On the Diffusion of Technologies in a Vintage Framework

Theoretical Considerations and Empirical Results

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On the Diffusion of Technologies in a Vintage Framework

Theoretical Considerations and Empirical Results

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Preface

About six years ago, I had to decide upon the subject for my Master's dissertation to finish my study of economics at the Faculty of Economics and Business Administration at the State University of Limburg. During this study, I was involved in research on vintage modelling and I decided to write my dissertation on vintage modelling and on the introduction of diffusion of new technologies in such a model. It soon became clear that this subject was too broad and too complicated to solve all problems in the short time I had to write the dissertation. Together with my present supervisors, Joan Muysken and Adriaan van Zon, I decided to write a proposal for a Ph.D. thesis on this subject, which was approved by the scientific committee of the faculty. The research started in 1989 and because of the relations of this subject with the research carried out at the research institute MERIT, my office was located in the MERIT building, although I was formally employed by the faculty.

Now, more than five years later, this book presents the results of the research. Although only my name is printed on the cover, and I take full responsibility for the views expressed here, this thesis would not have been finished without the help and encouragement of a number of people. A list follows here.

First of all, I would like to thank my supervisors, Joan Muysken and Adriaan van Zon. Joan provided me with valuable help when I got locked up in my own thoughts. He was always ready to listen to my — sometimes unstructured — ideas and appeared to be very good at organizing these ideas and putting them into a more general context. Moreover, he was very sympathetic to the ups and downs of in life. When I was pessimistic about the social usefulness of my research, for instance, he took me outside for a walk downtown to buy me an ice cream. It is true, the ice cream was refreshing in more than one way.

My second supervisor, and roommate, Adriaan van Zon, taught me the insights into vintage modelling and he was always prepared to give me helpful advice, which I needed especially on technical issues to put my views into a model in a consistent way. Whereas Joan had an eye for the general framework, Adriaan appeared to be very accurate in all details. In his enthusiasm, he sometimes came up with completely new ideas which left me even more confused than before. Nevertheless, especially from him, I learned to handle economic problems in a creative manner. Moreover, he proved to be a good friend who helped me a lot in bad times, for instance, during the illness of my daughter.

For taking part in the examining committee of this thesis, I would like to thank Luc Soete, and in particular Franz Palm and Paul Stoneman, for their constructive comments. Paul Stoneman's comments on an earlier paper presented on a conference were also very helpful, and he encouraged me to go on with the research.

A number of people in the macro-economics section at the Faculty, especially Clemens Kool, Eric de Regt and Tom van Veen, helped me by giving advice during several lunch seminars. MERIT's productivity group appeared to be a fruitful place for lively discussions and, in particular, I want to thank Paul Diederen, René Kemp, Bart Verspagen, Rombout de Wit and Thomas Ziesemer for this.

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I would also like to thank my parents for first providing me a pleasant and uncomplicated youth and later enabling and encouraging me to go to Technical College and to the University. Moreover, they were a great help coming to Maastricht many times and by taking care of my children (and of the garden). This enabled me to finish the thesis.

Finally, I want to thank Malva Driessen for sharing the pleasures and sorrows that life brings. Particularly during the last phase of the research, she did a terrific job of taking care of our children and running most of the household, next to her own job. Without her, the thesis would not have been finished yet and, more important, my life would not be as enjoyable and flourishing as it is today.

Whereas they are probably less aware of it, my daughter Teska and son Jorik took care of the necessary distraction. Although they delayed the progress of the research to some extent, they have made my efforts worthwhile.

I thank you all and hope to be able to return your favours some day.

Maastricht, October 1994

Samenvatting (Summary in Dutch)

Dit proefschrift handelt over de wijze waarop het gebruik van nieuwe technologieën gemodelleerd kunnen worden in een macro-economisch model. In tegenstelling tot de meer traditionele modellen — waarin technologische vooruitgang als een exogene factor wordt gezien — wordt in dit proefschrift technologische vooruitgang beschouwd als het resultaat van ondernemersgedrag. Hoewel technologisch nieuwe investeringsgoederen gezien kunnen worden als produktinnovaties, ligt de nadruk op de introductie, en met name de aanschaf en het gebruik van nieuwe procestechnologieën. Nieuwe procestechnologieën kunnen bijdragen aan de verhoging van de (arbeids-) produktiviteit maar hebben slechts invloed als ondernemers deze nieuwe technologieën daadwerkelijk kopen, installeren en ermee produceren. De ontwikkeling van nieuwe technologieën, bijvoorbeeld door het verrichten van (fundamenteel) onderzoek, wordt in dit boek buiten beschouwing gelaten zodat de aandacht gevestigd wordt op de motieven waarom nieuwe technologieën gekocht worden en waarom ze, in andere gevallen, niet gekocht worden. Nogmaals, dit alles wordt bezien vanuit een macro-economisch perspectief, wat wil zeggen dat de modellen, en met name de gegevens, geen betrekking hebben op een specifieke ondernemer of een specifieke technologie, maar dat beide als abstracte grootheden worden beschouwd. De gehanteerde gegevens hebben dan ook betrekking op een economie als geheel.

Aan het eind van de jaren zestig, en met name in het begin van de jaren zeventig, trad er een wereldwijde stagnatie van de groei van de arbeidsproduktiviteit op. Ook in Nederland is een dergelijke teruggang van de groei waar te nemen. Deze groeivertraging van de produktiviteit laat zien dat de invloed van technologische verandering niet constant is. Bovendien kan de groeivertraging niet zonder meer verklaard worden door bestaande modellen. Modellen die de invloed van technologische vooruitgang endogeniseren moeten naar mijn mening een dergelijke vertraging wel kunnen verklaren. De produktiviteitsontwikkeling loopt als een rode draad door de verschillende delen van dit boek, waarbij bekeken wordt in hoeverre de gepresenteerde modellen de teruggang in de groei van de arbeidsproduktiviteit kunnen verklaren. Naast het laatste deel — samenvatting en conclusies — bevat dit proefschrift drie delen.

Het eerste deel bevat een bespreking van de relevante literatuur waarbij de nadruk is gelegd op de ‘nieuwe groeitheorie’, de jaargangen- of bouwjaarmodellen en diffusiemodellen.[1] Daarnaast wordt bekeken in hoeverre deze theorieën c.q. modellen de groeivertraging in de arbeidsproduktiviteit kunnen verklaren. In het tweede deel wordt een macro-economisch jaargangen-diffusiemodel beschreven waarin de traditioneel losstaande onderdelen — jaargangen- en diffusiemodellen — zijn gekoppeld. Vervolgens wordt dit model geschat aan de hand van gegevens over de sector bedrijven binnen de Nederlandse economie. Om een indruk te krijgen van het belang van de diffusie-component in het model wordt bovendien een standaard jaargangenmodel geschat. De vraag dient zich echter aan waarom sommige ondernemers besluiten om meteen een nieuwe technologie te kopen zodra deze beschikbaar komt, terwijl anderen (lang) wachten alvorens over te gaan op een nieuw produktieproces. Alhoewel het jaargangen-diffusiemodel uit deel II het belang van een dergelijk verschil aangeeft, wordt hiervoor geen verklaring gegeven op het niveau van de ondernemers zelf. Deel III gaat hierop in en is meer theoretisch van aard. Het wordt afgesloten met een aantal simulaties om de werking van het gepresenteerde model te demonstreren. Wederom staat de groeivertraging van de arbeidsproduktiviteit in een van de simulaties centraal.

Theoretische achtergrond

Na een korte uiteenzetting van de traditionele groeitheorieën bevat hoofdstuk 2 een beschrijving van de zogeheten ‘nieuwe groeitheorie’ waarbij de nadruk is gelegd op het endogene groeimodel van Romer (1990) en het model van Scott (1990). Het model van Romer kan geen verklaring geven voor de teruggang in de groei van de arbeidsproduktiviteit. Scott kan dit wel, maar als hij een aantal correcties aanbrengt om het model een empirische invulling te geven — hij corrigeert voor wat betreft de kwaliteit van arbeid, de bezettingsgraad van kapitaalgoederen en voor wat betreft waarnemingsfouten in de investeringsquote — kan hij slechts nog een klein deel van de produktiviteitsvertraging verklaren.

Naast deze modellen worden de diffusiemodellen en de jaargangenmodellen in ogenschouw genomen. Diffusiemodellen, waarmee de verspreiding van nieuwe

1. Jaargangenmodellen (ook bouwjaarmodellen of in het Engels ‘vintage models’ genoemd) maken een onderscheid naar de leeftijd van kapitaalgoederen. Indien een ondernemer een nieuwe machine koopt, kan hij hiermee de produktiviteit verhogen, terwijl de mate waarin dit gebeurt afhangt van de hoeveelheid machines die gekocht worden. Dit wordt belichaamde (embodied) technologische vooruitgang genoemd. Daarnaast kan onbelichaamde technologische vooruitgang optreden waarbij gedacht kan worden aan een algemene produktiviteitsstijging, die dus onafhankelijk is van de leeftijd van de kapitaalgoederen, en die veroorzaakt kan worden door bijvoorbeeld betere scholing of beter management.

technologieën binnen een economie bestudeerd worden, kunnen in potentie de groeivertraging verklaren. Door onder andere David (1991) en Metcalfe en Gibbons (1991) wordt beargumenteerd dat door de twee oliecrises en door de toenemende inflatie aan het eind van de jaren zestig de onzekerheid is toegenomen, waardoor ondernemers minder geneigd waren nieuwe procestechnologieën aan te schaffen. Empirische invulling van diffusiemodellen vindt echter op het niveau van individuele technologieën of individuele ondernemingen plaats zodat geen uitspraak gedaan kan worden over de relevantie van deze modellen op macro-economisch niveau. Tevens beperken deze modellen zich vaak tot het bestuderen van de technologie die ondernemers kiezen, terwijl hun produktiebeslissingen en de relatie tussen de bestaande kapitaalgoederenvoorraad en de aanschaf van nieuwe investeringsgoederen, zowel in kwalitatieve als kwantitatieve zin, achterwege blijven.

Jaargangenmodellen daarentegen zijn bij uitstek geschikt om dergelijke relaties te modelleren. Tevens zijn zij veel beter in staat om de werkelijke produktiviteitsontwikkeling te meten. Een groot nadeel is echter dat bij deze modellen verondersteld wordt dat iedere ondernemer op hetzelfde tijdstip dezelfde technologie koopt. Dit is in hoge mate strijdig met de bevindingen in de diffusie-literatuur. Door beide elementen samen te voegen zou men een model kunnen verkrijgen dat de genoemde nadelen ondervangt. Tevens zou men een inzicht kunnen krijgen in het belang van diffusie en veranderingen in de diffusiesnelheid van nieuwe technologieën op macro-economisch niveau. De ontwikkeling van een dergelijk model staat in dit proefschrift centraal.

In deel II wordt een gecombineerd jaargangen-diffusiemodel beschreven waarbij de empirische toepasbaarheid een randvoorwaarde voor de ontwikkeling van het model was. Om aan deze randvoorwaarde te voldoen is een tamelijk eenvoudig diffusiemodel gekozen dat gebaseerd is op het epidemische diffusiemodel.[2] Als jaargangenmodel is voor de ‘putty-clay’ variant gekozen omdat deze variant het meest realistisch is en omdat er in het verleden redelijke empirische resultaten mee zijn geboekt.[3] In deel III staat de vraag centraal waarom sommige ondernemers een nieuwe en andere ondernemers een oudere technologie kopen. Bij de uitwerking van deze vraag is nog steeds het jaargangenmodel als uitgangspunt gekozen,

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2. Een epidemisch diffusiemodel veronderstelt dat een nieuwe technologie relatief onbekend is en dat ondernemers deze leren kennen door in kontakt te komen met gebruikers van deze technologie, danwel met de leveranciers ervan. Meteen na de introductie van een technologie zijn er weinig daadwerkelijke maar relatief veel potentiële gebruikers. De verspreiding van kennis omtrent de technologie verloopt dan traag. Echter door een toenemend aantal gebruikers zal de kennis sneller verspreid worden en meer ondernemers zullen de technologie aanschaffen. Uiteindelijk zullen er nog maar weinig potentiële kopers over zijn die de technologie nog niet kennen; het aantal aankopen per tijdseenheid neemt dan af totdat iedere potentiële koper in het bezit is van de technologie.

3. De term putty-clay slaat op keuzemogelijkheid die ondernemers ter beschikking staat om de verhouding tussen arbeid en kapitaal, die nodig is om een eenheid produkt voort te brengen, te kiezen. De term ‘putty’ geeft aan dat de ondernemer deze verhouding vrijelijk kan kiezen bij de aanschaf van een investeringsgoed. Na de aanschaf ligt de verhouding echter vast (clay) zodat gedurende de verdere levenstijd van het kapitaalgoed de hoeveelheid arbeidskrachten die nodig is om met dat kapitaalgoed te kunnen produceren vastligt.

maar het stringente criterium ten aanzien van de empirische toepasbaarheid is komen te vervallen.

Het Putty-Clay diffusie model

In hoofdstuk 3 wordt zowel een standaard putty-clay model als het (nieuwe) putty-clay diffusiemodel gepresenteerd. In Nederland zijn putty-clay modellen ontwikkeld door onder meer Kuipers en van Zon (1982), Gelauff, Wennekers en de Jong (1985) en door Muysken en van Zon (1987). Geen van deze modellen is echter in staat om de feitelijke ontwikkeling van de arbeidsproduktiviteit te volgen zonder ad hoc aanpassingen aan te brengen. Door de toevoeging van de diffusiecomponent wordt de invloed van nieuwe technologieën op de produktiviteit echter geëndogeniseerd. In deel II van dit proefschrift veronderstel ik dat ieder jaar een nieuwe technologie op de markt voor investeringsgoederen verschijnt. Ondernemers kunnen deze technologie kopen zolang de verwachte opbrengst positief is. Daar dit veelal langer dan een jaar zal zijn, zijn er op eenzelfde tijdstip meer technologieën te koop. Naar analogie van de epidemische diffusiemodellen wordt een verdeling van het aantal ondernemers over de verschillende technologieën verondersteld, waarbij deze verdeling afhankelijk is van de relatieve winstgevendheid van deze technologieën en van de kennis die ondernemers over dit nieuwe investeringsgoed hebben. Dit laatste wordt bepaald aan de hand van de hoeveelheid produkt die in het verleden met een specifieke technologie is voortgebracht. Na de introductie van een technologie is de kennis erover erg klein, maar de relatieve winstgevendheid ervan (naar verwachting) groot. Er zullen weinig ondernemers zijn die dit nieuwe kapitaalgoed aanschaffen. Naarmate de tijd vordert zal de kennis vergroot worden, maar omdat er tegelijkertijd nieuwe, en meer winstgevende, technologieën ontwikkeld zijn, zal de relatieve winstgevendheid afnemen. De diffusie van een bepaalde technologie hangt dus af van de relatieve winstgevendheid van deze technologie, terwijl de kennis voor een ‘pad-afhankelijkheid’ zorgt. De pad-afhankelijkheid komt als volgt tot uitdrukking: indien een technologie in het verleden veel gebruikt is zal de kennis groot zijn, zodat meer ondernemers in deze technologie zullen investeren dan in een andere, minder gebruikte technologie terwijl de verwachte winstgevendheid van deze twee technologieën gelijk is.

Terwijl een standaard jaargangenmodel rekening houdt met de verschillen in leeftijd binnen de kapitaalgoederenvoorraad, gaat het jaargangen-diffusiemodel een stap verder, door binnen iedere jaargang nog een onderscheid te maken naar diverse technologieën. Buiten de introductie van het diffusie-element zijn de overige kenmerken overgenomen uit bestaande modellen, zoals de keuze van de initiële arbeid/kapitaal verhouding — er wordt uitgegaan van winstmaximaliserend gedrag waarbij een ondernemer die verhouding kiest die de verwachte winst over de planperiode maximaliseert —, het afstootgedrag van investeringsgoederen — er wordt onderscheid gemaakt tussen technische slijtage, economische afstoot en afstoot ten gevolge van onderbezetting van de kapitaalgoederenvoorraad — en het gedrag ten aanzien van de gevraagde hoeveelheid arbeid — er wordt rekening gehouden met het eventueel oppotten van arbeid.

In hoofdstuk 4 beschrijf ik de schattingsresultaten van zowel het jaargangen-diffusie model als het standaard jaargangenmodel. De gegevens hebben betrekking op de sector bedrijven van de Nederlandse economie. De schattingsperiode loopt van 1960 tot en met 1988, wat inhoudt dat de meeste gegevens, vanwege de historisch bepaalde samenstelling van de kapitaalgoederenvoorraad, vanaf 1904 zijn gebruikt. Beide modellen zijn geschat met de bezettingsgraad van kapitaalgoederen en de vraag naar arbeid als de te verklaren variabelen.

Het jaargangen-diffusiemodel blijkt de ontwikkeling van de bezettingsgraad van de kapitaalgoederenvoorraad en de gevraagde hoeveelheid arbeid goed te kunnen verklaren. In vergelijking met het standaard jaargangenmodel valt met name de verklaringskracht met betrekking tot de vraag naar arbeid op.[4] Zelfs de markante terugval van de vraag naar arbeid tussen 1980 en 1983, van ongeveer 4.1 miljoen 3.8 miljoen mensjaren, en de daarop volgende opleving naar 4.1 miljoen mensjaren in 1988 blijkt het model redelijk goed te kunnen volgen. Het standaard jaargangenmodel kan het omslagpunt in 1984 daarentegen in het geheel niet volgen. Ook de vertraging van de groei van de arbeidsproduktiviteit kan door het model verklaard worden. In paragraaf 4.3 wordt dit onderzocht, waarbij de ontwikkeling van de arbeidsproduktiviteit wordt ontleed aan de hand van diverse oorzaken, zoals de invloed van veranderingen in de diffusiesnelheid op de produktiviteit. Het blijkt dat de terugval van de groei van de arbeidsproduktiviteit van gemiddeld 4.4% in de periode 1961-1973 naar 2.4% in de periode 1974-1988 voor ongeveer 75% verklaard kan worden door een vertraging in de verspreiding van nieuwe technologieën, dus door een sterk verminderde diffusiesnelheid. Het standaard jaargangenmodel kan een dergelijke ontwikkeling in het geheel niet volgen, wat het grote verschil in de geschatte vraag naar arbeid verklaart.

Tot slot wordt in hoofdstuk 4 een verklaring gegeven voor de vertraging van de diffusiesnelheid. Het blijkt dat de gematigde groei van de reële lonen leidt tot een kleiner verschil in de verwachte winstgevendheid zodat ondernemers minder geprikkeld worden om nieuwe, relatief onbekende, technologieën te kopen. De gematigde groei van de reële lonen wordt vervolgens verklaard door enerzijds een sterke stijging van de prijzen — als gevolg van de twee oliecrises — en anderzijds door een gematigde groei van de nominale lonen.

4. Zie de figuren 4.1 en 4.2 op pagina 110.

Ondernemersgedrag

Het macro-economisch model geeft het belang aan van de toevoeging van de diffusie-component in een jaargangenmodel. Zoals hierboven aangegeven wordt in het macro model niet ingegaan op de vraag, waarom sommige ondernemers een nieuwe technologie meteen kopen terwijl anderen lang wachten voordat ze tot aanschaf besluiten. Deel III gaat in op deze vraag en presenteert een aantal modelvarianten waarin een dergelijke keuze centraal staat.

De onzekerheid die met de aanschaf van kapitaalgoederen gepaard gaat is uitgangspunt in dit deel. Ik veronderstel dat er geen tweedehands markt is voor investeringsgoederen, zodat de verkoopprijs van een eenmaal gekocht kapitaalgoed nihil is. Dit betekent dat eenmaal gemaakte kosten niet meer ongedaan kunnen worden gemaakt. Aangezien de toekomstige ontwikkeling van bijvoorbeeld afzetprijzen of lonen onzeker is, dient een ondernemer een inschatting te maken van deze onzekerheden teneinde de investeringsbeslissing te kunnen nemen. In hoofdstuk 5 worden twee modellen beschreven. Het eerste model gaat expliciet in op onzekerheid en risico-afkeer en laat zien dat er voor nutsmaximaliserende ondernemers een verband bestaat tussen de mate van risico-afkeer en de lengte van de planperiode (de periode dat een ondernemer in de toekomst kijkt) die zij gebruiken om de toekomstige inkomstenstroom te beoordelen.[5]

Het andere model is een analytisch eenvoudiger variant hierop waarin aangenomen wordt dat de lengte van de planperiode een maatstaf is voor risico-aversie. Aangetoond wordt dat risico mijdende ondernemers minder lange planperioden hanteren waardoor zij minder geavanceerde (en per assumptie minder dure) kapitaalgoederen kopen. Tot slot wordt in hoofdstuk 5 ingegaan op de resulterende diffusie patronen en op de overeenkomst met het macro-economisch model uit deel II.

