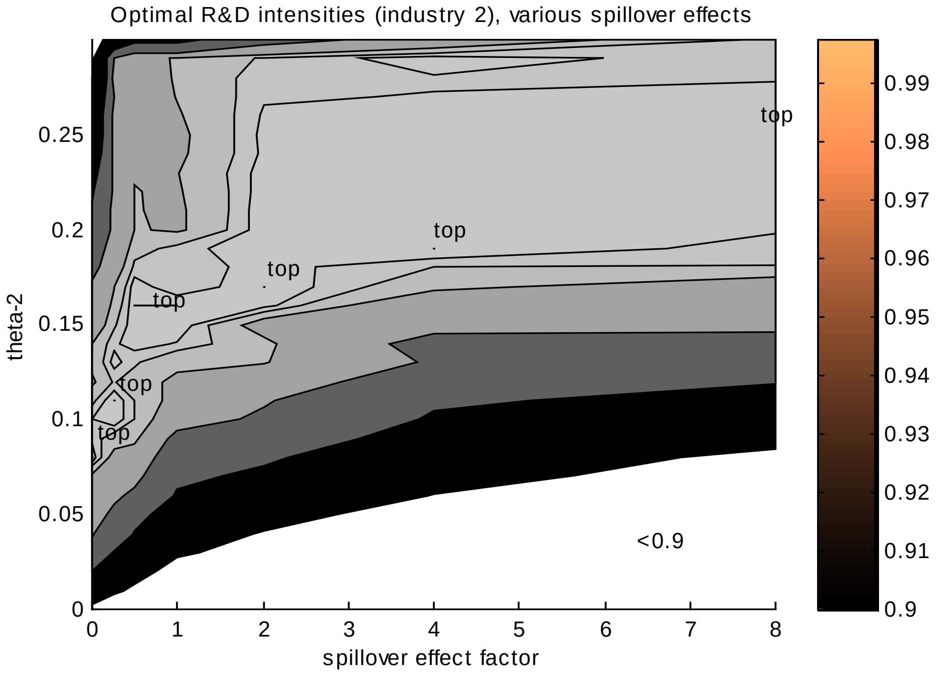


Figure 8

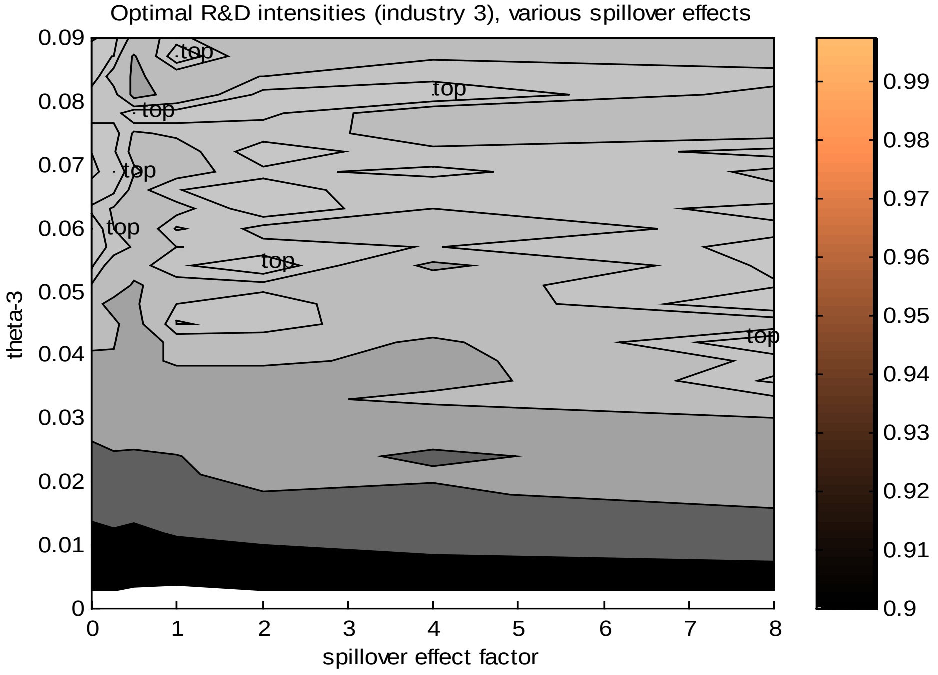
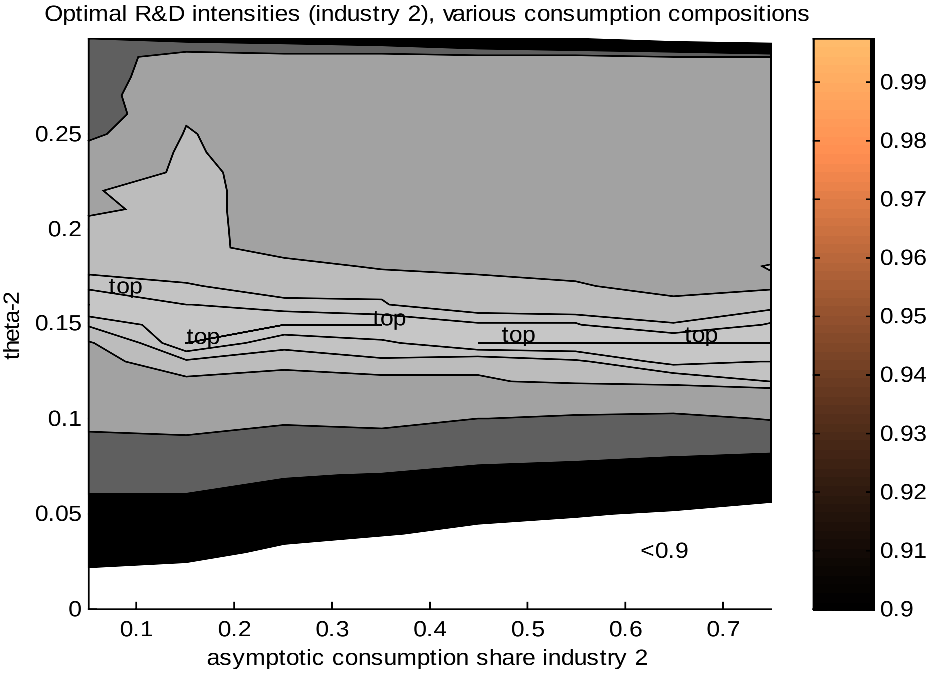


Figure 7 shows that the simulation results confirm the expectations with regard to the optimal R&D intensity for the spillover-generating industry: at very low productivity effects (at least compared to the benchmark) θ_2 should take on a value of slightly below 0.1, while very high productivity effects of spillovers would warrant a θ_2 of about 0.25. Further, the results for intermediate values of the ηs indicate that this relationship is of a monotonic nature. Figure 8 does not yield such a clear insight for a spillover-receiving industry. The optimal R&D intensity seems to increase with the spillover effect, but for larger values this observation does not hold. The optimal value jumps up and down, on a surface which is very flat like in the other results for industry 3, which I presented earlier (Figure 6). Some indication for a systematic relationship might perhaps be derived from the behavior of the relative loss incurred when far too few resources are devoted to R&D by industry 3. It seems that the relative loss slowly decreases if spillover effects become large, if the downward-sloping ‘isoloss’ lines in the lowest part of the diagram are considered. This possibly points towards a situation in which medium-tech industry 3 could best limit its R&D activities to a relatively modest level and rely on the positive productivity effects of knowledge spillovers from high-tech industry 2, if these exceed a certain threshold level.