Beide modellen die in hoofdstuk 5 worden gepresenteerd gaan overigens enkel en alleen in op de keuze van de technologie die in kapitaalgoederen belichaamd is; er wordt geen aandacht geschonken aan de hoeveelheid investeringen, noch aan de produktie en aan de vraag naar arbeid. In hoofdstuk 6 wordt de eenvoudige variant van het model uit hoofdstuk 5 ingepast in een volledig jaargangenmodel. Dit betekent dat de keuze van de technologie slechts een onderdeel van de beslissingen van ondernemers wordt. De ondernemers kunnen kiezen uit een reeks van verschillende technologieën waarbij iedere technologie gekenmerkt wordt door vaste verhoudingen tussen kapitaal en arbeid. Ze kunnen dus kiezen uit een reeks van ‘clay-clay’ technologieën en het gepresenteerde model kan worden beschreven als een ‘quasi-clay-clay’ jaargangenmodel. Ook hier worden twee varianten gepresenteerd: een statisch model en een dynamisch model. In het statisch model bekijkt een ondernemer enkel en alleen de gevolgen van een investeringsbeslissing, zonder

5. Omwille van de duidelijkheid wordt dit model overigens op de tweede plaats beschreven.

rekening te houden met toekomstige investeringsbeslissingen, terwijl het dynamische model daar juist wel rekening mee houdt. Het statische model is dus wederom een eenvoudige variant van het dynamische model. Ik laat in hoofdstuk 6 zien dat het dynamische model niet analytisch oplosbaar is terwijl dit voor het statische model wel mogelijk is. Bovendien leidt het statische model, bij benadering, tot dezelfde resultaten met betrekking tot de gekozen technologieën.

In tegenstelling tot het macro-economisch model veronderstel ik in hoofdstuk 6 dat de goederenmarkt niet door perfecte mededinging kan worden beschreven maar dat ondernemers een (al dan niet geringe) monopoliemacht hebben, hetgeen resulteert in een markt van monopolistische concurrentie. Dit houdt in dat ondernemers de prijzen van hun produkten zelf kunnen bepalen, terwijl de gevraagde hoeveelheid afhangt van, onder meer, de prijzen die de concurrenten zetten.

Tot slot laat hoofdstuk 6 de resulterende diffusiepatronen zien waarbij de diffusiesnelheid blijkt af te hangen van de marktvorm waarbinnen ondernemers opereren. Een meer monopolistische markt leidt tot langzamere diffusie dan een meer concurrerende markt. De reden hiervoor is dat er in een meer concurrerende markt weinig ruimte is voor prijsverschillen zodat de produktiekosten een belangrijke rol gaan spelen. Dit heeft als gevolg dat ook risico-mijdende ondernemers technologisch gezien niet te ver op de koplopers mogen achterblijven omdat anders de produktiekosten relatief te hoog worden, zodat ze zichzelf uit de markt prijzen.

Deel III wordt afgesloten met een aantal simulaties van het ‘quasi-clay-clay’ jaargangenmodel. Tevens worden de resultaten vergeleken met een standaard ‘putty-clay’ model. In het nabootsen van de teruggang van de arbeidsproduktiviteit blijkt dat het ‘quasi-clay-clay’ model een dergelijke groeivertraging beter kan verklaren dan een standaard ‘putty-clay’ model. Dus ook het model uit deel III leidt tot meer aannemelijke resultaten dan bestaande jaargangenmodellen. Tevens blijkt ook dit model pad-afhankelijkheden te bezitten. In standaard modellen wordt technologische vooruitgang gemodelleerd met een constante groeivoet. Dit betekent dat de economie na een turbulente periode veel meer in de buurt komt van het pad waarop het zou zijn gekomen zonder turbulenties. Dit is niet het geval in het ‘quasi-clay-clay’ model. De technologische achterstand die door een turbulente periode wordt bewerkstelligd heeft in dat model veel meer consequenties voor de toekomst.

Tot slot wordt in hoofdstuk 7 kort aandacht besteed aan het aanbod van nieuwe technologieën. Door middel van een simulatie laat ik zien dat de markt van *investeringsgoederen* sterk concurrerend is. Dit betekent dat de afzetprijs van aanbieders van kapitaalgoederen, bijvoorbeeld de machineindustrie, sterk afhangt van de kosten. Door naar analogie van Romer (1990) de ontwikkeling van nieuwe technologieën te koppelen aan de winstgevendheid ervan, zou een model kunnen ontstaan waarbij ook het aanbod van nieuwe technologieën geëndogeniseerd is. De verdere uitwerking van dit idee komt hier niet aan de orde, maar is nader onderzoek waard.

Deel IV bevat enkele andere aanbevelingen voor verder onderzoek. Uit de voorgaande delen blijkt, dat de groei van de arbeidsproduktiviteit sterk afhangt van de snelheid waarmee nieuwe technologieën geïntroduceerd worden. Zowel uit deel II als uit deel III valt af te leiden dat de groei van de lonen een belangrijke determinant is voor de diffusiesnelheid. Hogere lonen vergroten de verschillen in winstgevendheid tussen diverse technologieën waardoor ondernemers sneller over gaan tot de aanschaf van nieuwere produktietechnologieën. Echter, hogere lonen hebben ook een directe negatieve invloed op de produktiekosten, maar kunnen tevens leiden tot hogere inkomens, meer consumptie en meer produktie. Het gepresenteerde model kan dergelijke effecten slechts voor een deel verklaren zodat het aanbeveling verdient om het gepresenteerde jaargangen-diffusie model in een gesloten macro-economisch model te incorporeren zodat ook dergelijke vragen beantwoord kunnen worden.

Curriculum Vitae

Huub Meijers werd op 8 januari 1959 geboren te Belfeld. Van 1971 tot 1977 volgde hij middelbaar onderwijs; eerst aan de St. Martinus MAVO te Tegelen, gevolgd door de HAVO aan het Collegium Marianum te Venlo. Vervolgens studeerde hij landmeetkunde aan de HTS voor de Bouwkunde te Utrecht alwaar hij in 1982 afstudeerde. Vanaf 1982 tot 1984 was hij actief in de mileubeweging (Vereniging Milieudefensie en lid — later kaderlid — van de Werkgroep Energie Diskussie). Tevens sloot hij in deze periode een eenjarige post-hbo opleiding Milieukunde aan de HTS te Heerlen met goed gevolg af. Zijn interesse in het vak economie werd gewekt door het economisch kader waarbinnen de Brede Maatschappelijke Discussie over Energiebeleid werd gevoerd.

Vanaf 1984 studeerde hij algemene en kwantitatieve economie aan de Rijksuniversiteit Limburg te Maastricht, alwaar hij in 1989 afstudeerde (c.l.). Tevens was hij gedurende deze period student-assistent bij de vakgroep Macro-economie. Vanaf 1989 was hij als Assistent in Opleiding verbonden aan de Economische Fakulteit bij het Maastricht Economic Research Institute on Innovation and Technology (MERIT). Sinds eind 1993 is hij daar als onderzoeker werkzaam.

PART I

INTRODUCTION

1 General Introduction

The importance and the impact of technological change on our society has been a subject of economic research for a long time. In Adam Smith's pin factory, for instance, technological change takes place through the division of labour and specialisation of tasks, increasing labour productivity of all employees. Next to this specialisation argument, there are different ways in which technological change manifests itself in society. Learning, for instance, can increase the stock of knowledge and lead to the design of new products or new processes. New products, in the sense of consumer goods, can increase the feeling of well-being or improve productivity in for example households so that more time is left for leisure. Improvements in production processes, which can be the result of product innovations in the capital-producing sector, can increase productivity, as a result of which the same amount of resources (e.g., labour, capital, raw materials, energy) can be used to produce more output, or that the same output can be produced while making less use of (some) factors of input. Assuming that output and factors of input are scarce goods, process innovations can lead to an increase in welfare. This thesis is concerned with process innovations and with technological change in the form of improvements in the production process in general.

1.1 Background

During my study in economics, I was involved in research on technology and (un)employment relations, which focused on the decomposition of unemployment into different categories by means of a putty-clay vintage model and an employment function.[6] The vintage approach relaxes some of the stringent assumptions of the aggregate production function method to model the relation between technological change and economic growth. Solow (1957) is the most well-known study

6. cf. Muysken and van Zon (1987).

which estimates the relation between technological change and economic growth at a macro-economic level. Technological change itself, however, is treated as an exogenous factor and falls like manna from heaven. The transmission of technological change, through the use of new technologies for example, is not explained at all in Solow's model. Furthermore, the use of aggregate production functions is extensively criticized, for instance, for the assumption that factors of input, such as labour and capital, can be substituted, even if capital goods have already been installed.[7] Particularly the omission of the transmission mechanism has led to the introduction of vintage models, which were introduced in the late fifties. The main characteristic of vintage models is their ability to distinguish embodied from disembodied technological change. Consequently, this allows for a distinction between the old, existing capital stock and newly installed investments goods. The impact of embodied technological change is related to investment characteristics and focuses on the transmission of technological change. Disembodied technological change is not related to investment and can be modelled as an exogenous rate of growth or can be endogenized by, for example, learning-effects. Vintage models can also relax the rather restricted assumption of ex-post substitutability of factors of input, whereas they still allow for ex-ante substitution.[8]

The research I was involved in relies very much on the Dutch vintage modelling tradition, which differs from the international tradition by assuming that the ex-post factor coefficients are fixed. This implies that vintages differ from one another with respect to the labour intensity and that, eventually, factor productivities of older vintages become too low compared to the factor costs. As a result, they become economically obsolete and will be scrapped. This approach implies that a model which incorporates such an ex-post clay production function, must keep track of the characteristics of all individual vintages.[9] Technological progress enters the model of Muysken and van Zon (1987) by means of constant rates of embodied and disembodied technological change, both labour and capital augmenting. The impact of technological change depends on the rate of investment — the embodiment effect —, on changes in the age structure of the capital stock — the scrapping effect —, and on changes in the initial labour intensity — ex-ante substitution possibilities. However, these effects are not strong enough to capture observed variations of factor productivities, and Muysken and van Zon solved this problem by introducing a number of dummy periods. Although the use of dummies is accept-

7. The next chapter will discuss this point in more detail.

8. A putty-putty vintage model does not relax this substitutability assumption and this type of vintage model accounts for the embodiment effect only. Cf. Solow (1962) and Phelps (1963) for such an approach.

9. Recently, van Zon (1994) and Meijers and van Zon (1994) developed and estimated a putty-semi-putty vintage model in which the entire capital stock can be approximated by some simple recursive update mechanisms, which reduces bookkeeping to a minimum whereas it still incorporates the characteristics of a full putty-semi-putty vintage model.

able if one is interested in the final results of the vintage model — mainly time series on capacity output and on capacity demand for labour, which are used to obtain employment and unemployment figures — it is unsatisfactory from a theoretical point of view. The way technological change enters the model grasped my interest, and so I decided to write my master's dissertation on this subject.

It seemed quite natural to me to approach the impact of technological change by focusing upon the literature on adoption and diffusion of new technologies. In the empirically oriented part of this literature, two outstanding stylized facts can be found: (i) it takes a considerable amount of time for new technologies to be accepted by all potential adopters, and (ii) a graph of the cumulative amount of adoption of a technology against time is S-shaped. However, in vintage models, all firms adopt the same technology at each point in time and each firm invests in a technology only once. This contradicts the general findings of the literature on the diffusion of new technologies and therefore I decided to investigate a possible incorporation of models of adoption and diffusion of technologies in a vintage framework. Moreover, whereas both the vintage models and the models of adoption and diffusion of new technologies are used to model the transmission of technological change, only very few attempts have been made to combine both into a more general framework.[10] In addition, as we will point out in Chapter 2, there are several similarities between these models, and even more important, some inconsistencies.

My master dissertation was concerned with the introduction of the ideas of adoption and diffusion of technologies in a vintage model. It shows how an epidemic-like diffusion process can be integrated into a putty-clay vintage model (cf. Meijers, 1989). However, the speed of diffusion is exogenous in that model and I had to include several dummy parameters to describe the variations in the growth rates of factor productivities. The main purpose of this PhD-thesis is to develop a combined diffusion-vintage model in which the speed of diffusion depends on economic factors as a result of which the transmission of technological change is further endogenized compared to standard vintage models.

During my study, the phenomenon of the productivity slowdown also attracted my attention. The literature on this subject shows that the fall of the growth rate of labour productivity in the early seventies was a world-wide occurrence and not restricted to the Dutch economy. Several variables are suitable to measure the productivity slowdown, but total factor productivity growth and labour productivity growth are the most commonly used. Figure 1.1 shows the development of the labour productivity growth of a number of OECD countries. In this figure, the labour productivity is defined as the gross domestic product in constant prices per

10. Soete and Turner (1984) develop a model along these lines but because their model is not suitable for estimation purposes, the empirical importance of the introduction of diffusion into a macroeconomic model cannot be investigated.

employee.[11] The figure demonstrates that the productivity slowdown is most prominent for Japan, which experienced a high growth of labour productivity in the fifties and early sixties. Moreover, the productivity slowdown begins in the sixties in both Japan and the US whereas the European countries do not experience a fall in the growth rate of labour productivity until the early seventies. The slowdown becomes even more apparent if we investigate the growth rate of labour productivity in more recent years. This is done in Figure 1.2, in which we calculated the five-year moving average of the labour productivity. This figure shows that the slowdown persisted until the early eighties for most countries and that the growth rate of labour productivity was still far below pre-1970 values in the late eighties.

The productivity slowdown is thus a world-wide phenomenon and its persistence suggests that it is not a short-lived occurrence. As mentioned previously, standard vintage models are not capable of following this slowdown, and the question is whether a combined vintage-diffusion model is able to describe this development more accurately. Before we turn to the aim and outline of this thesis, we will briefly examine its position in the literature on the productivity slowdown.

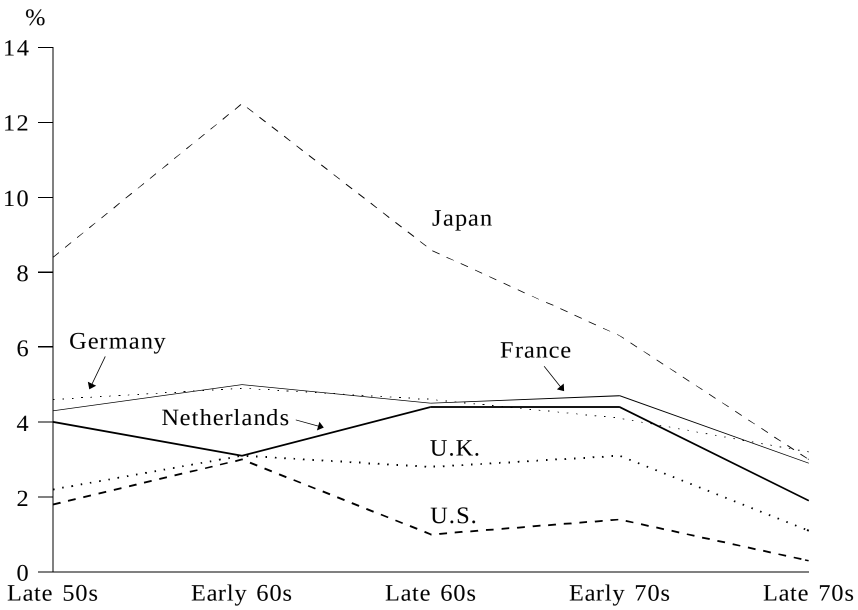

Figure 1.1. Labour productivity growth in selected OECD countries[12]

11. There are several other measures, such as the output per hour worked, but all these figures show about the same decline of the labour productivity growth, which starts in the late sixties or early seventies.

12. Source: Giersch and Wolter (1983), Table I, page 36.

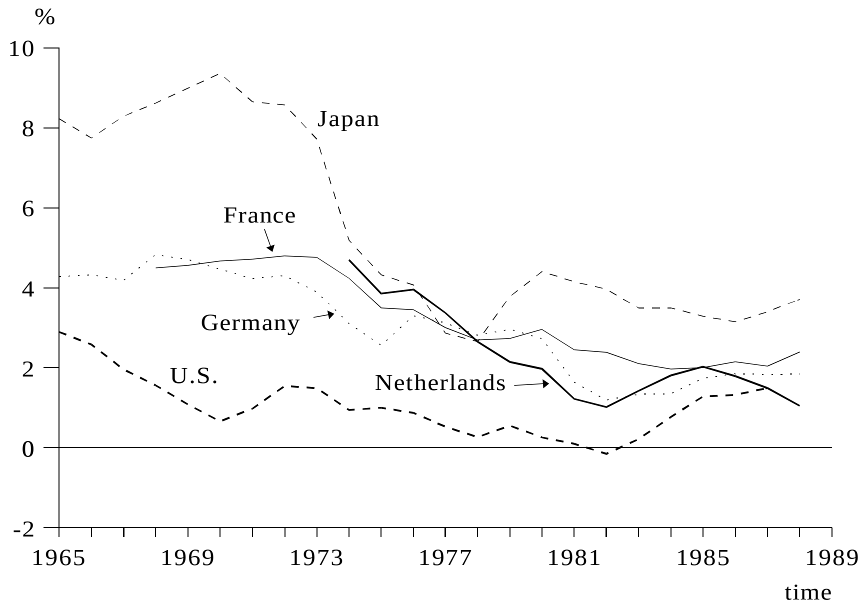

Figure 1.2. Five-year moving average of the growth rate of labour productivity[13]

There are several explanations for the productivity slowdown and, here, we will summarize the most important trends in the literature. The growth-accounting study is probably the most well-known direction of research on the productivity slowdown, of which Denison (1979, 1985) is the most prominent author. Denison 'explains' the labour productivity growth for about 50% after taking accounting for a 'smorgasbord' of fourteen possible factors that can influence the growth rate of labour productivity.[14] Possible explanations of the remaining fifty percent are summarized under five separate headings: (i) technological knowledge and R&D efforts, (ii) managerial knowledge and performance, (iii) work effort, (iv) misallocation of sources, and (v) energy prices. Although this work is important to obtain insight into possible explanations of the productivity slowdown, it is not based on a more structural approach. The influence of various variables on the productivity slowdown is not modelled otherwise than by including them in a (linear) regression equation, and it is highly questionable whether their influence on the growth rate of labour productivity is adequately measured.[15]

Another possible explanation of the productivity slowdown is that it is just a statistical artifact due to bad statistics. Although mismeasurements influence the

13. Source of the data (GDP in constant prices and total employment) is the ISDB database of the OECD (cf. Meyer-zu-Schlochtern, 1988). Data for the UK are available from the late seventies only and are not displayed.

14. These factors are: hours worked, age-sex composition, education, reallocation from farming, reallocation from non-farm self-employment, inventories, non-residential structures and equipment, land, weather, pollution abatement, worker safety and health, crime, economies of scale and intensity of final demand.

15. For example, Denison argues that the changes in the age of the capital stock can account for at most 0.16%-point for the productivity slowdown. In part II we will show that this effect is much more important if it is measured by means of a (standard) putty-clay vintage model.

'observed facts', this argument has been widely rejected as an adequate explanation of the slowdown (cf. Gordon and Baily (1991) and Denison (1985), for example). Closely related to this topic are the measurement issues which result from different types of models used to model technological change. Van Zon (1991), for instance, shows that measures of total factor productivity growth differ considerably when they are measured in an aggregate production function model or in a vintage model. By using a vintage framework, we are able to include changes in the growth rate of factor productivities which are due to changes in the age structure of the capital stock. This provides a more accurate measure of the relation between technological change and the growth rate of factor productivities.

The modelling of technological change is the last and broadest explanation of the productivity slowdown we will mention in this introduction. The literature ranges from the evolutionary models on economic systems (cf. Freeman (1991) or see Dosi et al. (1988) for a more general discussion of this school of research), via the Keynesian views (cf. Boyer and Petit, 1991) to the neoclassical studies, including the endogenous growth theories. Chapter 2 will review some of these models and shows that most studies can explain the productivity slowdown. However, almost all studies include several ad hoc adjustments to the structural models to obtain this result. In order to position our research in the broad field of economics, from our more or less natural departure from the vintage models, this thesis has its roots in neoclassical theories, although some links are made to more Keynesian-oriented views.

1.2 Aim of the Thesis

The general purpose of this thesis is to develop a new model which incorporates the idea of vintages as well as the idea of adoption and diffusion of new technologies. From this general purpose, we will define two directions of research on which this thesis is based. The first direction is concerned with the importance of diffusion of new technologies in a vintage model at a macro-economic level. Studies of adoption and diffusion are mostly applied to single technologies or single firms or groups of firms. Furthermore, even if they are modelled and estimated on a macro-economic level, they are never incorporated in a broader macro-economic model, which means that the impact of diffusion on macro-economic variables is unknown. Moreover, we will examine to what extent the productivity slowdown can be explained by a combined vintage-diffusion model. Chapter 2 shows that there are some similarities but also some inconsistencies between vintage models and models on the adoption and diffusion of new technologies. This thesis will remove some of these contradictions by developing a combined model that captures the main characteristics of both models. In addition, Chapter 2 reviews a number of studies on the explanation of the productivity slowdown by changes in the speed of diffusion. It is argued that an increase of uncertainty

— induced by high rates of inflation in the late sixties and early seventies — and decreasing profit opportunities of new technologies, decreases the speed of diffusion and, consequently, the influence of technological innovation on factor productivity growth. Taking this into consideration, it seems worthwhile to investigate the effects of diffusion on productivity in a combined vintage-diffusion model.

The second direction of this thesis is more micro-economically oriented. Chapter 2 will show that the integration of an epidemic diffusion model into a vintage framework is the most attractive way to capture the general implications of the ideas of diffusion of technologies without making the resulting model unnecessarily complicated. However, this model will not answer the question why some firms invest in new or advanced technologies whereas others invest in more old-fashioned equipment at the same point in time. Thus, whereas the first purpose is concerned with the macro-economic implications of adoption and diffusion, the second purpose of this thesis is to integrate the ideas of adoption and diffusion into a vintage model. This should result in a model in which the interaction between adoption decisions and decisions about production capacity and labour demand becomes more clear. It is our explicit intention to incorporate adoption decisions in an optimizing framework, that is, the choice of technologies should be the result of rational behaviour.

The rest of this thesis is organized as follows. Chapter 2 gives a brief overview of the literature on technological change, economic growth and on several vintage and diffusion models. In that chapter, we will also reconsider the aim of the thesis in the sense that the route along which it will answer the main questions is pointed out. This chapter will finish with a detailed outline of the thesis.

Part II is concerned with the macro-economic model. In Chapter 3, we will present a vintage diffusion model, which will be compared with a standard, non-diffusion, vintage model. Chapter 4 presents the estimation results of both models for the Dutch economy. As an application of the vintage-diffusion model, we will discuss the influence of diffusion on the growth rate of labour productivity at the end of that chapter.

Part III is concerned with some micro-oriented models. First, Chapter 5 develops some versions of firm behaviour regarding the choice of technologies. One of these versions is incorporated in a vintage model, and is discussed in Chapter 6. Chapter 7 presents some simulation results of that model in order to highlight its performance and its behaviour under non-steady-state conditions which cannot be traced analytically. That chapter will also present a simulation experiment which determines the slope of the demand function of new technologies. Its result is used in the last section of Chapter 7: the supply of new technologies. Although being only in its infancy, we will present some possible extensions of the present analysis in the direction of the production and the supply of new technologies. Finally, part IV, which consists of Chapter 8, will summarize the main findings and give some possible directions for further research.

2 Technological Change: An Overview in Outline

This chapter will provide a brief overview of the literature on technological change. However, it is not my intention to review all topics within this diverse field. Standard textbooks like Jones (1975), Freeman (1982), Link (1987), Coombs, Saviotti and Walsch (1987) and Gomulka (1990) portray this topic in a much more sophisticated and comprehensive way than I ever could in this thesis. The reasons, to write this chapter, are twofold. First, it will show the position of this thesis in the field of technological change, it will show in which paradigm the research has been done and, above all, it will show what I left aside. Secondly, it enables me to highlight some lacunae and incompatibilities in and between the existing theories. These gaps and contradictions are the basic inputs of this thesis. In the previous chapter, I stated that the theory of adoption and diffusion should be incorporated into a more general theory of technological change and growth. It is therefore meaningful to start this chapter with some, more or less, basic views of this subject. The next section describes some theories on economic growth and the Kaldorian stylized facts. When talking about facts, and about modelling of technological change in general, one cannot ignore the worldwide decrease of the rate of productivity growth in the seventies and eighties. Where applicable, we will review the theories on economic growth and technological change in relation with this slowdown. Three different theories are treated as representatives of the Post-Keynesian, the Neo-Keynesian and the Neoclassical view of economic growth. Technological change is viewed as one of the most important determinants of economic growth. The literature on technological change will be reviewed in section 2.1.4. In a discussion on technological change and economic growth, the so-called ‘new growth theory’ cannot be ignored, although it will play a minor role in this thesis. Section 2.1.5 describes some features of new growth theory in a nutshell. Section 2.2 will give a brief overview of the literature on vintage models. Vintage models are one of the main ingredients of this book. The second ingredient is the models on adoption and diffusion of innovations. A brief overview of the research within this field is given in section 2.3. The last section will summarize this chapter, it will highlight the gaps and incompatibilities and provide an outline of this thesis in more detail.

2.1 Economic Growth and Technological Change

Technological change has been a subject of interest to economists for many decades. Adam Smith's *"An Inquiry into the Nature and Causes of the Wealth of Nations"* is for many colleagues a starting point. In his work, Smith introduced technological change as the result of the division of labour, which in turn leads to economic growth. The theory on economic growth became really popular after the second world war, with prominent economists like Harrod and Domar, Kaldor and Solow, amongst others. This will be the starting point of this review in outline.

In the written version of the oral contribution to the Round Table conference on the theory of capital, held in Corfu 1958, Kaldor argued that an (economic) theory should explain the characteristic features of real economic processes and that *"the theorist, in choosing a particular theoretical approach, ought to start off with a summary of the facts which he regards as relevant to his problem."* (Kaldor, 1961:178). His study on capital accumulation and economic growth, starts with a set of stylized facts which are often used as a guideline or rough framework of theories on economic growth. The Kaldorian facts are (all quoted from Kaldor, 1961:178):

- The continued growth in the aggregate volume of production and in the productivity of labour at a steady trend rate; no recorded tendency for a falling rate of growth of productivity.
- A continued increase in the amount of capital per worker, whatever statistical measure of 'capital' is chosen in this connection.
- A steady rate of profit on capital, at least in the 'developed' capitalist societies.
- Steady capital-output ratios over long periods.
- A high correlation between the share of profits in income and the share of investment in output; a steady share of profits (and of wages) in societies and/or in periods in which the investment coefficient (the share of investment in output) is constant.
- Appreciable differences in the rate of growth of labour productivity and of total output in different societies.

The last fact refers to growth differences between countries, whereas the first five refer to the events within an economy. Not all economists agreed with these facts, for instance Solow, who stated that *"There is no doubt that they are stylized, though it is possible to question whether they are facts"* (Solow, 1970:2). Solow was especially concerned with the third fact: the constancy of the capital-output ratio. He argued that, first there are problems with the definition and measurement of the capital stock and secondly, that the data, however the measurement problems are solved, are not that clear about the constancy. These remarks are the introduction of Solow's model in which the capital-output ratio may vary through time. This model will be described in section 2.1.2.

After the time Kaldor presented these facts, GDP and labour productivity increased steadily in most western countries, at least in the sixties and early seventies. But in the mid seventies and eighties, both economic growth and labour productivity growth slowed down sharply in most countries. For instance, the average annual growth of GDP in four major European countries[16] and Japan decreased from 5.6 per cent in the period 1950-1973 to 2.1 per cent after 1973.[17] In the US, growth of GDP fell from 3.7 to 2.3 per cent. The growth rate of output per hour worked decreased from 5.3 to 2.8 per cent in the above mentioned European countries and Japan and decreased from 2.5 to 1.0 per cent in the US. Additionally, some major technological innovations were observed during the 1970s in the area of microelectronics and communication technology, in biotechnology and composite materials. Both, the existence of new innovations and the slowdown in growth, are often referred to as the 'productivity paradox' or the 'Solow paradox'.[18] When reviewing the literature on growth and technological change, one cannot ignore the slowdown in growth of output per capita and in productivity. In the next sections, we will discuss some possible explanations of the productivity slowdown in the light of the models discussed.

The next sections review some traditional models in a nutshell. We begin with the Harrod-Domar model, which is representative of the post-Keynesian growth theory. After the Neoclassical view, represented by the model of Solow, a short impression of the neo-Keynesian reaction is given, embodied by the work of Kaldor. After that we will review some more recently developed endogenous growth models. This section concludes with some possible explanations of the productivity slowdown.

2.1.1 The Harrod-Domar Model

Both Harrod and Domar developed, independently from each other, a similar model of economic growth which is known as the Harrod-Domar model. In this review, however, we will concentrate on the Harrod version of the model. With this model a renewed interest in growth theory has been raised. The vision of a steady-state growth is not optimistic in this model. The price mechanism is

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16. France, Germany, UK and the Netherlands.

17. Source: Maddison (1987), Tables 1 and 2.

18. "*We see the computers everywhere but in the economic statistics*" (Solow, quoted in David, 1991:316).

assumed to be absent such that market clearing is more an accidental occurrence than a rule. The basic assumptions of the Harrod-Domar model are:

- Savings are proportional with income, and the average rate of savings is constant.
- The labour force grows at a constant rate.
- The average capital-output ratio is constant in time.
- The input-output relation can be characterized by a fixed proportions Leontief production function.
- Technological progress is Harrod-neutral, i.e., of a purely labour augmenting nature.

From these assumptions, it follows that, if the economy is in an equilibrium steady state, the growth rate of the effective labour force must be equal to the growth of output, which is ‘The Golden Age’ rule in the Harrod-Domar model. The first observation is that it is possible to obtain a steady-state equilibrium growth path in this model. The second observation is known as the first Harrod problem. The question is how an economy reaches and/or stays at this steady-state growth path. There are no forces which will move the economy to such a growth path, or to put it differently, it is most unlikely that an economy will reach this path, given the independence between the variables. The reason for this is clear: the population grows at a constant rate, therefore no Malthusian forces are at work, the propensity to save is constant and there are no possibilities of factor substitution. This illuminates the Keynesian nature of the model — there is no guarantee that a full employment equilibrium will be attained. The conclusions of the Harrod-Domar model can be summarized as follows:

- It is possible to achieve a steady-state at full employment;
- It is highly unlikely that this full employment steady state will be realized, and if it is achieved, it is unlikely that it will maintain;
- It has the knife-edge property which refers to the instability of the model.

Both these underlying assumptions, the persistent disequilibrium issue and the instability, are typical Keynesian features of this model. They are subject to criticism, mainly from the Neoclassical school of thought. The next section reviews some of these criticisms. It is possible, and even one of the main issues, to describe the slowdown in output with the Harrod-Domar model. However, the model is not suitable to describe the productivity slowdown. The demand for labour decreases with the same relative amount as output, so that the ratio remains constant.

2.1.2 Solow's Growth Model

Neoclassical authors reject the assumption that labour and capital are complementary factors of input. Firms are assumed to choose the capital intensity (capital/labour ratio k) in such a way that total costs are minimized. Furthermore, they rely heavily upon the price mechanism and on clearing markets. This section will review the model of Solow as a representative of the neoclassical school.

The basic assumption in this model is that capital and labour are substitutes along a constant returns to scale Cobb-Doubles aggregate production function. That is, output (X)is a function of:

$$X_t = f(N_t, K_t) = A_t N_t^{\beta} K_t^{1-\beta} \tag{2.1}$$

in which N_t denotes the amount of labour, K_t is the capital stock, and A_t represents the exogenous rate of technological change. There is no underutilisation of capital and capital does not depreciate which means that the change of the capital stock is equal to the amount of investment. The labour force is assumed to grow at a constant proportional rate, which is the same assumption as put forward in the Harrod-Domar model. The same holds for the savings function: the amount of saving is assumed to be proportional to the amount of income, which is equal to the amount of output by the income identity. The fundamental equation of neoclassical economic growth can be easily derived:

$$\dot{k}_t = sf(k_t) - nk_t \tag{2.2}$$

which says that the change of the amount of capital per worker is equal to the amount of savings, and therefore equal to the amount of investment per worker minus the growth rate of the labour force times the amount of capital per labourer. The latter term denotes the amount of investment per worker that is required to keep the capital-labour ratio constant in time. It can be easily shown that the steady-state solution is a stable one.

Technological progress is purely labour augmenting in this model. This implies that both the production function $f(k)$ and the amount of investment per labourer $sf(k)$ will shift upwards due to technological change. Although the equilibrium capital/labour ratio and the output per worker will increase, the amount of capital and the amount of output per worker, denoted in efficiency terms, will remain the same. The actual output-labour ratio and the capital-labour ratio will grow at a constant proportional rate μ, the rate of labour-augmenting technological progress.

The first Harrod problem is solved in the neoclassical model by the assumption that labour and capital are substitutes with diminishing marginal productivities of each factor. This implies that the capital-labour ratio and, consequently, the capital-output ratio, is adjusted towards its equilibrium value. The capital-output ratio is assumed to be fixed in the post-Keynesian models of Harrod and Domar. The second Harrod problem, the knife-edge property, does not appear in the neoclassical model because it does not contain an independent investment function. The markets operate perfectly and instantaneously so that there is no deviation from the expected and the 'warranted' rate, which was possible in the Harrod-Domar model.

Solow's model cannot explain the productivity slowdown if the propensity to save is constant, i.e., if output growth is at its steady-state. The productivity growth is determined by the (exogenous) rate of technological change — thus, a ceteris paribus change of the rate of growth of the labour force will be matched by an increase in the growth of output by the same amount.

Next to this, the relation between investment and growth of output is rather weak. Writing the production function (equation 2.1)) in growth rates implies that the growth rate of output is equal to:

$$\hat{X}_t = \hat{A}_t + \beta\hat{N}_t + (1-\beta)\hat{K}_t \tag{2.3}$$

in which β denotes the labour share of total income and has a value of about 0.75 in most developed countries. This implies that an increase in the investment-output ratio of Δ leads to an increase in the growth of output equal to $(1-\beta)\Delta(X/K)$. If, for example, the capital-output ratio is 3 and the share of investment in total output is decreased by 10 per cent, output will decrease, given $\beta = 0.75$, by less than one per cent. However, it is possible that the exponent on labour (β in equation 2.1)) is smaller than the labour share of income, for instance due to negative external effects on labour which can arise in the endogenous growth models. This is elaborated in section 2.1.6 below. Furthermore, the rate of technological change is independent of investment or changes in the labour force, that is, technological change is completely disembodied and falls like manna from heaven. Both observations convinced Solow that technological change must be embodied in new investment, for which he developed a vintage model (Solow, 1959). In this model, technological change originates from (unmeasured) quality changes in capital inputs. This is elaborated in section 2.2 below.

2.1.3 Kaldor's View of Economic Growth[19]

Whereas authors from the neoclassical school relied heavily on the price mechanism and on the assumption that labour and capital are substitutes, the neo-Keynesian authors did not believe that markets always clear by means of the price mechanism and that the aggregate production function is an unrealistic description of the real world. The main objective against the use of the aggregate production function is that technological progress as well as substitution of factors of production affect the whole capital stock, and that this adjustment is costless and instantaneous. Instead of this production function, Kaldor introduced a technological

19. This section is based on Kaldor (1961).

progress function in which the growth rate of the average labour productivity is assumed to be a positive function of the growth rate of the capital intensity. Furthermore, he assumes that the rate of savings out of labour income differs from the rate of savings out of profits, which is the fundamental difference between the neo-Keynesian and the neoclassical and post-Keynesian models. The growth rate of labour productivity is assumed to be equal to:[20]

$$\hat{\lambda} = \alpha + \beta(\hat{K}_t - n) \tag{2.4}$$

which says that the growth rate of the labour productivity ($\hat{\lambda}$) is equal to a constant term plus a term which depends on the growth rate of the capital stock per labourer. The capital stock changes with the amount of savings and depends therefore on the income distribution. If the rate of profits is above its equilibrium level, the amount of investment and the growth rate of the capital stock will be larger than the growth rate of labour supply such that there will be a shortage on the labour market. This will decrease the capital-output ratio which decreases the amount of savings until the profits share is at its equilibrium level. If the rate of profits is below its equilibrium level, the growth rate of the supply of labour exceeds the growth rate of the capital stock. This will increase the profits share, leading to an increase in the amount of investment until the equilibrium is reached.

The Harrod problems are solved by the Kaldorian savings function. Thus, whereas the neoclassical writers solve the problem by assuming a flexible capital-output ratio, the neo-Keynesian authors found a solution by assuming two different propensities to save which implies that the average savings rate depends on the income distribution.

Verdoorn’s law, in which productivity gains are related to demand growth, is closely related to, and later, explicitly modelled in the work of Kaldor. According to Kaldor, increasing returns to scale constitute the most important factor in this relation. Boyer and Petit (1991) estimate Verdoorn’s law on data of manufacturing industries of groups of developed countries in their study on the productivity slowdown. They find that the relationship breaks down in the mid-seventies. Furthermore, they show that a ‘typical Kaldorian model’ breaks down in this period. They argue that forms for increasing returns, associated with Fordism, have been exhausted in such a way that productivity gains are not directly related to increasing returns. Productivity gains are, in their view, more related to innovation pushed by expenditures. Finally, they argue that, due to more international openness, trade, finance direct investment and foreign competition have changed the income distribution and consequently demand generation.

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20. This linear form is chosen for convenience. In addition to this linear form, Kaldor uses a function in which the growth rate of the labour productivity has a positive initial value, like α in equation (2.4), and increases at a diminishing rate such that it will reach an upper boundary asymptotically. However, the linear form does not alter the main conclusions.

2.1.4 The Importance of Technological Change in Economic Growth

Solow used the concept of the aggregate production function to estimate the size and the nature of technological change. From his empirical study, using aggregated non-farm US data from 1909 to 1949, he concludes that *“gross output per man-hour doubled over the interval, with 87.5 per cent of the increase attributable to technological change and the remaining 12.5 per cent to increased use of capital”* (Solow, 1957:319). This research, both the theoretical and the empirical part, induced an enormous number of reactions and new directions of research within the field of economic growth. This section will give a very short impression of the main findings and the conceptual problems.

Since the pioneering work of Solow, the aggregate production function has often been used to determine the growth rate of total factor productivity, TFP for short. This term is used to indicate the importance of technological progress in total output growth. In the case of the Cobb-Douglas production function, TFP is equal to the growth rate of the shift variable A_t, that is, the growth rate of output minus the growth rates of the inputs.[21] Other early growth accounting studies, e.g., Kendrick (1961) and Denison (1962, 1974), also attributed a major role to TFP growth in the growth of total output. In a recent overview, Maddison (1987) compiled growth accounting figures for several industrialized countries, which again showed the importance of total factor productivity in the growth rate of GDP. Nevertheless, growth accounting is not without criticism. Grossman and Helpman (1991), for example, list three points of critique. First, the problems in separating the quality and the quantity of output and the factors of input. It is believed that the index of GDP underestimates the advances in the quality of output, which in turn leads to an underestimation of the contribution of technological change to output growth. Secondly, the TFP measure is based on the assumption that factors are paid their marginal products, i.e., that markets are competitive — it is highly questionable whether this is an appropriate representation of the real world. Finally, the growth accounting exercise does not say anything about the causality of economic growth.[22]

The first criticism has led to several attempts to adjust the factors of input for changes in their quality. Maddison (1987), for instance, shows that his ‘augmented joint factor productivity’, the TFP corrected for the changes of the labour quality and the capital quality, still shows strong evidence for the contribution of technological change to total growth.[23] The second argument applies only to the absolute

21. This type of TFP measure is therefore often called the ‘Solow residual’.

22. See also the contribution of van Zon (1991) in which mismeasurements due to the aggregate production function are investigated. This is elaborated below.

23. Correction of the GDP for changes of the quality of output would further increase this contribution.

levels of TFP. As long as the deviation of the measured income distribution from the income distribution based on marginal productivities is more or less constant, this argument does not influence the growth rates dramatically. The third and last point is in fact a warning to the reader, who is made aware of both the implications and the limitations of this measure.

From these studies, it is clear that technological change, however measured, is an important determinant of economic growth. Or, as Baumol et al. (1989) stated in their conclusions of the chapter entitled ‘Why Productivity Matters — and Why it Does Not’: *“The central implication of this chapter’s discussion is that in the long run productivity growth can make an enormous contribution to living standards, and that there is no substitute for productivity growth in this respect.”*

From this, we may conclude that technological change is indeed an important factor, if not the most important, in economic growth. Until now, technological change has been treated as an exogenous factor. The next section is devoted to several attempts made to endogenize technological change.