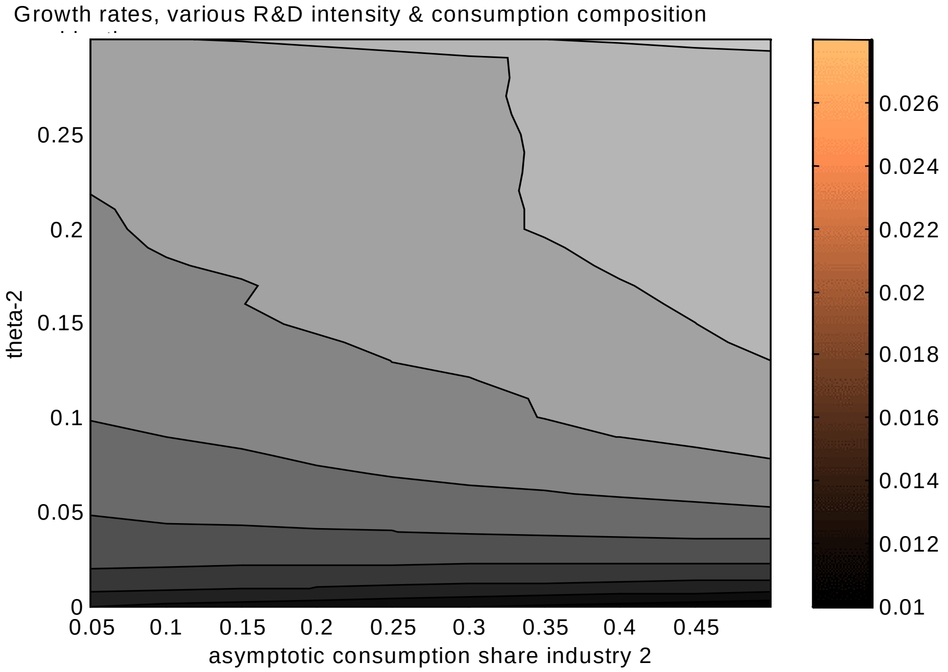
Figure 9



The last issue I would like to discuss is the effect of consumption bundle dynamics on optimal R&D intensities and long-run growth rates. A shift towards consumption of the high-tech commodity is likely to yield higher real GDP growth, since a larger share of labor will be active in activities with high-productivity growth. An interesting question is whether such a shift would also affect the optimal R&D intensity of this industry. According to equation (10), increasing the scale of the spillover-producing industry relative to the other industries would enhance the productivity effect of these spillovers. Consequently, one could expect that the optimal R&D intensity of the main spillover-producer would increase with its size, keeping the results for various spillover effects (Figure 7) in mind.

The results are in Figures 9 and 10. The horizontal axes of both figures represent the consumption share of the high-tech industry 2 at infinite consumption levels (b_2*). To satisfy the adding-up constraint of consumption shares, I assume that an increase of industry 2's asymptotic share leads to a decrease of the other four shares in proportion to their benchmark values. The results in Figure 9 are clear. The optimal R&D intensity (as found for a discount rate of 0.05) is hardly affected by the consumption shares. If there is any effect, it is a negative effect, which is contrary to my above-formulated expectation. More in line with this expectation is the result that the loss incurred by investing to little in R&D seems to increase with the consumption share of industry 2.

Figure 10



Although the optimal R&D intensity does not appear to be very sensitive in the simulation results, Figure 10 shows that the long-run growth rate of real GDP can be affected to a substantial extent. For high consumption shares of the high-productivity growth industry, relatively low R&D intensities suffice to attain a given growth rate. Of course this result is not surprising, but it can have important policy implications, in particular when an economy is considered which competes for market share with other countries. In that case, extra export demand for high-tech commodities would be equivalent to a higher consumption share of these products. In the concluding section, I will deal with some possibly worthwhile extensions of the model, one of which is to incorporate international trade.