2.1.5 Endogenous Growth Models

Endogenous technological change is not new in the economic literature, although it has become a rather popular subject of research in recent years. This section will not go into detail about all attempts which have been made. We will limit ourselves to the knowledge-based models of endogenous growth and the work of Scott. But first, we will review the learning-by-doing model of Arrow (1962), which can be seen as the forerunner of the knowledge-based models on endogenous technological change.

Arrow’s Learning-by-Doing Model

In his article, Arrow (1962) presented technological change as an unintended by-product of capital formation, which implies that technological change is embodied in new capital goods.[24] Arrow used a vintage model in which the production structure can be characterized with fixed technical coefficients. Furthermore, he assumes that actual lifetime of capital is fixed but that the expected lifetime is determined by the expected data of economic obsolescence, which depends on the (expected) labour productivity and the expected real wage rate. Arrow assumes that a vintage

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24. In the introduction of his article, Arrow presents two examples of technological change which are inconsistent with his model. The first example is about the production of airframes. It was observed that the number of working hours expended in the production of an airframe decreases as the total number of previously produced airframes increases. The second example comes from the Swedish manufacturer Horndal, which had no investment over a period of 15 years whereas labour productivity increased by about 2% per annum. Both examples indicate disembodied technological change whereas technological change is purely embodied in the capital goods of the consumption goods producing sector in Arrow’s model.

is scrapped if the quasi-rents are equal to, or below, zero. In the case of full employment, the current wage rate is determined by the labour productivity of the oldest vintage, given the quasi-rent scrapping rule and the fixed lifetime. The labour productivity depends on the society stock of knowledge, which is in turn related to the cumulative amount of investment. The labour productivity of each new vintage exceeds the productivity of its predecessors if the stock of knowledge has increased, that is, if investments are non-zero.

Although the aggregate production function inhibits increasing returns to scale, both factors of input, labour and capital, are paid their marginal products. The social marginal productivity of capital exceeds the private one because the learning effect is not compensated in the market. This solves the problem of the existence of a competitive equilibrium in the case of increasing returns to scale. A second problem in models which inhibits increasing returns to scale is the existence of a social optimum. The objective function, e.g., some function of the discounted future levels of consumption, should be finite, which implies that the growth rate of consumption should be less than the discount rate. To obtain a finite objective function in the determination of the social optimum, Arrow assumes that the labour productivity is an increasing but concave function of the stock of knowledge. This implies that the growth rate of output is limited by the growth rate of the labour supply (or population). This is the main point of criticism of Romer (1986) to Arrow's model: *"Interpreted as an aggregate model of growth (rather than as a model of a specific industry), this model leads to the empirically questionable implication that the rate of growth of per capita output is a monotonically increasing function of the rate of growth of the population. Like conventional models with diminishing returns, it predicts that the rate of growth in per capita consumption must go to zero in an economy with zero population growth."* (Romer, 1986: 1006)

d'Autume and Michel (1993), however, show that there is a situation in which the model of Arrow leads to an endogenous growth path. This is the case if the labour productivity of a vintage is a linear function of the stock of knowledge and if there is no population growth. But their solution applies only to this special case.

The model of Arrow is in many ways the starting point for the new growth theory. Especially the increasing returns to scale production function at an aggregate level with private constant returns to scale at the firm level and the source of growth, i.e., accumulation of knowledge, can be found in many new growth studies.

Knowledge-Based Models of Endogenous Growth

In the first papers in this field (Romer, 1986, and Lucas, 1988), the stock of knowledge is taken as an extra factor of input. The production function exhibits constant returns to scale with respect to the inputs of the individual firm, that is, for a given stock of knowledge, but has increasing returns to scale at an aggregate level, i.e., with a varying stock of knowledge. An unbounded solution is obtained by the specification of the production function of knowledge. Romer (1986) assumes diminishing returns in the research sector, thus creating a finite social optimum. Furthermore, he assumes that a relative change of the stock of knowledge is a function of the amount of investment relative to the existing stock of knowledge. The early new growth theories of Romer and Lucas are not based on explicit micro foundations of the production of knowledge itself — knowledge is just taken as an extra factor of input in the production structure.

Later, Romer (1990) and Grossman and Helpman (1991), amongst others, defined, in a different setting, the production structure of knowledge more explicitly.[25] Here, we will give a brief overview of Romer's (1990) model. Romer assumes that production of knowledge by the research sector has two effects. First, the research sector will produce blueprints which can be protected from imitation by patent rights. This implies that these blueprints can be sold, or rented, to the capital good-producing, or the intermediate, sector as normal goods so that the research sector receives a stream of monopoly profits. Secondly, Romer assumes that production of a new design, through R&D efforts, generates new knowledge which is added to the total stock of knowledge. This stock of knowledge is freely available to all researchers and, contrary to blueprints, a public good. Due to the increase of general knowledge, the productivity of researchers will increase such that the marginal amount of labour, needed to produce a new blueprint, will decline. This is the source of growth in the Romer model. The intermediate sector buys, or rents, blueprints and is able to produce some new types of capital goods. These goods are sold to the third sector which produces homogeneous consumption goods with the new machinery. Furthermore, Romer assumes that all capital goods are equally productive irrespective of the age of the design they are built upon.

The production function of final goods is taken from Ethier (1982) and based on the 'love of variety' idea of Dixit and Stiglitz (1977). Both, total output and productivity depend positively on the number of different capital goods used to produce output. This production function exhibits constant returns to scale and depends on the variety of inputs. This form stems from the classical economists, e.g., Smith's pin factory in which an increasing number of specialized inputs leads to higher productivity. If the research sector invents a new design for a capital good, the intermediate sector will buy this blueprint and build a new type of capital good. The final good sector buys this capital good, which is as productive as all other capital goods, and extends the number of different machineries. This expand the number of ways in which the (homogeneous) consumer good can be produced and will increase productivity of all, existing and new, types of capital goods. This will increase utility, at least if the labour force employed in the final goods sector remains unchanged.

25. See, for instance, Verspagen (1992) or van de Klundert and Smulders (1992) for a more detailed and more complete review of the new growth theory.

Especially, Romer assumes that the output of a researcher is a multiplicative function of the amount of labour input and the stock of knowledge, which is modelled as the number of designs. At the aggregate level, the number of designs (A) will evolve according to $\dot{A} = \varrho H_A A$, in which H_A denotes total human capital employed in the research sector and ϱ is a productivity parameter. The production function is specified in such a way that the rate of growth of new designs is constant if the employment in the research sector is constant. By doing so, Romer solves the problem of the infinite objective function in calculating the social optimum.[26] Labour is allocated between the R&D and the final goods sector according to the relative wage rates between these two sectors. By changing the wage rate, one can influence employment in the R&D sector, and also in the final goods sector, such that production of new blueprints and knowledge, i.e., the source of growth, changes. Because individual researchers are not paid for their contribution to general knowledge, employment in the R&D sector will be lower in a market optimum than it is in a social optimum. This model reinforces the need for governmental policy.

One of the basic characteristics of Romer's model, and new growth models in general, is that they use an aggregate production function to describe the production structure. As already stated previously in the criticisms of the Keynesian schools concerning the early neo-classical model of (exogenous) growth, it is doubtful whether such an aggregate production function is a realistic description of the real world. Another point of criticism is related with the model of Romer (1990), in which the number of blueprints, as an output of the research sector, is used to model technological progress. In this model, Romer implicitly assumes that all types of investment, i.e., machinery made using different blueprints, are equally productive and will be in use for ever. Economic growth is obtained by a larger variety of capital goods increases productivity of all machinery. Simple examples such as the difference of the productivity between steam and internal combustion engines and the number of steam engines currently in use in our 'modern' economies show that these assumptions are rather inappropriate to describe these characteristics. Another drawback of the new growth models is that it is assumed that all types of capital goods produce an equal share of total output. In other words, there is no diffusion of new technologies other than changes of the capital stock of a certain capital good through changes of aggregate output and/or changes of productivity. In section 2.3, we will show that S-shaped diffusion patterns are common findings within the literature on adoption and diffusion of new technologies. New growth theories are not able to generate such patterns.

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26. As in Arrow, the static problem of an increasing returns to scale production function is solved by differentiating between private blueprints and public knowledge.

Scott's New View on Economic Growth

Scott (1989) rejects the production function as an appropriate tool to describe production possibilities. His main objection to aggregate production function models is the way in which technological change is modelled. Income can grow even if there is no investment and if the labour force is constant in such models. He argues that technical change has to be embodied in capital goods, implying that growth depends on investment.[27] Furthermore, he argues that, even if new technologies are embodied in investment goods, a large number of investments, such as investment in infrastructure and investment in research and development, cannot be described by vintage models.

In Scott's view, investment is the carrier for learning possibilities and generates new opportunities for learning and is not just adding the same to an (already) existing capital stock. Instead of a production function, Scott introduces an investment programma contour map, IPC for short. This IPC symbolizes a relation between investment, the growth of output and the growth of labour input:

$$\frac{\hat{X}}{s} = \varsigma f\left(\frac{\hat{N}}{s}, \frac{1}{\varsigma}\right) \tag{2.5}$$

in which s denotes the investment ratio, $\hat{X}$ the growth of output capacity and $\hat{N}$ the growth of the labour force. The parameter ς denotes the radius of the IPC. An example of an IPC is given in Figure 2.3. A firm can choose an investment project which increases both, the rate of growth of output and the growth of the required labour force, such as point a_1 in Figure 2.3. But it may also invest in a project which decreases the growth of the required labour force at the expense of growth of output, for instance at point a_2. The IPC is concave leading to a decrease in the marginal rate of substitution ($d\hat{X} / d\hat{N}$). Furthermore, we assumed constant returns to scale with respect to the investment ratio, so both axes can be divided by s. For diminishing returns to scale to the rate of investment, the IPC should move towards the origin as the rate of investment increases. The radius of an investment programme, i.e., the distance Oa_1 or Oa_2, measures this effect. It also measures another effect which Scott calls the expansion of contraction of investment opportunities which arise from factors that are outside the model, such as 'catch-up' phenomena due to imitation. The radius is relatively low for leading countries and high for countries which can imitate the leader in a relatively cheap manner.

27. Note that the Horndal effect shows that growth is possible over a longer period without investment (cf. footnote 24). However, this example indicates the potential importance of disembodied technological change whereas it says nothing about the significance of its embodied counterpart.

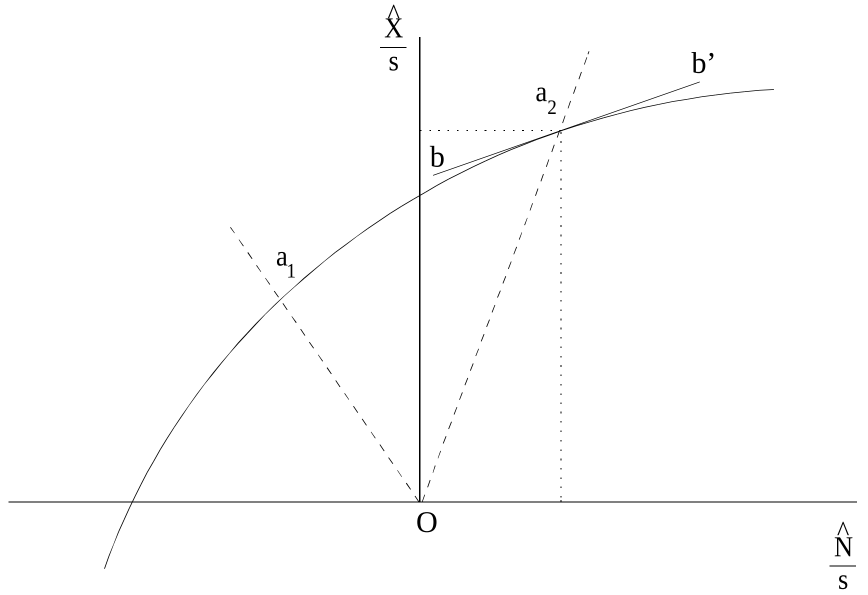

Figure 2.3. The Investment programme contour

Scott shows that combinations of $\hat{X}/s$ and $\hat{N}/s$ which yield the same expected net present value of rents are located on a straight line in this figure. The slope of this line, for example line bb' in Figure 2.3, is equal to the wage share in total cost. Profit-maximizing firms will choose the point for which the IPC is tangent to the iso-profit line. If the wage share increases, firms will choose a point that is located more to the left, so that the labour force is less expanded or even reduced, for example at point a_1. Consequently, the growth of output is reduced.

Finally, the model is closed with a Keynes/Ramsey optimum steady state growth rule, i.e., the growth path which maximises consumption per head for which the required rate of return on capital equals the sum of the discount rate and the product of the intertemporal substitution parameter and the growth rate of output.[28] Scott shows that steady state is a stable solution — in other words, if the actual rate of return on an investment project is higher than the optimum rate, the rate of investment will increase since the marginal capital productivity is high enough to compensate for the direct loss of utility due to higher savings (Keynes/Ramsey rule). A higher rate of investment implies more growth of output and employment but the growth of labour productivity falls due to the concavity of the IPC. If there are decreasing returns to investment, the warranted rate of return on investments will fall to the optimum rate of return so that the optimum rate is stable.

To conclude, the role of investment in generating growth is central to Scott's model. Furthermore, investment embodies new production techniques but also, and more importantly, it creates new possibilities for learning. The radius of the IPC denotes increasing, decreasing or constant returns to investment but also expansion

28. See for instance Blanchard and Fischer (1989) for an exposition of this rule.

or contraction of investment opportunities. However, the generation of new technologies, as we find in the models of knowledge-based models on economic growth, is not modelled by Scott. He (simply) assumes that investment opportunities are not exhausted due to learning effects. In that sense, his model is not really an endogenous growth model.

2.1.6 Some Explanations of the Productivity Slowdown

In the introduction to this section, we mentioned that we cannot ignore the productivity slowdown and the productivity paradox when reviewing models on technological change. This section discusses some explanations which arise from the models discussed above. But first, we will briefly review possible measurement errors of factors of input and output as a possible explanation for the slowdown.

Griliches (1960, 1971 and 1988), for instance, argues that the quality of output is not accounted for in the measurement of GDP. The slowdown could be explained if the quality of output has changed since 1973, resulting in an increase in productivity measures, based on the quality-adjusted measure of output. However, one should note that the factors of input are also subject to quality changes. Labour productivity would not change if, for instance, the quality of output and the quality of labour changed by the same, relative, amount. This implies that one should investigate both inputs and outputs in order to determine whether the productivity slowdown can be regarded as a real fact. An extensive study on this subject was carried out by Baily and Gordon (1988). They investigate labour productivity growth as well as multifactor productivity growth at the aggregate level and for a number of different US industries. Their conclusion is that different measures of inputs, outputs and deflators, in which one includes quality changes, reshuffle the productivity growth between industries, but do not affect the measures at the aggregate level to a large extent. Furthermore, they find some mismeasurements in the construction of price indices, but this holds true both for the pre-1973 and the post-1973 period, so that the productivity slowdown remains unexplained. In Gordon and Baily (1991) they extend their analysis for some major European countries but conclude that the productivity slowdown is not the result of bad statistics. The quality-adjusted measures explain just part of it at most. Closely related to these studies are growth-accounting studies, e.g. Denison (1985). Denison can explain about fifty per cent of the productivity slowdown by taking fourteen separate factors into account, leaving a large part of the productivity slowdown unexplained.

We will now examine whether the models discussed above can explain the productivity slowdown. We will concentrate on the work of Romer (1987) — which reviews the endogenous growth theories in relation with the productivity slowdown — and of Scott (1989). Romer argues that due to negative external effects on labour, the exponent on labour in a simple aggregate model like $X = K^{\alpha} L^{0.75}$ may be smaller than the labour share of income. He relates the productivity slowdown to the business cycle and tries to find some relation between the growth rate of the labour force, the wage rate and the productivity slowdown. This argument runs as follows: suppose that innovations increase labour productivity and that these innovations have positive external effects due to knowledge spillovers. If the growth rate of the labour force increases, the wage rate will decrease leading to a decrease in the incentive to innovate. This has a negative impact on the generation of knowledge. The net effect on output of such an increase of the labour supply is a positive effect of the number of workers and a negative effect of fewer innovations. This implies that the growth rate of labour productivity will decrease if the labour supply increases, due to negative external effects of labour. But the question is whether the magnitude of such a relationship is large enough to explain the slowdown. *"As a result, the exercise undertaken here does not fully resolve the productivity puzzle, but rather converts it into a different, possible more suggestive, puzzle. Reconciling this explanation with these apparently reasonable prior beliefs, or finding an alternative explanation for the low apparent elasticity of output with respect to labor is the new puzzle suggested here."* (Romer, 1987:167). According to Romer's analysis, the productivity slowdown cannot be explained by endogenous growth models without introducing business cycles. Moreover, the wage rate plays an important role in his study, in addition to the difference between the elasticity of output with respect to labour and the labour share of income. Finally, as the quotation indicated, a new puzzle arises which he cannot solve.

Scott (1989) investigates the productivity slowdown by using his model which is based on the Investment Programme Contour map. He estimates the radius of the IPC, i.e., the measure of efficiency of investments, for the US, Japan and the UK, both for pre-1973 and post-1973 periods.[29] He finds that the radius decreases for all countries which means that the investment opportunities decrease after 1973. Additionally, he investigates three other possibilities: a mismeasurement of quality-adjusted employment, the effects of a fall of the rate of capacity utilisation, and a mismeasurement of the investment ratio. The quality index of employment should be corrected downwards due to shifts of employment towards relatively low-wage sectors and due to the fact that the growth of employment after 1973 can be attributed for a large extent to small firms, which pay relatively low wages. Scott

29. He uses the following equation:

$$\frac{\hat{X}^c}{\varsigma} = p_1 s + p_2 \frac{\hat{N}_q}{\varsigma} + p_3 \left(\frac{\hat{N}_q}{\varsigma}\right)^2 \frac{1}{s}$$

which is derived from a non-linear form of the IPC. N_q denotes the quality-adjusted employment, X^c denotes capacity output, s denotes the gross investment ratio and ς is the radius of the IPC. He estimates the parameters of this equation so that the radius of the IPC (ς) can be obtained by solving the quadratic function.

measured the rate of capacity utilisation by estimating a trend term on the actual output. But by considering more sophisticated measures, including business surveys, he concludes that the rate of capacity utilisation has decreased to a larger extent after 1973 than his trend estimate suggests. This implies that (i) the actual rate of growth of capacity is higher than that measured by a simple trend term, (ii) the investment ratio, which should be measured at a constant ratio of output to capacity, should be adjusted downwards, and (iii) employment may decrease less than one-to-one due to, for example labour-hoarding effects. Finally, the investment ratio should be adjusted downwards due to decreased lifetimes of the capital stock and due to an increased number of bankruptcies after 1973 in which still profitable equipment is scrapped. A correction for these terms leads to a higher estimate of the radius after 1973. Taking these effects into account, he finds that his model can explain just a small part of the productivity slowdown. This implies that Scott’s model is a long-term model and that the productivity slowdown cannot be explained without correcting for e.g. labour hoarding, the rate of capacity utilisation, changes of the lifetime of equipment and high scrapping rates due to bankruptcies.

Finally, another explanation of the productivity paradox is given by David (1991). In his historically oriented essay, he compares the diffusion of computers with the introduction and adoption of the dynamo at the beginning of this century, he argues that adoption may take such a long time that it is too early to talk about the productivity paradox. Metcalfe and Gibbons (1991) argue that efficient operation of the profit mechanism is crucial for rapid diffusion. Furthermore, and related to this, they argue that sufficiently skilled people and abundant financial resources are needed to be able to adopt a new technology quickly. Moreover, as we will see in section 2.3 below, uncertainty may play an important role in the adoption of new technologies. The turbulent developments in the 1970s are likely to have increased uncertainty, thereby decreasing the speed of diffusion. This could be another explanation of the productivity slowdown. Furthermore, if the speed of diffusion has slowed down after the mid-seventies, the productivity slowdown is not directly related to the development of new technologies which would explain the Solow paradox.

Van Zon (1991) investigates possible measurement errors which are due to the use of an aggregate production function method. He compares TFP measures which result from an aggregate production function approach with measures resulting from a putty-clay vintage approach. He uses the vintage model, as a ‘true’ model, to generate capital stock and labour demand data. Using these generated data, he estimates TFP according to the Solow approach. He finds that the Solow TFP measure lags behind movements of ‘actual’ changes and that the Solow approach underestimates the measured TFP value when the lifetime of equipment is falling and the capital stock is, consequently, more productive. It is worthwhile to estimate productivity growth on the basis of a vintage model and to examine whether the productivity slowdown can be explained by changes of the age structure in the capital stock. This is elaborated in the next section.