5. Conclusions

This paper started off with Leontief's (1989) statement that the main task of IO analysts should be to provide tools which could reduce the widening gap between abstract economic theory and factual observation. In the previous sections I presented a dynamic IO model which preserves some of the characteristic elements of a relatively recent aspect of mainstream theory (endogenous growth theory) and showed that it yields intuitively plausible results in simulation experiments. The main message of the model is that differences between industries as well as their economic and technological linkages matter for R&D-driven long run growth rates. As such, one could say that endogenous growth theory gains from an explicit IO approach. It must be admitted, however, that the model itself has little to say to policymakers who are faced with decision problems with regard to enhancing the innovativeness of particular industries or supporting threatened industries with a substantial contribution to national (or regional) economies in terms of output or employment. The model is simply to simplified, and results for hypothetical economies do not tell us too much in relation to real economies. In this concluding section, I will therefore point out some opportunities for further research, of which I think that successful completion could increase the practical relevance of both endogenous growth theory and IO analysis.[26]

First, the model contains only two types of inputs, labor and intermediate inputs. This is clearly at odds with reality, in which many types of durable capital inputs are used in both production processes and R&D activities. Some preliminary experiments (which are not documented in this paper) indicated that inclusion of capital goods and associated profits should be possible in the framework of this model. One could, for example, think of a two-stage investment decision process in which an industry-specific fraction of profits from the previous period is retained for total investment.[27] Given the investment budget resulting from this first stage, industries spend a fixed fraction of this budget on R&D. This decision implies a choice between enlarging future productive capacity and lowering future labor requirements. Next to the single constraint on consumption in the present model (the labor constraint), at least n additional capacity constraints should be included. A mechanism in which the n profit rates are sensitive to the utilization rates of the n capital stocks and the aggregate unemployment rate should be expected to ensure a type of growth cycle. The preliminary experiments, however, suffered from 'fatal' short-term instabilities which occur when the model switches from a 'capacity of industry i-constrained' maximum consumption level to a 'capacity of industry j-constrained' maximum consumption level.

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[26] The absence of product innovations was mentioned earlier and will not be discussed further here.

[27] Alternatively one could argue that households save a fixed fraction of non-wage income and allocate these funds to the industries in proportion to their share in aggregate profits. See Dervis *et al.* (1982, p. 177) for a more detailed discussion.

Modeling capital stocks does not only render the model more realistic, it is also a way to incorporate industry-specific constraints on production and consumption. A potentially worthwhile alternative with a more or less similar nature would be to introduce various types of labor, which are required in different industry-specific proportions. If one would, for instance, make the assumption that all R&D activities and high-tech production require relatively scarce highly-skilled engineers, R&D decisions by medium-tech industries are likely to have much more impact than in the simulations I presented in this paper. The inclusion of several skill categories would also allow for IO-approaches to the class of non-Schumpeterian endogenous growth models where economies grow as a consequence of investment in human capital. The most straightforward way to take human capital formation into account seems to be to specify an education industry, which can be financed by taxes levied on production or consumption.

A final word on extensions of the model to make it more suitable for policymaking concerns the modeling of international trade. In particular for most European and Asian countries, effects of newly created technology on export performance should be included, since their openness causes a strong relation between exports and growth. Incorporation of technology-exports links is likely to overturn the simulation result that the optimal R&D intensities are quite insensitive to the shares of industries in total production, since loss of world market share in high-value added industries could result. In my view, a natural way to proceed in this direction would be to integrate the R&D-driven model in this paper with a modified version of the two-country IO growth model recently proposed by Los & Verspagen (1999). In the latter model, market shares are dependent on differentials in technology, which are widened by (exogenous) innovation in the leading country and reduced due to intra-industry knowledge spillovers to the lagging country. Further, the feedback effects of technology on endogenous specialization patterns, balance-of-payments (dis)equilibria and exchange rate movements can be studied. Endogenizing the capabilities to innovate and to absorb knowledge spillovers by devoting part of the resources to R&D may prove a useful improvement.