To conclude, the models discussed above are not able to describe the productivity slowdown without making additional assumptions. The arguments of Romer, i.e., decreased wages, and David, i.e., decreased speed of diffusion, seem to coincide with each other. Furthermore, Scott's arguments with regard to decreased lifetimes of the capital stock and excess scrapping due to bankruptcies fit well in the vintage approach of van Zon. Moreover, such a vintage approach could remove some mismeasurements of the aggregate production function approach. A model in which both the vintage and the diffusion approach, and thus most of these arguments, are combined, could be the solution to model output, employment, technological change and investment. But before we turn to such a model, we will briefly review the literature on vintage models and models of adoption and diffusion of new technologies.

In the next section, we will discuss the vintage type models, which have the advantage over the aggregate models that the allow for a clear distinction between embodied and disembodied technological change. The transmission of technological change is made more explicit in the vintage models. Moreover, these types of models can describe the rise and the decline of new (process) technologies in a very natural way.[30] After that, we will turn to the models of adoption and diffusion of new technologies, which show that it takes a considerable amount of time for a new production process to spread over an economy.

2.2 Vintage Models

The models described so far assume that the capital stock is homogeneous so that technological change alters the total capital stock in the same way.[31] Another implication of the homogeneous capital stock assumption is that, if one allows for substitution between the factors of input, the total capital stock as well as the total labour force are subject to this substitution. One of the main criticisms of the neo-Keynesian authors concerning the Neoclassical model of growth is that the total capital stock is adjusted immediately to a changed factor price ratio. In his above-mentioned address to the Round Table Conference, Kaldor describes this as follows: *"The production curve thus represents a kind of boundary indicating the maximum output corresponding to each particular 'quantity' of capital, a maximum which assumes that the whole productive system is fully adapted to each particular state of accumulation. In an economy where capital accumulation is a continuous process this boundary is never attained-since the actual assortment of capital goods at any point in time (...) will consist of*

30. At least in the clay-clay and putty-clay types of vintage models as we will show in the next section.

31. The model of Arrow (1962) is a notable exception.

items appropriate to different states of accumulation, and the output corresponding to any particular 'quantity' of capital will be less than the equilibrium (or maximum) output associated with that quantity." (Kaldor, 1961:204-5).

The assumption of immediate adjustment of the total capital stock has been viewed as being unrealistic by a large number of authors. This induced a new view of the composition of the capital stock. The homogeneity is replaced by a heterogeneous capital stock which contains different vintages. The capital within a vintage is assumed to be homogeneous, but heterogeneity between vintages is allowed for. The introduction of vintages does not only relax the assumption of substitutability of the input factors at the aggregate level, it also allows for a distinction between disembodied and embodied technological change. Embodied technological change is incorporated in equipment and this type of technological change can only become effective by the installation of new types of machinery. Introducing embodied technological change, one is able to model the transmission of technological change. Moreover, investment decisions become more important because they alter the overall productivity of a firm. The role of investment is to modernize or to widen as well as to deepen the capital stock. The investment in new machinery does not affect the productivity of existing, and therefore, older types of equipment. In contrast to embodied technological change, disembodied technological change alters all vintages in the same way and is not directly connected with investment decisions.

However, the possibility of substitution between capital and labour continues to be a point of discussion. Whereas substitution affects the total capital stock and the total labour force in the aggregated models, it affects only newly installed capital and labour in vintage models. The question as to whether capital and labour are substitutes prevails. Two extreme versions with respect to the substitutability are the models of Kaldor (no substitution at all) and Solow (always substitution possibilities). Jorgenson came up with an intermediate version. These three versions will be discussed in the next section.[32]

2.2.1 Ex-Ante and Ex-Post Substitutability

In 1960, Robert Solow introduced a vintage model based on the Cobb-Douglas production function. His special interest was to emphasize the distinction between embodied and disembodied technological progress. In his paper, technological progress is assumed to be exponential in time and purely embodied of nature. In other words, there are no further improvements once the capital goods have been constructed. Furthermore, Solow assumes ex-post substitutability between capital

32. A putty-semi-putty model, i.e. ex-post less substitution possibilities than ex-ante, is another possibility which in fact covers these three variants, cf. e.g. Meijers and van Zon (1994). This overview is limited to the three 'pure' versions.

and labour and that the labour market is competitive. Labour, which is assumed to homogeneous, is paid the same wage regardless of the age of the capital stock on which it operates. That is, the marginal product of labour must be the same for all vintages. The possibility of ex-ante as well as ex-post substitution is called 'putty-putty' nowadays. From these assumptions, and the assumption that capital deteriorates exponentially, Solow derives an aggregate production function similar to the Cobb-Douglas function with labour and a quality-adjusted index number of the amount of capital as input factors.

The marginal product of labour is the same for all vintages in the Solow model. Furthermore, technological change is Hicks-neutral, which implies that the capital-labour ratio increases with the age of the vintages. The labour-output ratio is the same whereas the capital-output ratio decreases as vintages are younger. This type of technological progress is purely capital-augmenting. Because the capital-labour ratio can be changed even after the moment of installation in the putty-putty model, there will be no economic reason to scrap vintages and the lifetime will be infinite, unless the physical lifetime is bounded to a maximum.

Although their model is based on the technical progress function and does not contain a production function as such, Kaldor and Mirrlees (1962) assume another extreme version of substitutability. Their work is an example of a fixed coefficients vintage model, in which it is assumed that there is no substitution before and after the moment of installation. This type of models is called 'clay-clay'. The factor coefficients of each vintage may change due to embodied and disembodied technological change. Furthermore, firms are able to alter the average factor coefficients by changing the lifetime of equipment.

A third variant of the possibility of substitution, and in fact a compromise between the two extremes, are the putty-clay models of Johansen (1959) and Salter (1960). Factors of input can be substituted before the moment of installation, but once installed, capital and labour will be operated in fixed proportions, at least in the absence of technological change. Economic scrapping is relevant in this model due to the fixed coefficients ex-post. This implies that the average capital-labour ratio can be altered by changing the lifetime of equipment, as is the case in the clay-clay model. This kind of 'indirect substitution' is noticed explicitly by Salter (1960).

2.2.2 Intermezzo: How long is the Long Run?

Phelps (1962) uses Solow's model to examine long-run properties and to determine the importance of the differences between embodied and disembodied technological change on long-run growth rates. He shows that, in a Solow-type vintage model, the long-run growth rate depends on the rate of embodied technological progress plus the rate of disembodied technological progress plus the growth rate of the labour force. It does not depend on the investment ratio, which implies that the embodiment effect can be replaced by disembodied technological change without altering the long-run properties of the model. Note that this result holds only for steady-state solutions, that is, if the investment ratio is constant over time. The main force behind this property is the age distribution of the capital stock. If this distribution is constant, together with a constant investment ratio, the effect of embodied technological change is constant, which leads to the conclusion that the embodiment effect can be replaced by disembodied technological change. There is no difference between the aggregate model and the vintage model in such a case. In the short run, however, there are major differences between the models. A sudden change of the rate of investment, for instance, can alter the age-distribution of the capital stock so that embodiment effects can be identified. Such a deviation is shown in Figure 2.4. In this figure, we plotted the growth rates of output according to the aggregate Solow model and according to the Solow / Phelps putty-putty vintage model. In the aggregate model we assumed a 2% disembodied technological change against a 2% embodied technological change in the vintage model. Furthermore, we kept the labour force constant which implies that both models generate a 4% growth, given a capital elasticity of output of 0.25 (cf. Appendix 2A on page 63 for a description of the model and the other parameter values). At time t=10, we changed the investment-output ratio from 0.25 to 0.30. As expected, the change in output is larger in the vintage model than it is in the aggregate model, due to the embodiment effect. This implies that the amount of investment is adjusted to a larger extent in the vintage model, which implies that the vintage model will move towards the steady-state more rapidly. At time t=60, we restored the investment ratio to its original value so that an opposite, and symmetric, adjustment occurs. Three conclusions can be drawn from this. First, the reactions to changes of the investment ratio are larger in the vintage model. The relative change of the growth rate of output is 25% in the vintage model, whereas it is 10% in the aggregate model. Secondly, the vintage model returns towards the steady-state growth path faster. The time needed to reach the steady-state, is 19 years for the vintage model and 33 years for the aggregate model.[33] Finally, both intervals are rather sizeable.[34] Phelps noticed the first and second conclusion but he argues that the differences between both models disappear in the long run. This leads to the familiar question: how long is the long run? It appears to me that intervals of about 20 or 30 years, of about the period between two generations in human life, or even

33. Here, the steady-state rate of growth is said to be restored if the relative deviation is less than 1%, i.e., if the rate of growth reaches a value between 4.0 ± 0.04%.

34. If we use a rate of depreciation of 10%, instead of 5%, the period before the equilibrium is restored is equal to 17 years for the vintage model and 25 years for the aggregate model. Furthermore, if the investment ratio is changed to 0.26, i.e., a change of 4% instead of 20%, the intervals are 10 and 11 years, respectively.

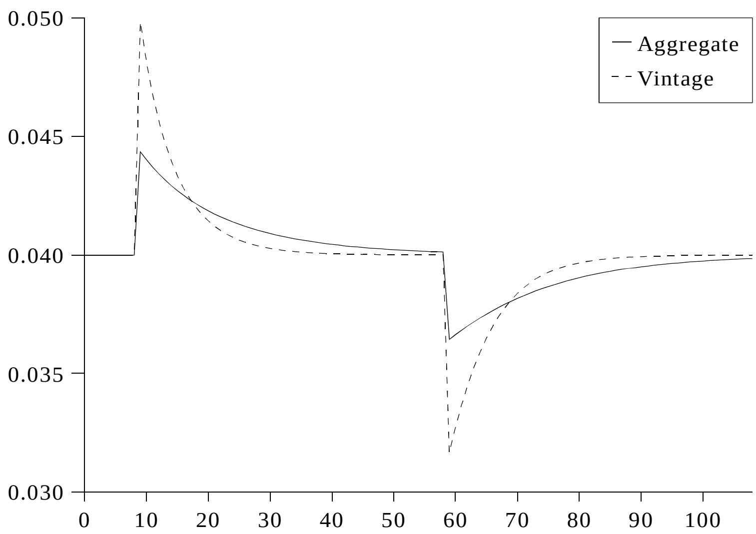

Figure 2.4. The growth rates of output in the aggregate model and in a putty-putty vintage model

about 10 years as follows from a change of 4% of the investment ratio, cannot be ignored or disposed of as short term effects. This is especially true if the models are used for policy recommendations for 'day-to-day' problems. Moreover, if disturbances are not symmetric, there are level effects, even in the long run.

From this short intermezzo we may conclude that in both aggregate and vintage models, steady-state results are useful if one is concerned with long-term effects but that such long periods are far too long for most policy recommendations, even if they concern technological change and economic growth.

2.2.3 Scrapping of Equipment

All models mentioned above allow for scrapping due to wear and tear. Kaldor and Mirrlees (1962) assume that a proportion of the existing stock of equipment disappears each year due to physical causes (accidents, fire, explosions, etc.). This type of scrapping is referred to as 'radioactive decay'. Solow uses a constant 'rate of mortality', which is the same as the Kaldor-Mirrlees assumption. Radioactive decay, or a proportional decrease of the physical amount of capital, will go on forever implying that the lifetime of equipment is not determined by scrapping due to wear and tear in this case.[35,36]

35. Note that an exponential depreciation scheme with δ as the rate of depreciation implies an average lifetime of capital goods of $1/\delta$ years.

36. Another scheme to model scrapping due to wear and tear is used by the Dutch Central Planning Bureau, for instance. They assume, on the basis of survey data, a scrapping scheme which has approximately an inverse S-shaped, or Gaussian-distributed, form: an increasing proportional amount of scrapping at the beginning and decreasing proportional deterioration at the end. The maximum physical lifetime is assumed to be 45 years.

The ex-post fixed-coefficient models, i.e., the clay-clay and putty-clay variants, allow for economic scrapping. Kaldor and Mirrlees apply the zero-quasi-rent condition whereas Salter investigates also another possibility. The zero-quasi-rent condition says that a vintage is scrapped if the variable costs exceed the returns of that vintage. Let labour be the only variable factor of input, then this condition is equal to:

$$X_{\tau,t}\, p_t - N_{\tau,t}\, w_t = 0 \tag{2.6}$$

in which $X_{\tau,t}$ denotes the output at time t of the vintage which is installed at time τ and $N_{\tau,t}$ denotes the corresponding amount of labour, p_t is the output price and w_t is the nominal wage rate. Rearrangement of this equation gives the condition in productivity terms, that is, a vintage τ is scrapped at time t if the labour productivity ($\lambda_{\tau,t}$) is equal to the real wage rate:

$$\lambda_{\tau,t} \equiv \frac{X_{\tau,t}}{N_{\tau,t}} = \frac{w_t}{p_t} \tag{2.7}$$

The zero-quasi-rent condition implies that, in general, a firm avoids losses on individual vintages. This is in contrast with the maximum-profit approach, where a firm compares the total marginal costs of a new vintage with the total marginal costs of an older one. If the costs of the new vintage are lower than the costs of the older one, a firm can increase profits by replacing the old by the new. This will lead to a shorter lifetime of equipment compared to the lifetime under the zero-quasi-rent condition. There is one important exception, however. If the output market is competitive, the price of output is equal to the marginal costs of the newest vintage. Comparing the marginal costs of the new vintage with the marginal costs of an older one is equivalent to comparing the marginal costs of the old vintage with the price of output. This implies that, in the competitive market, the 'optimal' scrapping condition and the zero-quasi-rent condition are exactly the same. The scrapping rule under the maximum-profit assumption is investigated and formalized by Malcomson (1975). In this thesis, we will refer to this approach as the Malcomson scrapping condition.

The difference between quasi-rent scrapping and the Malcomson scrapping rule is shown in Figure 2.5, where the left part shows quasi-rent scrapping. In that figure, we plotted six different vintages of which vintage V6 is the oldest and V1 is the newest or most recently installed vintage. The height of the rectangles denotes the variable costs per unit of output (UVC) for all older vintages whereas it includes capital costs, the filled rectangle, for the first vintage which implies that the total hight denotes total costs per unit of output (UTC). If the price of output falls to P, total costs of the oldest vintage exceeds total returns and this vintage will be scrapped. The new vintage replaces the old one and the size of that new vintage is determined by total capacity output, X^c, and the capacity gap which exists after

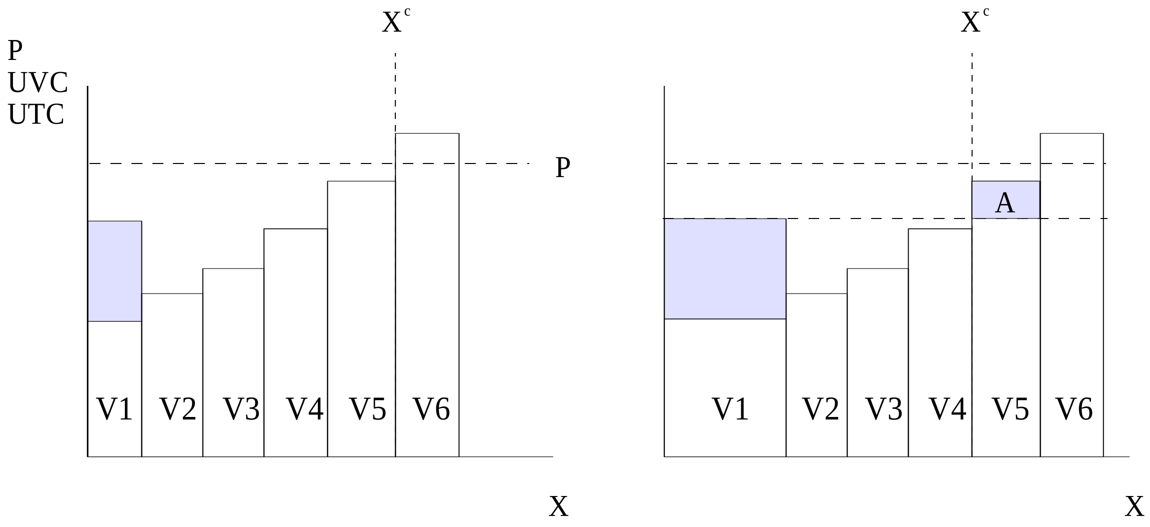

Figure 2.5. Quasi-rent and Malcomson scrapping rules

scrapping. The figure at the right-hand side represents a similar situation, but here we assume that a firm applies the Malcomson rule. Total unit costs of the first vintage are below variable unit costs of the fifth one. This implies that a firm can increase profits by scrapping the fifth vintage, in addition to V6, and replacing both by the new vintage. Investments will be raised and profits will increase by rectangle A.

2.2.4 Empirical Evidence

Following the introduction of vintage models, the importance of the embodiment effect has been studied by several authors. A brief overview of this discussion can be found in Gregory and James (1973). The studies on the macro level do not find strong evidence for the embodiment hypothesis. Gregory and James try to explain this by pointing to severe collinearity of the data and to little variance in the capital stock data. However, at the firm level, and for the electric power industry in particular, several authors find support for the vintage hypothesis. Finally, the cross-section production function studies find almost no support for the vintage hypothesis. Gregory and James have tried to measure the embodiment effect by comparing the factor productivities of older firms with the productivity of newer firms. The basic assumption underlying their research, is that new firms will invest in the most advanced, i.e., the best-practice, technologies. By comparing the productivity of these new firms with the productivity of the older firms, one is expected to find a significant difference if technological change is embodied. Gregory and James observe that the age of the factories is not an important explanatory variable of the differences in the value added per worker within each industries studied.

It should be noted, however, that almost all studies mentioned above, as well as those referred to Gregory and James, draw heavily on the Solow/Phelps approach

— that is, they all view capital as being malleable after the moment of installation so that there is no economic scrapping or, in the case of ex-post fixed coefficients, they do not account for changes in the age structure. The research of Gregory and James is a notable exception to this rule, but in section 2.3 below, we will argue that their assumption with regard to the relation between age and productivity is doubtful.

Finally, the measurement of the capital stock has been discussed at length. One of the arguments is that price indices of investment goods incorporate quality changes in equipment, which implies that the embodiment effect is underestimated.[37] Hulten estimates that, on the basis of a Solow-type vintage mode and by decomposing price indices to quality and ‘real’ price effects, “*approximately 20 per cent of the residual growth of quality adjusted output could be attributed to embodied technical change.*” (Hulten, 1992:976).

From the literature mentioned above, it seems that we can conclude that the embodiment hypothesis has never been rejected, whereas it is supported by some studies, which are mainly based on micro data. We will reconsider this conclusion in the next section, where we will discuss the Dutch implementation of vintage models, which explicitly accounts for changes in the age structure of the capital stock.

2.2.5 The Dutch Experience[38]

The vintage approach became popular in empirical research in the Netherlands after the pioneering work of Den Hartog and Tjan (1974). The discussion which followed these publications was focused on several aspects in which the effects of the real wage costs on employment is one of the central issues. The first applications were based on the clay-clay model, but the putty-clay variant has also been considered. We will briefly discuss the specifications of the models, followed by a quick overview of the empirical results.

In the clay-clay models, the capacity output of a vintage is defined as:

$$X_{\tau,t} = B_{\tau,t} I_{\tau,t} = B_0 (1+\mu_i)^{\tau} (1+\varepsilon_i)^{t} I_{\tau,t} \tag{2.8}$$

where the capacity output at time t of a vintage installed at time τ is equal to the capital productivity times the amount of investment which still exists at time t. The capital productivity is defined as a constant term times the influence of capital-augmenting *embodied* technological change (μ_i) times the influence of capital-augmenting *disembodied* technological change (ε_i). The physical deterioration follows an exogenous, approximately Gaussian-distributed, scrapping scheme, which implies

37. See for instance Cole et al. (1986) for a study of price and quality changes in the computer industry, and Gordon (1990) for a wider range of equipment prices.

38. This section draws heavily on Den Hartog (1984).

that the amount of capital of a vintage at time t is a fraction of the amount of investment at time τ. The amount of labour which corresponds with the output of a vintage is defined as:

$$X_{\tau,t} = A_0(1+\mu_n)^{\tau}(1+\varepsilon_n)^t N_{\tau,t} \tag{2.9}$$

in which the embodied labour augmenting technological progress is denoted by μ_n and the disembodied counterpart by ε_n. Note that all variables are defined in capacity terms. Since the output market is assumed to be competitive, a vintage is scrapped if the quasi-rents equal zero. The total capacity output and total capacity demand for labour is equal to the sum of capacity output and demand for labour of all existing vintages. In the original Hartog and Tjan paper, the actual demand for labour depends on the regime of the labour market (supply shortage versus supply surplus). This approach has been used by several authors. The empirical models furthermore account for changes in working hours, war damage, and different pre- and post-war rates of embodied technological change. The estimation results, taken from about 15 different studies based on macro data from about 1950 to 1975, show that the annual rate of embodied labour-augmenting technological progress ranges from about 2 to 5 per cent, whereas there was almost no disembodied technological change, about 1 per cent at most. Furthermore, the results showed almost no capital-augmenting technological progress.