I saved a brief discussion of the highest hurdle with regard to practical implementation of these models to the end. Widely published input-output tables, data on international trade by industry and data on R&D expenditures by industry may well be sufficient to prepare initial variable configurations that resemble actual economies reasonably well.[28] Nevertheless, the reliability of simulation results will be questionable as long as the parameters linking productivity growth to R&D efforts are not fixed at sensible values. The problem is that empirical studies come up with rates of return to ‘own’ R&D and R&D spillovers which vary across such a wide range that it is impossible to tell what values are sensible and which are not.[29] Therefore, continued research efforts and strong interactions between growth theorists, input-output

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[28] See e.g. the OECD IO, STAN, BTD and ANBERD databases which distinguish between about 35 industries for a number of well-developed countries.

[29] Surveys of estimation results can be found in Nadiri (1993) and Mohnen (1994).

researchers and applied econometricians seem indispensable to turn the theoretical advances in growth theory into a useful tool for policymakers.

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Appendix

This appendix contains the parameter values which were used in the benchmark run for which simulation results were presented in Section 3.a. Further, the initial variable configuration which was used throughout the entire simulation analysis is documented. Matrices are presented in the usual way: rows denote delivering industries, columns using industries.

a. Parameter values in benchmark configuration

0.05 δ {consumption discount rate}

0.00 ν {labor supply growth rate}

0.005 σ {innovation size}

1.0 w {nominal wage rate}

12.0 γ {'productivity effects of own R&D'}
80.0
30.0
12.0
10.0

0.3 α {'diminishing returns to R&D parameter'}
0.8
0.4
0.2
0.2

0.0 0.0 0.0 0.0 0.0 η {'returns to knowledge spillovers'}
10.0 0.0 12.0 10.0 8.0
8.0 0.0 0.0 15.0 10.0
5.0 0.0 0.0 0.0 8.0
0.0 0.0 0.0 0.0 0.0

0.005 θ {R&D to sales ratios}
0.100
0.020
0.005
0.005

0.050 b* {'asymptotic consumption shares'}
0.150
0.200
0.250
0.350

0.000 0.001 0.001 0.001 0.001 τ {consumption share adjustment}
0.001 0.000 0.001 0.001 0.001
0.001 0.001 0.000 0.001 0.001
0.001 0.001 0.001 0.000 0.001
0.001 0.001 0.001 0.001 0.000

b. Initial values for all reported simulation runs

1314.0					l^{max}	{maximum labor supply}
1334.0					c	{consumption level}
0.245					$\mathbf{l}_c^P$	{labor requirements (for production) per unit of output}
0.200						
0.210						
0.195						
0.395						
0.35	0.00	0.10	0.20	0.00	$\mathbf{A}$	{intermediate input requirements (for production) per unit of output}
0.00	0.30	0.15	0.10	0.10		
0.10	0.20	0.25	0.15	0.10		
0.20	0.10	0.10	0.30	0.10		
0.10	0.10	0.15	0.05	0.30		
0.333	0.000	0.000	0.000	0.000	$\mathbf{Z}_c^R$	{materials requirements (for R&D) per unit of labor in R&D}
0.333	1.000	0.500	0.333	0.333		
0.000	0.000	0.500	0.000	0.000		
0.000	0.000	0.000	0.333	0.000		
0.000	0.000	0.000	0.000	0.333		
1.0	0.0	0.0	0.0	0.0	$\mathbf{Z}_s^R$	{materials used in R&D activities}
1.0	50.0	5.0	1.0	1.0		
0.0	0.0	5.0	0.0	0.0		
0.0	0.0	0.0	1.0	0.0		
0.0	0.0	0.0	0.0	1.0		
1.0					$\mathbf{p}$	{prices}
1.0						
1.0						
1.0						
1.0						
3.0					$\mathbf{l}_s^R$	{labor employed in R&D}
50.0						
10.0						
3.0						
3.0						
1000.0					$\mathbf{x}$	{output levels}
1000.0						
1000.0						
1000.0						
1000.0						
0.262					$\mathbf{b}$	{consumption shares}
0.219						
0.146						
0.149						
0.224						