The putty-clay models, for instance those developed by Kuipers and van Zon (1982), Gelauff, Wennekers and de Jong (1985), and Muysken and van Zon (1987), are all based on a CES production function. The optimal labour intensity stems from maximizing firm behaviour.[39] The results with respect to the size and the nature of technological change are not very different from the clay-clay studies, meaning that they are sizeable, mainly embodied and labour-augmenting. The main difference between the estimation results of the putty-clay and the clay-clay models is that the former describe the demand for labour more accurate. Or, in the words of Den Hartog: "*Though the answer of putty-clay models to the question of some of the origins of productivity growth seems somewhat meagre for the time being, it should be noted that their results do not contradict, to say at least, the impression given by clay-clay studies: The impression being that real labour costs do matter where employment is concerned. Being an answer also to the original question which initiated vintage model research in the Netherlands.*" (Den Hartog, 1984:342).

Whereas most vintage models based on the Solow / Phelps approach do not find strong evidence for the embodiment hypothesis, the Dutch vintage models, which are based on the work of Johansen and Salter, strongly support this view. This suggests that the age structure of the capital stock, which may vary in time through scrapping behaviour, plays an important role.

39. In chapter 3, we will review this approach in more detail, and we will also discuss several aspects of the models of Gelauff, Wennekers and de Jong, and Muysken and van Zon.

2.2.6 Vintage Models and the Productivity Slowdown

Two of the main problems of these putty-clay models are concerned with the description of technological change and estimation problems which are due to discontinuities of the models. The performance of the models is somewhat disappointing, especially in the late seventies and early eighties, if the technological change parameters are assumed to be constant. Therefore, Gelauff, Wennekers and De Jong have partly endogenized technological change by making a number of rather ad hoc assumptions. In their model, they try to incorporate learning-by-doing effects as well as economies of scale due to international specialisation. In their view, embodied technological change depends positively on the difference between the lagged five-year moving average of the growth rate of exports and the lagged five-year moving average of growth of production. This structural change in the export share is assumed to stand for increasing returns to scale, induced technical progress and changes in sectoral composition of capital. Disembodied technological change depends positively on, again, the five-year moving average of the growth of production plus the average growth rate of exports. The growth of production results in learning-by-doing and in returns to scale effects whereas the growth in export is assumed to result in more rapid diffusion of knowledge and increasing competitive pressure.[40] By doing so, they are able to describe the productivity slowdown. Although the ideas of economies of scale and learning-by-doing are likely to play a role in the process of technological change, one can doubt whether the implementation has been correctly chosen. Moreover, nearly all of the estimated parameters proved to be at their imposed lower level of zero, with the exception of labour-augmenting technological change. This indicates a tendency to negative parameter values in which case the interpretation becomes very unclear.

Muysken and van Zon, on the other hand, use several dummies in the technological progress variables to obtain a satisfactory fit. Although this gives sizeable effects on the estimation results, it does not say anything about the underlying forces. They find about 5% embodied labour-augmenting technological change for the period 1960-1975 while it is reduced to 0.5% for the period 1975-1981. Disembodied technological change is also reduced in the latter period, but the changes are less sizeable. Thus both models notice a slowdown of (labour) productivity growth but they introduce some unsatisfactory assumptions regarding the description of technological change.

Van Zon and Muysken (1992) develop a vintage model in which the learning-by-doing argument is explicitly incorporated. This type of disembodied technological change is assumed to be firm-specific. Furthermore, they apply the Malcomson scrapping condition in their model, which implies that the impact of embodied

40. Why production and exports can be added, which implies an equal contribution to disembodied technological change, is not clear at all.

technological change varies with replacement investment and high profits on new equipment will induce large replacement and will increase productivity of the entire capital stock. Van Zon and Muysken perform some simulations with this model and compare the results with the aggregate production function approach and with some other vintage models.[41] The results are promising, particular those with respect to the role of technological change in the explanation of employment, but the model is not estimated and a decisive answer cannot be given.

Although vintage models describe the process of technological change and growth in a more realistic manner, they are not able to provide a satisfactory explanation of the productivity slowdown. The homogeneity of each vintage implies that all firms will invest in the best-practice technology, that is, all firms adopt new technologies immediately. This is in sharp contrast with the findings of the research on adoption and diffusion of innovations. Moreover, as argued previously, the speed of diffusion of new technologies has decreased which implies that the impact of technological change on the capital stock may have declined, even if the development of new technologies has been constant (cf. David, 1991). The next section will review the literature on the adoption and diffusion of new technologies. After that, section 2.4 will compare the vintage models with the models of adoption and diffusion of new technologies. This will lead to the basic method to give answers on the problems defined in the first chapter.

2.3 Adoption and Diffusion of Process Innovations

Ever since the seminal work of Schumpeter, it has been a tradition to divide the process of technological change into three phases: the invention, the innovation and the diffusion. *"An invention is an idea, a sketch or model for a new or improved device, product, process or system. Such inventions may often (but not always) be patented but they do not necessarily lead to a technical innovation. In fact the majority does not."* (Freeman, 1982:7). The innovation is the first commercial transaction involving this new product, product, system or device. After that, the diffusion or spread of the innovation may take place as more economic subjects buy or imitate the invention. Although both the invention and the innovation are of high importance in the process of technological change, we will concentrate on the last phase: the diffusion.

Moreover, as we are interested in the transmission of technological change, we will concentrate on the diffusion of process technologies. It should be noted, however, that a process technology, which is used to produce consumer goods, for instance, is in fact a product innovation of the capital-producing sector. In general,

41. They compare their model with VINSEC, cf. Central Planning Bureau (1987), and with the HERMES model, cf. Italianer (1984).

the difference between process and product innovations is not very clear, although studies of the diffusion of process technologies are initially demand-based, while those on product innovations have mainly focused on supply-side effects as being a natural starting point. In more years, however, the research into adoption and diffusion has tended to integrate both, the demand and supply side. In this thesis, we will consider process innovations mainly from the viewpoint of the users of new technologies.

The diffusion process can be studied on several different levels. First the use of an innovation within a firm, measured in terms of inputs, or in terms of the output produced using that technology. This type is called inter-firm diffusion. Another level is intra-firm diffusion, the number of firms using an innovation is considered.[42] The distinction between intra- and inter-firm diffusion disappears if one is interested in the utilisation of a process innovation in terms of cumulative amount of investment or in terms of productive capacity at an aggregate level. In that case, the distinction is only important from the theoretical point of view.

This section will review some studies on the diffusion of process innovations. The next sub-section will summarize some results of the empirical research and put forward some ‘stylized facts’ within the field of adoption and diffusion of new technologies. Subsequently, we will introduce some preliminary and commonly used concepts of adoption and diffusion. The main part of this section is devoted to different demand-based models. Without intending to be complete, we will discuss some different approaches within this field.[43] It is argued by many authors that the supply side cannot be ignored if one wants to explain adoption and diffusion phenomena. A short overview of the supply side is provided in section 2.3.4. Finally, section 2.3.5 presents a concluding summary of the models on the adoption and diffusion of new process technologies.

2.3.1 Some Empirical Facts

Since the pioneering work of Griliches (1957) and Mansfield (1961), there has been a drastic increase in the number of studies on the adoption and diffusion of new process innovations. From the data, mostly collected by surveys, several, more general, conclusions can be drawn. A large number of process innovations are reviewed in the studies of Mansfield (1968b), Nabseth and Ray (1974) and Davies (1979), among others. The common findings are as follows:

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42. International adoption and diffusion is another possible level. However, this international dimension falls outside the scope of this thesis and will be ignored.

43. The reader is referred to the excellent overviews of Stoneman (1983 and 1991), Feder, Just and Zilberman (1984), Thirtle and Ruttan (1987) and Metcalfe (1988), to mention just a few.

- A considerable amount of time passes between the date at which the innovation is adopted for the first time and the date at which the last firm adopts the innovation. In the above-mentioned studies, this time span ranges from about 5 to more than 50 years;
- The ceiling level, or the saturation level, is found to be at a 100% use of the technology in some cases, but is far below that level in most cases;
- The cumulative number of innovations, as well as the cumulative amount of investment in a new process technology, can, in general, be described by S-shaped, or sigmoid, diffusion curves. That is, the number of adoptions, or the corresponding amount of investment, per unit of time increases in the first stage of the diffusion process and decreases afterwards;
- It often happens that different firms invest in different technologies at the same point in time.

Studies of adoption and diffusion try to underpin these common findings. In general, diffusion studies try to explain the diffusion pattern in which the speed of diffusion is related to characteristics of the innovation, i.e., diffusion processes are studied at an aggregate level whereas adoption theories try to characterize the decisions of potential adopters. Of course, both are directly related to each other but the distinction between diffusion and adoption theories is, in this context, comparable to the distinction between macro and micro economic approaches to economic issues.

In the next section, we will review some ideas and finding of the literature on diffusion of new technologies followed by an overview of different theories on adoption of new technologies.

2.3.2 The Spread of Innovations: Some Preliminary Concepts

The first studies on the diffusion on innovations (Griliches, 1957 and Mansfield, 1961) rest upon the idea that information about the existence of an innovation will spread through personal contact between non-users and users. It is assumed that a non-user will become a user if he/she is informed about the existence of the new technology. This section will give a brief introduction to this type of diffusion models.[44] The reason for this is twofold. First, I think it is a good starting point to obtain some insights into the modelling of diffusion processes. Secondly, this short overview will clarify the stringent restrictions of this model.
The assumptions underlying the derivation of a purely logistic curve are:

- The number of adopters (firms, consumers) is assumed to be constant in time;

44. This section draws mainly on Mahajan and Peterson (1985) and on Gomulka (1990).

- Contact is the only way information can be transferred and it is assumed that the frequency of contact between any two (potential) users is constant. Note that a potential user can be a user or a non-user. If the number of users is small compared to the number of potential users, the change of a user meeting a non-user will be large. On the other hand, if the relative amount of users is fairly large, the probability of a contact between a user and a non-user will be small, and will approach zero as the number of users becomes equal to the number of potential users. This is the main mechanism of the diffusion process.
- The probability that information will be transferred if a non-user has contact with a user is constant in time. The information itself does not change either.
- The characteristics of the innovation do not change over time;
- If an agent adopts the innovation, he/she will be a user for ever, or at least until the end of the diffusion process.

The diffusion curve can be easily derived from these assumptions. If N_t denotes the number of users at time t, and $\bar{N}$ is the total number of potential users, the number of adoptions per unit of time is equal to:

$$\frac{dN_t}{dt} = \alpha N_t(\bar{N} - N_t) \tag{2.10}$$

where the number of adoptions is equal to the probability that information is transferred (α) times the probability that there is contact between the user and the non-user ($N_t(\bar{N} - N_t)$). Solving this differential equation by integration yields the logistic diffusion curve:

$$N_t = \frac{\bar{N}}{1 + e^{-(\alpha t + \beta)}} \tag{2.11}$$

where β is a constant of integration, which is defined by the number of users at time zero. In the above equation, it is assumed that every non-user will adopt the technology as soon as he/she is informed about its existence. A slightly different interpretation is that the probability of adoption, if the non-user is informed about the technology, is constant in time, but not necessarily equal to one. The constant α is then defined as the probability that information is transferred times the probability of adoption once the information is actually transferred.

The logistic diffusion curve is symmetric around the point of inflection, and the point of inflection is fixed. A closely related diffusion curve is the Gompertz curve in which the number of adoptions per unit of time is defined as:

$$\frac{dN_t}{dt} = \alpha N_t\left(\ln(\bar{N}) - \ln(N_t)\right) \tag{2.12}$$

The resulting diffusion curve is skewed to the right and the point of inflection is reached if about 37% of the potential users adopted the technology.

Because the information is transferred between the potential users, this model is often called an ‘internal’ influence model, which rests upon the imitation behaviour of (economic) agents. The above-mentioned diffusion curves assume that there are some initial users. If nobody adopted the technology before, there is no information to transfer and nobody will ever learn about the technology. In contrast, the ‘external’ influence model is built on the assumption that all information is spread from an external source, e.g., the suppliers of new technologies, the government, etc. In mathematical terms, the term αN_t in equation (2.10) is replaced by a variable which denotes the effect of the external information. However, the resulting diffusion curve is concave at every point in time. It should be clear that external influence models are particularly useful in marketing studies to measure the effect of advertisement activities. Finally, a combination of both models gives a mixed influence model which results in a generalized logistic diffusion pattern.[45]

The ceiling level of the logistic diffusion curve is reached if all firms adopted the technology, which is often denoted as the saturation level. This is in contrast with the equilibrium view of the ceiling level. In the latter view, the end of the diffusion process in determined by economic factors such as profitability or firm size. For instance, in the case of indivisible technologies or considerable scale effects due to, for instance, learning-by-doing, some firms are too small to make such investment profitable so that they will never adopt an innovation. The saturation view implicitly assumes that it is profitable for all firms to adopt an innovation.

The above-mentioned assumptions which underlie the purely logistic diffusion curve are rather restrictive. The facts that information is only transferred by users to non-users and that the profitability of an innovation does not change over time are considered by many authors as being unrealistic assumptions in a dynamic world. There are no differences between firms, firms do not behave strategically and there is no risk or uncertainty. Furthermore, since there are no supply-side considerations, the price of new technologies and/or capacity shortages at the supply side are not accounted for. These shortcomings resulted in several attempts to obtain a better understanding of the nature and the motives of adoption and diffusion of new technologies. The next two sections will briefly go into these studies, starting with the demand-based theories.

2.3.3 Demand-Based Theories on Adoption and Diffusion

This section provides a brief review of the demand-based theories on the adoption and diffusion of innovations.[46] Although there are other ways to explain this field

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45. The reader is referred to Mahajan and Peterson (1985) and the literature referred to there.

46. This section draws heavily on the reviews of Stoneman (1983), Stoneman (1991) and Gomulka (1990). Another interesting, and more evolutionary based, review is given by Metcalfe (1988).

of research, I have chosen to use a more or less chronological order. The first attempts are referred to as the epidemic approach, in which the work of, for example, Griliches, Mansfield and Romeo are viewed as the most important contributions. One of the main drawbacks of this approach is that it is not based on decision-theoretical foundations. Such foundations are introduced by the probit approaches of Davies and David, which are briefly discussed in the second subsection. A vast amount of research has been conducted in the areas of risk, uncertainty, information and learning. This literature will be reviewed in the third subsection. Another direction of research within this field is the game-theoretic or strategic approach. Although this direction of research is interesting and the methods employed show a great variety, we only refer the reader to the original work of Reinganum (1981a, 1981b, 1983) and Grindley (1986, 1988) and to the (very) condensed overviews in Gomulka (1990) and Stoneman (1991).

Epidemic Approaches

The celebrated work of Griliches (1957) and Mansfield (1961) are the first studies in the economic literature in the field of adoption and diffusion of new technologies.[47] First, we will briefly present the pure epidemic approach of Griliches and give a more detailed description of Manfield's contribution.

In his PhD thesis, and particularly in his 1957 article, Griliches tries to find economic explanations for the differences in the rate of adoption of hybrid corn between several states within the US. He uses the log form of the logistic curve and is able to estimate the date of origin and the slope, or rate of acceptance, of the diffusion curve for several states.[48] Differences in the dates of introduction are attributed to supply-side effects, that is, differences in the dates on which the hybrid seed became available in the (local) markets. Differences in the rate of acceptance are attributed to differences in profitability. The more profitable the new technology is, the steeper will be the diffusion curve. This hypothesis was tested and confirmed in the study of Griliches.[49]

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47. The concept of diffusion has a longer tradition in other sciences, such as sociology, epidemiology and geography, but these go beyond the scope of this thesis.

48. The form used by Griliches can be obtained by taking logarithms of equation (2.11):

$$\ln\left(\frac{N_t}{\bar{N} - N_t}\right) = \alpha t + \beta$$

The ceiling level ($\bar{N}$) is determined by *"plotting the percentage planted to hybrid seed on logistic graph paper and varying $\bar{N}$ until the resulting graph approximated a straight line"* (Griliches, 1957:504, our notation).

49. Dixon (1980) revisits the analysis of Griliches by using other (econometric) techniques and longer time series. From the latter, Dixon was able to conclude that the ceiling level as predicted by Griliches was not very accurate. However, the main conclusion that the rate of acceptance depends on the profitability is confirmed.

Another important contribution to the theory of technological change is Mansfield (1961, 1968b). In his 1968 book, Mansfield presents two models, or in fact two different versions of the same model: an inter-firm and an intra-firm diffusion model. The way in which information enters the model is the fundamental difference between the two models. The source of information is external to the firm in the inter-firm diffusion model and internal to the firm in the intra-firm model. The inter-firm model is presented in a deterministic version — which we will discuss here — and a stochastic version. Let n_t be the proportion of firms that do not use the innovation at time t, but that will invest in the innovation at time $t+1$, and let, as before, $\bar{N}$ be the total number of firms and N_t the number of firms using the new technology. n_t is defined as:

$$n_t = \frac{N_{t+1} - N_t}{\bar{N} - N_t} \tag{2.13}$$

or, as a differential equation:

$$\frac{dN_t}{dt} = n_t(\bar{N} - N_t) \tag{2.14}$$

Mansfield assumes that n_t depends (i) on the proportion of firms that already introduced the innovation ($N_t / \bar{N}$), (ii) on the profitability of the innovation (π_t), (iii) on the size of the investment required to install it (I_t), and (iv) on further, unspecified variables. The proportion of firms that already installed the innovation is used as a measure of risk accompanying the introduction of this technology. Furthermore, competitive pressures increase and bandwagon effects occur if more firms already adopted the innovation. The size of the investment is used to model the fact that for a given profitability, it is more difficult to finance larger investments than it is for smaller ones. The unspecified variable is introduced to capture differences between industries, such as different market structures. Mansfield continues by assuming that the variable n_t can be approximated by a Taylor expansion in which the third and higher order terms drop out. After some rearrangements, Mansfield derives the diffusion curve:

$$N_t = \frac{\bar{N}}{1 + e^{-(\phi_t t + \eta)}} \tag{2.15}$$

in which η is a constant of integration. The rate of adoption (ϕ_t) depends on profitability, the size of the investment and an error term.

This logistic curve is estimated by Mansfield for four different industries and it contains twelve different innovations. He first estimates values of the rate of adoption and correlates this estimate with the profitability and the size of the investment. Furthermore, he adds several additional factors to include other variables which may be important. The main conclusions are that the profitability of an innovation is highly significant (t-values ranging from about 15 to about 35 if different additional factors are included) with the expected positive sign, and that the size of investment is negative, as expected, but less significant (t-values ranging from 1.3 to 1.9).

The Mansfield approach is criticised by several authors. Davies (1979) for example states that *"To all intents then, this model is merely an (ingenious) application of the simple epidemic model: 'uninfected' firms (non-adopters) are more likely to 'catch the disease' (adopt), the more of their competitors that are already infected (having adopted); the 'infectiousness' of the innovation is determined by its financial characteristics (profitability and cost)"* (Davies, 1979:15).

The model does not explain the question why some firms adopt an innovation more quickly than others. Although it is not based on a decision-theoretical background, this does not imply that the model is not relevant. If one is interested in diffusion at the aggregate level, or in the implications of diffusion for other macroeconomic variables, Mansfield's model is very attractive because of its simplicity. It confirms (or is based on) the main findings that the diffusion curve is S-shaped, and that, due to differences in for instance the profitability and the size of investment, the speed of diffusion differs between several innovations and/or industries. Both Griliches and Mansfield show that in particular the profitability of the innovation relative to the profitability of the alternative is found to be an important factor in the explanation of the speed of diffusion.

Besides profitability and size of investment, the intra-firm version of the model of Mansfield includes uncertainty and the liquidity of the firm as explanatory variables. The lines along which the model is developed are similar to those in the inter-firm model. It results in an internal diffusion pattern in which the proportion of the (number of) inputs which are based on the new technology, increases along a S-shaped diffusion curve.[50]

The epidemic approach is used by many authors to examine intra- or inter-firm diffusion. Romeo (1975), for instance, uses the same model as Mansfield but assumes that the rate of diffusion depends on several variables, such as expected profitability, number of firms in the industry, firm size, R&D expenditures, in a multiplicative way. The derivation of equation (2.15), the logistic in Mansfield's model, does hold for a linear form only, however, which implies that Romeo assumes that diffusion patterns can be described by a logistic curve. From the diffusion of numerically controlled machine tools in ten different industries, Romeo concludes that all variables mentioned above are significant when explaining differences in the rate of adoption between industries.

Finally, in a broad inter-country approach, Nabseth and Ray (1974) brought a large number of different studies together. Although each research group used different approaches, the common starting point is the epidemic model. In the final

50. In his empirical part, Mansfield uses the number of diesel locomotives, that replace the steam-driven ones, in several US railway companies.

conclusions, Nabseth and Ray summarize the main findings. The speed of diffusion is affected by (i) first information — there are considerable differences between countries with respect to the dates at which information about a technology becomes available — (ii) profitability, (iii) institutional circumstances, such as the nationalization and denationalization of the British steel industry, (iv) management attitudes, and (v) other economic variables. In my opinion, this study gives very broad support to the idea that the speed of diffusion is affected by variables such as profitability. However, it does not explain why some firms will adopt a technology sooner than others or why some firms adopt it more slowly than others. The next sections are devoted to more theoretical approaches which try to get a better understanding of these underlying relationships.

The Probit Approach

Both the models of David (1969) and Davies (1979) are based on the probit, or threshold value, approach, and focus on finding theories which can explain the empirical fact that some firms will adopt an innovation earlier than others. The decision to adopt or not to adopt an innovation depends on the characteristics of the firm as well as on the characteristics of the innovation. Furthermore, David and Davies require that their models be able to result in an S-shaped diffusion path.

David defines firm size as the crucial variable and he argues that firms are log-normally distributed with respect to their size. In the derivation of the critical firm size, he assumes that the new technology is indivisible and that technological progress is purely labour-saving. This implies that, in order to increase profits by switching to a new technology, a firm must be large to the extent that additional capital costs are smaller than, or at most equal to, the gains which results from decreasing labour costs. These gains are defined as the amount of output, times the wage rate, times the difference in labour inputs between producing with the old and with the new technology. The critical firm size is derived by equating costs and gains, and depends on the inverse of the wage rate and on the price on the new technology. Thus, in terms of Figure 2.6, the firms whose size exceeds the critical size will adopt the innovation and firms which are smaller than the critical size will not. New adoptions can occur by either a shift of the critical size to the left, or a shift of the distribution to the right, or both. Assume that the distribution does not move and that the wage rate rises relative to the capital costs. This implies that the critical firm size decreases over time. If the critical size decreases linearly in time, that is, if the critical line moves to the left at a constant speed, the number of adoptions at each point in time will be equal to the distribution of firm sizes. In that case, a symmetric distribution would lead to a symmetric diffusion curve. On

the other hand, the diffusion curve will be skewed with respect to the distribution of firms if the critical size does not move at a constant speed.[51]
David assumes that the wage rate rises and that the prices of capital goods remain the same. This implies that the critical firm size declines in the course of time so that the diffusion process continues until the smallest firm adopts the technology.

Whereas the model of David does not specify firm behaviour in detail, it relies very much on the assumption that firms will adopt an innovation as soon as the critical firm size becomes equal to the size of the firm. Davies (1979) treats the decision process more explicitly. Like David, he assumes that all firms are aware of the existence of the technology as soon as it become available on the market. He argues furthermore that a firm will invest in a new technology if the actual (expected) pay-back period (PBP) of that innovation is equal to or below an acceptable pay-back period (PBP^*). The pay-back period is, in Davies view, a measure of the profitability of an innovation. Both the actual and the acceptable pay-back period depend on firm as well as on non-firm-specific characteristics, in which the size of the firm is a crucial variable. Broadly speaking, Davies argues that firms are lognormally distributed with respect to their size and that the critical firm size, and consequently the acceptable pay-back period, decreases in time due to improvements of the innovation and due to reduction of the risk of adopting the new technology. This leads to S-shaped diffusion curves.[52]

Davies tested his model using a sample of twenty-two innovations and he finds, not surprisingly, that firm size is indeed an important factor when explaining of the decision to adopt an innovation. Furthermore, Davies finds that the speed of diffusion depends negatively on the number of firms in the industry, which is more or less consistent with the relation between firm size and speed of diffusion. This implies that firms will adopt a technology sooner if the market is less competitive. The size of the firm is, in the views of both David and Davies, an important factor when determining of the moment at which a firm will adopt a new technology.

Nevertheless, this finding is not generally supported. Oster (1982), for example, finds that larger firms innovate later than smaller ones in the US steel industry. The more theoretically oriented studies on the relation between market structure and innovations support both views.[53] Schumpeter (1942) argues that monopolistic

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51. David assumes that the wage rate increases exponentially. This implies that the critical firm size, which depends on the inverse of the wage rate, decreases at a decreasing rate. In other words, the critical size moves to the right with decreasing step sizes. The lognormal distribution of firm sizes will be transformed in a cumulative normal diffusion curve in this case.

52. The model of Davies is much richer than presented in this paragraph. In addition to the original work, see Stoneman (1983) for a more complete overview. Furthermore, Davies extends his model by allowing for industry growth and for changes in the industry structure.

53. Note that these theories are not directly concerned with adoption and diffusion. But the arguments could be extended in this direction.

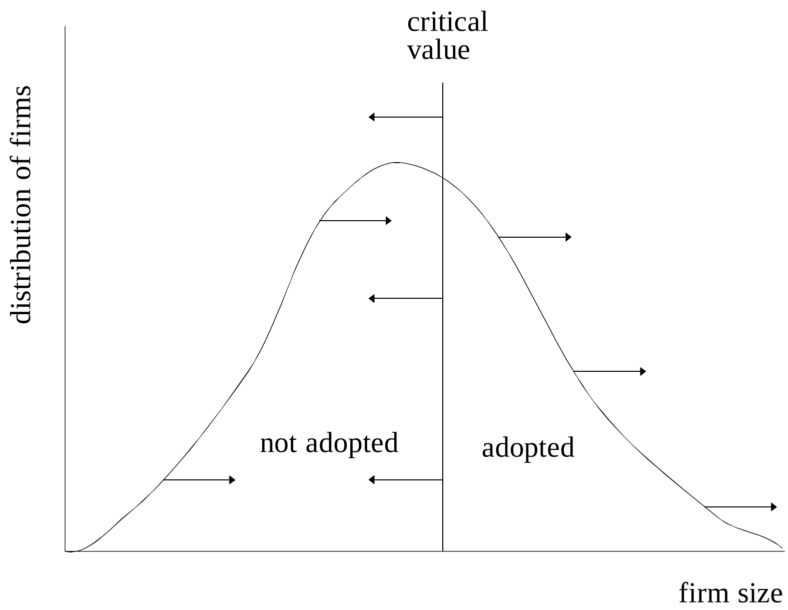

Figure 2.6. The stylized probit model

profits are needed to finance R&D expenditures which implies that large companies innovate faster. Fellner (1951), however, argues that the gains from a process innovation are larger if the market is more competitive. This implies that firms will innovate faster in a competitive market.[54] Scherer's theory can be located between Schumpeter and Fellner, and he, Scherer, argues that the optimal introduction time to adopt an innovation is the smallest in intermediate market structures. This implies that neither the theoretical nor the empirical studies give a univocal answer to the question as to whether it's large or small firms that will adopt a technology faster. Without providing conclusive evidence, the above-mentioned studies as well as the findings of for example Mansfield (1968) tend to support the vision that larger firms will innovate faster.

Before concluding this section, we would like to mention the role of expectations. Studies like Rosenberg (1976), David and Olsen (1984) and Balcer and Lippman (1984) are particularly concerned with the technological expectations of firms. If firms expect technologies to become more productive in the (near) future or expect prices to fall, they may increase expected profits by postponing the investment decision. This argument can be included in the probit approach so that differences in expectations can lead to different points in times at which firms will adopt a technology. The expectations of future prices of new technologies depend, among other things, on the price-setting behaviour of the supplying industry. The above-

54. Fellner's argument can be summarized as follows. The marginal returns are downward sloping in a monopolistic market whereas they are horizontal in a competitive market. The marginal costs are upward sloping and will shift to the right due to a process innovation. The price of output will fall in the monopolistic market while it will remain the same in the case of competition. This implies that the gains increase in both cases but the increase is larger in the competitive market.

mentioned expectation-oriented studies are closely related with supply-side models, which are discussed in section 2.3.4. Other approaches are more concerned with uncertainty and the way information enters the model. The next section will review some of the studies conducted within this field of research.

Uncertainty and Learning

One of the main criticisms concerning the approaches of David and Davies is that uncertainty and learning are not adequately incorporated in the models.[55] It is argued, and confirmed by many survey studies, that uncertainty plays a major role in the adoption decisions of firms. This section will review some studies in which the adoption depends on uncertainty and on the reduction of uncertainty through learning. Although this approach can be used to explain both intra- and inter-firm diffusion, we will concentrate on the intra-firm diffusion model of Stoneman (1981). As we have done previously, we will not go into details but will just summarize the main arguments.

Stoneman assumes that firms are uncertain about the profitability of a new technology. Initially, they produce with an old technology with a known mean and variance of the profitability.[56] The central question is at which speed firms will adopt the new technology, if they adopt at all. Firms are assumed to learn about the actual performance of a new technology in a Bayesian manner, that is, they have a prior belief about the mean and the variance of the profitability of a new technology. By installing a (small) unit of this technology, they can gather information about the actual performance so as to update their prior belief. A central assumption is that profitabilities are always subject to some variation. This implies that the posterior expectations are still denoted in terms of expected mean and variance. Furthermore, Stoneman tries to find some connection with the (standard) investment theory by introducing adjustment costs in his model. He assumes that these costs depend on the change in the relative amount of output produced by the new technology (α_t). Firms are assumed to maximize expected utility which depends positively on the mean and negatively on the variance[57] and on the adjustment costs. By assuming myopic behaviour with respect to the future, Stoneman derives an intra-firm diffusion curve by maximizing the utility function. He shows that the diffusion curve is S-shaped, in fact logistic, if there is no learning at all, i.e., if the mean of the expected returns is known. The adjustment cost function has two properties: (i) for a given α_{t-1}, the adjustment costs increase at an increasing rate

55. Although learning affects the acceptable pay-back period in the model of Davies, the learning mechanism is not explicitly defined.

56. This assumption is not necessary to obtain sigmoid diffusion paths but it simplifies the analysis to a large extent.

57. In fact, this mean/variance approach stems from a constant absolute risk aversion (CARA) utility function. See chapter 5 of this thesis.

with the change of $\alpha_t - \alpha_{t-1}$; and (ii) the adjustment costs decrease for a given change of $\alpha_t - \alpha_{t-1}$ if the level of past usage (α_{t-1}) increases. The first property is common within the theory on investment whereas Stoneman argues that the greater the proportion of the new technology in total production is, the more experience a firm has and the less costly adjustment is. In appendix 2B, we show that this second property is crucial in order to obtain a sigmoid diffusion path. If the adjustment costs function inhibits the first property only, the diffusion path will be concave as is shown in the appendix. Stoneman validates the use of adjustment costs by referring to the investment theory literature, and to the work of Nickell (1978) in particular, in which the adjustment costs functions do not, however, incorporate the second property. The results of Stoneman can therefore be seen as a more special case.

Finally, Stoneman shows that the diffusion curve is likely to be S-shaped in the case of learning, that is if the expected mean returns are updated according to the Bayesian learning rules.[58] If the expected returns on the new technology exceed the actual returns, a firm would overinvest in this new technology. Stoneman argues that it is not likely that a firm would reverse this investment decision once it becomes aware of the actual returns. In the decision to revert, the firm should compare total costs and returns on the old technology with variable costs and returns on the new technology. Although this is true, it does not ensure that such situations do not occur. It is plausible that adjustment costs of reverting the investment decision, i.e., investing in the old technology again, will be less high than in the case of replacing the old by the new technology — in other words, the adjustment function is likely to be asymmetric. If this is the case, and if the investment decision is reverted, the adoption path will no longer be S-shaped and Stoneman's arguments are less general. Furthermore, if there is some overshooting whereby reversion is not profitable, the firm will not invest in the new technology until its profitability increases, relative to the profitability of the old technology. This implies that the diffusion path is horizontal for some time. Moreover, it is not clear at all why firms tend to be pessimistic in making their first guess about the profitability of the new technology, that is, it is not clear why the case of overshooting is an exceptional one.

The main conclusions of Stoneman's analysis are that (i) intra-firm diffusion can be obtained by the introduction of uncertainty and learning; (ii) adjustment costs can lead to S-shaped diffusion paths if they take a special form; (iii) the speed of diffusion depends on the prior beliefs of the firm; (iv) it is possible that some firms will never adopt a new technology even if this is more profitable on average, namely if their prior beliefs are pessimistic; on the other hand, overshooting can occur if firms are too optimistic so that further investment in the new technology is

58. The proof of these results cannot easily be summarized. The reader is referred to the original work of Stoneman (1981).

delayed or even reversed; (v) the speed of diffusion depends on the risk aversion of firms, and finally (vi) the firm will always become less uncertain about the ‘true’ mean by learning in a Bayesian way, but the mean itself can increase or decrease, depending on the expected profitability relative to the actual one. Note that two (related) properties of this model have some connection with vintage models. First, it shows that investment in the new technology replaces the old technology and secondly, the old technology is only replaced by the new technology if the returns minus the total costs on the new technology exceed the variable costs of the old one, i.e., if the Malcomson condition holds.

Tsur et al. (1990) extend the model of Stoneman by incorporating dynamic factors in their model. They are especially concerned with expectations on future prices of innovations and on learning-by-doing effects in the sense of Arrow (1962). Learning-by-doing differs from Bayesian learning as modelled by Stoneman in that the actual profitability is affected by learning whereas learning affects only the expected profitability in the model of Stoneman. Furthermore, they introduce a fourth type of learning in adoption models which is originated by Stiglitz (1987): learning to learn. This reflects a positive relation between the ability to process information and the stock of knowledge.

Finally, Kim et al. (1992), present a model in which there exists general uncertainty about future output prices. In their agriculture-based model, they assume that two different technologies are introduced at the same point in time. One technology is characterized as being yield-increasing (per acre land) whereas the other is cost-reducing (same yield per acre but less variable inputs). The yield-increasing technology can be characterized as being factor-using technological change, while the other is factor-augmenting in nature. They assume that firms maximize end-of-harvest wealth and behave in a myopic manner. The output price is the only random variable, and they show that an increase in the price variability increases the use of the factor-saving technology at the expense of the yield-increasing technology. An S-shaped diffusion path is obtained by assuming adjustment costs à la Stoneman. The main conclusion is that the speed of adoption of a certain technology can be influenced by governmental price stabilization policies. A similar approach, also applied in an agricultural setting, is given by Just and Zilberman (1983, 1988). They assume aggregate labour supply uncertainty which is transformed into wage rate and output price uncertainties. They show that if the wages become more uncertain, firms will invest in labour-saving technologies if the final demand is elastic. This is not necessarily the case if the demand is inelastic.

To summarize, we have seen several approaches and definitions of uncertainty and learning. Apart from the learning to learn variant of Tsur et al., learning appears in three different ways: (i) gathering information on the existence of a technology, (ii) learning about the actual performance of a technology, and (iii) learning how to use a new production process. The first type of learning is introduced in the seminal work of Griliches (1957) and afterwards extended by

Mansfield (1968) and Davies (1979) and is a typical inter-firm explanation. The second type of learning is closely related with uncertainty and can explain both intra- and inter-firm diffusion, depending on whether the information comes from an internal or external source, respectively. Above, we reviewed the analysis of Stoneman (1981) in the case of intra-firm diffusion. Studies like Mansfield (1968), Jensen (1982) and Reinganum (1983) use this type of learning to explain inter-firm diffusion. Learning as a cost-reducing or productivity-increasing mechanism is introduced by Arrow (1962) and is used in an adoption and diffusion setting by Tsur et al. (1990), for instance.

The second topic, uncertainty, can be viewed in two different ways: uncertainty about the (technical) performance of a new technology or uncertainty with respect to wages, output, output prices, etc. Almost all authors mentioned above implement the first type of uncertainty. As firms are assumed to be averse to risk, and production with new technology is more uncertain than production with an old and well-known technology, less risk-averse firms will invest sooner and / or more in the new technology than others. Or, on the other hand, if firms can learn about the characteristics of the technology, they can invest a small amount in it initially, learn from that and revise their investment decisions according to their new beliefs about the performance of the new technology (Stoneman, 1981, Tsur et al., 1990). The second type of non-technology-specific uncertainty is used, for instance, by Just and Zilberman (1983) and by Kim et al. (1992).

Finally, Stoneman (1981) introduces a connection between theories of adoption and the investment literature. New technologies replace older ones if the Malcomson condition holds.

2.3.4 Demand and Supply

Many authors have noted that adoption and diffusion of new technologies cannot solely be the result of demand-side effects, and it is often argued that the supply-side deserves more attention. At the theoretical level, there are some contributions in this field, but these are not empirical. The work on the supply side concentrates mainly on the price-setting behaviour of suppliers of an innovation, including differences in market structures, and on the generation of new technologies and capacity constraints. Stoneman (1991) lists five topics which are related with the modelling of the supply side: (i) the time structure of the supply industry’s costs, (ii) the output capacity of the suppliers, (iii) the number of suppliers, (iv) the price and quantity-setting behaviour, and (v) the nature of market interactions between demand and supply. This section is restricted to a brief discussion of the model of Metcalfe (1981), which is more evolutionary oriented, and of the model of Stoneman and Ireland (1983).

Metcalfe is especially concerned with the output capacity of a supplying industry. The demand for an innovation is modelled by a logistic function in which the equilibrium market demand, which is comparable with the potential number of adopters in the epidemic diffusion function, depends on the price of the technology. The rate of adoption is assumed to be constant. Thus, if the price of the innovation falls, the equilibrium demand will increase and the potential adopters will buy the innovation according to a logistic pattern. The supply side is typically Keynesian in nature, i.e., the amount of investment depends on the profit rate. The profit rate is, of course, positively related with the price of output and negatively with the variable costs, a composition of wages and prices of raw material. Furthermore, Metcalfe assumes, without further argumentation, that the price of the composite input is positively related with the amount of output, which implies that the rate of return decreases as the scale of production increases. Assuming equilibrium between the growth rate of the demand and the growth rate of supply, Metcalfe derives an S-shaped diffusion pattern. If there are post-innovation improvements, the demand curve will shift upwards due to decreasing output prices, which yields a positively skewed curve. Note that the increase in input prices, as output increases, is needed in order for the profits, and consequently the rate of investment, to fall at the end of the diffusion curve. That is, this relationship is needed to obtain an S-shaped diffusion path. Stoneman (1983) criticizes Metcalfe on two points: (i) there is no explicit consideration of the rational behaviour of firms, and (ii) the assumption of the positive relation between prices of composite inputs and output is not really supported by empirical analysis. The first objection depends on the question as to whether an economic theory should be based on rational behaviour. It is clear that evolutionary oriented economics is based on rules of thumb or satisfying behaviour rather than on optimizing or maximizing behaviour. With respect to the second objection, Stoneman suggests the introduction of learning economies in the supplying industry to overcome this problem, but in general, learning economies would increase productivity so that profits will increase as output increases, and not decrease, which is needed to obtain the S-shaped diffusion path. I simply cannot see why Stoneman’s suggestion would overcome this problem. However, although we support the second objection and although the study of Metcalfe is limited to one supplier and to one innovation, it is one of the first attempts in the diffusion literature to model supply-side constraints.

In contrast to Metcalfe’s ideas, the model of Stoneman and Ireland (1983) is based on optimizing behaviour. It basically comes in two versions: a monopolistic supplier and an oligopolistic market at the supply side in which each firm selects its optimal path, given the paths of the competitors which are also optimal and correctly anticipated. The monopolistic case can be solved analytically whereas only steady-state solutions can be obtained in the oligopolistic case. The arguments in the monopolistic case are as follows. The demand is given by a probit model as discussed above, in which the critical size is determined by the price of the innovation which is set by the supplier. There are no other forces, i.e. wages are constant, so that the question as to whether to adopt the technology is determined by its price. If the price is high, only a few firms will adopt the technology but as the price decreases, more firms will follow. This leads to the conclusion that the price of the technology will always decrease in time, otherwise, no other firm would buy the innovation. The production costs of the supplier are characterized by learning economies and a minimal optimal scale (MOS) of production. If there is no impatience, i.e., if the discount factor of the supplier is zero, the firm will operate at the MOS so that the amount of output is constant in time, i.e., there are no sigmoid diffusion path. If the discount factor is above zero, the output depends on the learning curve. Early production is attractive now because of the discount rate, but on the other hand, if the costs of production fall with cumulative output, production at a small scale, and therefore over a longer period, is attractive from that point of view. A combination of arguments leads to an output path whose characteristics depend on the learning curve. Stoneman and Ireland show that the diffusion curve is S-shaped when the learning curve is S-shaped. The general conclusion is that the diffusion process is completely endogenized in this model, but that an S-shaped diffusion pattern requires a very special form of the learning curve. Moreover, the model disregards capital goods in the supplying industry, which implies that there are no investment decisions to be made and that there are no capacity problems. Furthermore, it is assumed that each firm buys the innovations only once, and it buys only one unit. If the price of the innovation falls, it is likely that firms will decide to invest more units, for instance, so that this assumption is rather unrealistic. Finally, price changes are infinitely small, thus creating perfect intertemporal price discrimination. This implies that the critical size moves continuously, meaning that all adopters buy the technology at the maximum price they are willing to pay. This is rather unrealistic.

2.3.5 Concluding Summary

From this limited overview of the literature on adoption and diffusion of process innovations, we can draw the following conclusions:

The epidemic models are able to capture diffusion processes very well and show that the expected profitability of a technology has major impacts on the speed of diffusion. The rate of adoption is found to be positively related with the size of the firm in some studies, but this hypothesis is not univocally confirmed. However, the epidemic approach is criticized because of its lack of a decision-theoretical basis. Furthermore, it does not explain the shape of the diffusion curve. Moreover, the purely logistic function does not allow for post-diffusion improvements of the technology, and it is assumed that the number of potential adopters is constant in time and that the group of adopters is homogeneous.

The adoption theories try to explain why some firms invest sooner and / or more rapidly in a new technology than others. An S-shaped diffusion pattern should be the result of the model, not the proposition. The adoption studies discussed are the probit models and models on uncertainty and learning.

The probit models put forward by David and Davies introduce a description of firm behaviour in order to explain diffusion phenomena. The size of the firm is taken as the critical value, but it is not clear at all that increasing returns to scale or indivisibilities are present in all economic sectors. Risk and uncertainty, as well as learning, are taken into account very implicitly in these models. The resulting diffusion patterns rely very much on the distribution of firms with respect to their size.

The last demand-based models of this overview are concerned with learning, risk and uncertainty. There are several different connotations of learning and uncertainty. The model of Stoneman incorporates technology-specific uncertainty which is directly related with learning about the true characteristics of a technology. Learning in the sense of Arrow is used by Tsur et al., for instance, in addition to the Stoneman type of learning and learning-to-learn capabilities. One of the main criticisms of these models is the lack of investment-theoretical considerations, in which the model of Stoneman is a notable exception. Furthermore, total firm output is given exogenously and therefore not influenced by adoption decisions.

Finally, many authors express their concern about the lack of supply-side considerations. Although some attempts have been made in the past, it is still a relatively unexplored field. Recalling the five topics which are related to the supply side, and the difficulties which arise from them, gives at least an indication of the question why little has been done in this field. Although the model of Stoneman and Ireland can be criticised on several grounds, it is, in my opinion, a fruitful direction for further research.

With respect to the explanation of the productivity slowdown, we already mentioned the work of David (1991). The speed of diffusion slows down if the incentives to adopt a new technology decrease. There can be several sources for such a decrease: for instance, if uncertainty, both technology-specific and non-specific uncertainty, increases or if differences between technologies become smaller, for instance due to smaller differences with respect to profitability. It is obvious that the growth rate of labour productivity will decline if the rate of adoption of new technologies decreases. This notion will be used to explain the productivity slowdown within a more general vintage-diffusion framework.

2.4 Differences and Similarities: Outline of the Thesis

Let's go back to the goals, or research questions, of this thesis. The first question is concerned with the introduction of diffusion phenomena in a vintage model, and with determining the importance of such introduction in a macro-economic model. The second question is concerned with the implementation of a model of adoption and diffusion of new technologies in a vintage model at a micro economic level. Keeping in mind the discussion of the previous sections, we will discuss the route along which we will try to answer these questions in this section.

The putty-clay version of the vintage models seems to be the most realistic one, although the clay-clay model has been put to fruitfully use in the past, especially in the Dutch tradition. The ex-post substitutability of factors of input is less realistic in our opinion. Moreover, several studies have shown that the lifetime of equipment decreased in the last decades, and it is highly questionable whether such a decrease is the result of physical deterioration only. Economic scrapping plays an important role, besides the feeling that ex-post substitutability is not in accordance with reality from a more technical point of view. Both arguments are contra a putty-putty approach. The clay-clay approach has the disadvantage that its description of the economy, in particular the demand for labour, is less accurate, as pointed out for instance by Den Hartog (1984). In our opinion, the putty-clay approach is a fruitful compromise between the two. Additionally, studies like Gelauff, Wennekers and de Jong and Muysken and van Zon have shown that the estimation results of such models are encouraging.

We also argued that both models use some rather ad hoc assumptions with respect to the description of technological change. Although vintage models imply a heterogeneous total capital stock, it is assumed that each vintage is homogeneous. This implies that all investment is in the latest type of technology. Previously, we argued in the discussion on models of adoption and diffusion of new technologies that this is not the case. Some firms invest in a new technology while others invest in an older one. The assumption that a vintage is homogeneous contradicts these findings, or to phrase Stoneman *"The vintage model does have some disadvantages, however. For example, it argues that all investment is in the latest type. This has found to be empirically suspect"* (Stoneman, 1983:115). The solution to this contradiction is obvious: combine both vintage models with models of adoption and diffusion so that a vintage contains several technologies. In fact, this implies that the capital stock is divided into several vintages and that vintages are divided into several technologies. Such a model implies that investment can be in the latest type, but also that older technologies will be installed at that moment. The latest vintage is no longer identical to the best-practice technology. This indicates that the hypothesis of Gregory and James (1973) in their article 'Do new factories embody best-practice technology?' should be answered negatively, but this does not answer the question whether or not vintage models are superior to non-vintage models. New firms, i.e., firms with a relatively young capital stock, may invest in relatively old technologies whereas old firms may be very innovative and invest in the latest technology at each point in time. Thus, a comparison of the age of the capital stock with the productivity of the firm does not explain the importance of the embodiment hypothesis, as suggested by Gregory and James.

Although models of adoption and diffusion relax the assumption of the homogeneity of each vintage, they are often modelled in isolation. In other words, general firm decisions about the amount of investment, amount of output, the demand for labour and the like, are missing in these models. Moreover, these models are mostly used to describe the introduction of one or two innovations. The macro-economic aspects of diffusion are ignored.[59] Moreover, these models do not allow for scrapping of technologies in that they describe only the first part of the life cycle of the technologies.[60] The combination of a vintage-type model with a model of adoption and diffusion of new technologies is a possible solution overcoming these shortcomings of the general adoption and diffusion models. The replacement of older technologies by newer ones could be modelled explicitly in such a combined model.

It is clear that vintage models give a more realistic description of the economy in comparison with the aggregated models. On the other hand, models of adoption and diffusion suggest that vintages are not homogeneous, but may contain a number of different technologies. Integrating both ideas leads to a further disintegration of the capital stock. The total capital stock is subdivided into several vintages and each vintages is subdivided into several technologies. This further decomposition of the capital stock is the central issue of this thesis. Furthermore, the transmission of technological change is partly endogenized which implies that changes in productivity growth are affected by changes in the speed of diffusion. If the speed of diffusion would slow down, the impact of embodied technological change on aggregate productivity growth would also slow down. If the analysis of Davies (1991) is correct, we could explain the productivity slowdown by such a combined model.

Now the question arises which type of the adoption or diffusion models discussed above should be incorporated in the vintage model. In fact, this depends on the question which of the research questions should be answered. When answering the first research issue, the macro-economic implications of diffusion in a vintage model, it is obvious that all models presented above are in principle good candidates. The adoption models (probit, learning and uncertainty) rely very much on a decision-theoretical background by assumption. It is highly questionable whether

59. One exception is for instance the model of Soete and Turner (1984). Their model is restricted to the introduction of one new technology but the aggregate amount of investment is explicitly determined by the use of a simple saving function. Furthermore, the model has not been designed for estimation purposes.

60. The model of Stoneman (1981) is a notable exception.

such a model can be introduced in a vintage model so as to result in an estimable macro-economic model. The epidemic-based diffusion models, however, are far more easy to incorporate and describe diffusion processes fairly well, at least at an empirical level. A combined model of a diffusion model and a putty-clay vintage model should be able to capture the main characteristics of the diffusion process in a vintage framework. Thus, in order to answer the macro-oriented issue, we would prefer the diffusion model because of its simplicity and because it describes the general characteristics of the adoption decisions. These models do have some shortcomings, however. One point of criticism, which is put forward by for instance Gold (1981), is that the characteristics of the technology, as well as the characteristics of the (potential) adopters, do not change over time in purely epidemic diffusion models. Moreover, the assumed constancy of the total number of potential adopters is subject to critique. To overcome these problems, we will allow for improvements of existing technologies by allowing for ex-post embodied technological change. Additionally, we will allow for changes in firm characteristics such as changes in wages, rental rates, etc., and we will not determine the total number of potential adopters in advance. Hence, we will not use a logistic function as such, but the general idea of our model still stems from the diffusion literature.

From the discussion of the models of Griliches, Mansfield and Romeo, among others, we can conclude that the profitability of a new technology is an important factor when determining the speed of diffusion. Moreover, from the probit and learning and uncertainty models, it is shown that information also plays a major role in the diffusion process. This implies that, if we combine a epidemic diffusion model with a vintage model and if the speed of diffusion depends on factors like expected profitability and information, we would be able to build a relatively simple model which incorporates the basic ideas and empirical findings of the diffusion literature. Furthermore, if we compare the estimation results with a similar vintage model without a diffusion component, we are able to get an impression of the importance of diffusion phenomena in a macro-economic model. This would answer the first research issue.

Thus, to answer the first question, we will incorporate an epidemic-based diffusion model in a putty-clay vintage structure. Moreover, the rate of adoption will depend on the expected profitability and on the available information about that technology. The expected profitability is reconsidered at each point in time so that the speed of adoption may change during the diffusion process.

Both a non-diffusion putty-clay vintage model and the model in which we introduced an epidemic diffusion curve are presented in Chapter 3. The choice of the initial labour intensity stems from optimizing firm behaviour. Furthermore, in the vintage-diffusion model, it is assumed that a new technology becomes available at the market for investment goods each year. Although some firms will invest in this best-practice technology, the vast majority will invest in older technologies, i.e., in technologies that used to be the best practice some time ago. The distribution of firms with respect to the chosen technology depends on the expected profitability of each technology and on the available information about it. Information is treated as a public good and generated by previous production with that technology. Although the spread of technologies is introduced in this model, the generation of it is left unexplored. This implies that the rates of technological progress of the best-practice technologies are exogenous. Besides this embodied type of technological change, we also allow for its disembodied counterpart.

Chapter 4 will present the estimation results of both models. We will use Dutch annual data of the manufacturing sector and we will estimate the model for the period 1960 to 1988. Next to the discussion of the differences between the two models, we will compare our results with the results of Gelauff, Wennekers and de Jong (1985) and of Muysken and van Zon (1987).[61] Finally, we will shed some light on the development of the labour productivity and we will investigate whether our model is able to describe the productivity slowdown. Moreover, we will investigate the role of diffusion on that development. This concludes the answer to the first research issue and it also completes Part II of this thesis.

Part III will answer the second research issue: the incorporation of models of adoption and diffusion in a vintage model so that the choice of technologies is the result of optimizing firm behaviour. The epidemic models are, in general, not based on optimizing behaviour which implies that they cannot answer this second issue. Moreover, the shape of the diffusion pattern should be the result of the model rather than the postulate. The adoption models are, again in general, based on optimizing behaviour and making the use of such model is a natural starting point to answer the second issue. From the discussion of the literature above, we may conclude that these adoption models include uncertainty, learning and/or supply-side effects.[62]

It is shown that learning can come in three varieties: learning concerning the existence of a technology; learning concerning the actual characteristics of a technology, such as profitability or productivity; and learning how to use a new technology, resulting in higher productivities. Firms can be uncertain about the technology-specific characteristics but also about, more general, non-technology specific aspects. Learning concerning the existence of the technology is the backbone of the epidemic approaches. Learning about the true characteristics of a technology is directly related with the technology-specific uncertainty. If there is no technology-specific uncertainty, nothing can be learned, and learning is only meaningful if it

61. The model of Kuipers and van Zon (1982) is estimated for the period 1950-1977, so that a comparison would make much sense. Cf. Muysken and van Zon (1987) for a comparison of their model with the models of Kuipers and van Zon (1982), Gelauff, Wennekers and de Jong (1985).

62. We already dropped strategic behavioral models and the evolutionary models. Evolutionary models are, in general, not based on optimizing behaviour so that these models cannot answer the second issue.

leads to valuable knowledge, which is not the case in the absence of technology-specific uncertainty. Finally, learning-by-doing in the sense of Arrow so that the productivity increases due to increasing experience, is not related to uncertainty and can be combined with the other types of learning. Non-technology-specific uncertainty can be combined with the Arrow-type of learning.[63]

The literature on the adoption decisions of firms in a uncertain world with learning possibilities relies mainly on technology-specific uncertainty and consequently on learning in the sense that information is gathered about the ‘true’ performance of a production technology. However, it is not clear at all why this type of uncertainty is more important than non-technology-specific uncertainty. It is not unlikely that technology-specific uncertainty is important in the initial stage of the diffusion process, but it is hard to imagine whether this type of uncertainty plays a dominant role during the rest of the diffusion process. Non-technology-specific uncertainty, on the contrary, may play an important role during the whole diffusion process. Firms may not invest, or may invest in a less advanced and less expensive technology, if the future is more uncertain. In other words, if future output prices or future final demand fluctuates, firms may be reluctant to invest in large, or expensive, projects.[64] Moreover, there are abundant studies on technology-specific uncertainty, while the role of non-technology-specific uncertainty is underexposed in the literature on adoption and diffusion of new technologies.[65] As far as I know, there are no surveys to confirm the impact of non-technology-specific uncertainty on adoption decisions of firms. But the same applies to the technology-specific counterpart. Thus, there seems to be no evidence that indicates which of the two plays a more or a less important role. In our micro-oriented model, which should answer the second issue, we introduce the non-technology-specific type of uncertainty.

Chapter 5, the first chapter of Part III, will present the choice of technologies which corresponds to some extent with the model of Davies, i.e., the probit model in which the length of the pay-back period is used as the threshold variable. Davies argues that the pay-back period is a measure of the profitability of an investment. We will use the profitability in a more direct way. Firms are assumed to differ with respect to their level of risk aversion and a distribution regarding risk aversion is transformed to different lengths of the planning period. A more risk-averse firm will apply a shorter planning period than a less risk-averse firm. It is assumed that

63. Another possibility depends on the characteristics of the stochastic process which is underlying non-technology-specific uncertainty. If a firm is able to postpone the investment decision, and future information would decrease uncertainty, or would change the expected value of such an investment project, it could be optimal to postpone the investment decision until new information arrives. See for instance Pindyck (1991) for an application of such model. This type of learning is beyond the scope of this thesis, however.

64. It is implicitly assumed that such projects are irreversible or that they bear large adjustment costs.

65. Some exceptions are the studies of Just and Zilberman (1983), Kim et al. (1992) and Tsur et al (1990). The first two rely purely on this type of uncertainty while Tsur et al. include both types.

the number of different technologies available on the market for capital goods is infinite. Technologies differ from one another with respect to the incorporated labour productivity and the price of the capital goods. For analytical convenience, we assume that the ex-ante as well as the ex-post factor coefficients are fixed and that the capital-output ratio is the same for all technologies and constant in time. A more advanced technology is more expensive but also more productive, which implies that the fixed costs are higher and the variable costs lower than would be the case for a less advanced technology. Because firms with a longer planning period can spread the investment costs over a longer period, they can invest in more expensive technologies which are more productive. Firms with a shorter planning period have to conduct their investment expenditures in a shorter period, so that they will invest in less expensive, but also less productive, technologies. It should be clear that this approach is very similar to the pay-back period approach of Davies. One of the main differences is that our model does not assume that firm size is important. Moreover, we assume constant returns to scale and perfectly divisible investment goods. On the other hand, we will derive the choice of technologies in a framework in which firms maximize the net present value of future profits.

Chapter 5 is only concerned with the choice of new technologies. Neither the amount of investment nor other firm decisions are incorporated. This will be done in Chapter 6, where the choice of technologies are incorporated in a clay-clay vintage model so as to analyze the amount of investment. Both a static and a dynamic approach are presented. Furthermore, we will explore the properties of the diffusion process in this chapter and derive some more general steady-state properties of the model. Special attention will be given to the relation between the price of investment goods and the choice of technologies and the amount of investment in these technologies. Surprisingly, this relationship has not been explored to date. The behaviour of this clay-clay diffusion model outside the steady state is presented in Chapter 7 by means of some simulation results.

Finally, note that the macro model is based on uncertainty of the performance of technologies and that this uncertainty is reduced by the accumulation of knowledge. The micro model is based on non-technology-specific uncertainty and does not include its technology-specific counterpart. Thus, in this respect, the macro and the micro model are not comparable, and it should be noticed that the macro model is not an aggregation of the micro model. To keep the model analytically traceable, we made some simplifying assumptions in Part III, such as purely labour-augmenting technological change. Although we will use a clay-clay vintage model, firms may choose between several technologies which differ from each other with respect to the incorporated labour productivity and the price of investment. This implies that the model in Part III is comparable with the vintage-diffusion model which is developed in the second part of this thesis.

Up until now, we have assumed, both in Part II and in Part III, that the prices of technologies are given. Furthermore, in Part III we assume that the number of available technologies is infinite. The last section of Chapter 7 will provide a short view on possible extensions of the present model with a supply side of technologies. Some light is shed on the formation of investment prices and we will investigate possible extensions of our model with the endogenous growth model of Romer (1990). Previously, we have shown that Romer's model has some drawbacks, for instance the assumption that all technologies are equally productive and that there is no diffusion of technologies. A combination of the ideas of Romer and the vintage-diffusion model could relax these stringent assumptions. On the other hand such integration allows for an explicit production structure for new technologies. Chapter 7 will not present a complete model but will explore some possible extensions of the demand based vintage-diffusion model. These explorations are left for further research. Finally, Chapter 8 will give a brief summary of the conclusions of this thesis.

Appendix 2A. Aggregate Production Function Model and a Putty-Putty Vintage Model

This appendix presents the aggregate model as well as the vintage model which are used to generate Figure 2.4. The models as well as the derivation is taken from Phelps (1962).

The original, aggregate, Solow model is based on a Cobb-Douglas aggregate production function:

$$X_t = A_0 e^{\varepsilon t} K_t^{\alpha} N_t^{(1-\alpha)} \tag{2A.1}$$

where ε denotes the rate of disembodied technological change, X_t denotes total output and K_t and N_t denote capital and labour input, respectively. The stock of capital is equal to:

$$K_t = \int_{-\infty}^{t} I_\tau e^{-\delta(t-\tau)} d\tau \tag{2A.2}$$

where I_τ is the amount of investment at time τ and δ denotes the annual rate of depreciation.

In Solow's putty-putty vintage model, output can be modelled as:

$$X_t = B_0 e^{\varepsilon t} J_t^{\alpha} N_t^{1-\alpha} \tag{2A.3}$$

where J_t denotes the amount of effective capital, that is:

$$J_t = \int_{-\infty}^{t} e^{\frac{\mu}{\alpha}\tau} I_{\tau,t} d\tau = e^{-\delta t} \int_{-\infty}^{t} e^{(\frac{\mu}{\alpha}+\delta)\tau} I_{\tau,\tau} d\tau \tag{2A.4}$$

in which μ denotes the rate of embodied technological change. $I_{\tau,t}$ is the amount of investment at time τ which still exists at time t, which is rewritten as the initial amount of investment times the survival fraction. Equations (2A.3) and (2A.4) are equal to the aggregate production function model (equations (2A.1) and (2A.2)) if the rate of embodied technological change is zero.

Phelps uses a simple investment function:

$$I_t = sX_t \tag{2A.5}$$

and the labour force grows at a constant rate:

$$N_t = N_0 e^{nt} \tag{2A.6}$$

which completes the model.

Phelps shows that growth rate of output in the steady-state solution is equal to:[66]

$$\hat{X} = \frac{\mu + \varepsilon}{\alpha} + n \tag{2A.7}$$

Equations (2A.3) to (2A.6) are used to run the simulation, in which we replaced the integral from $-\infty$ to t by a summation over $t-100$ to t.

To generate the results which are shown in Figure 2.4, we used the following parameters: $n=0$, that is a constant labour force, $\delta=0.05$, $\alpha=0.25$ and $s=0.25$. In the aggregate model we used $\varepsilon=0.03$ and $\mu=0$ whereas the parameters of the vintage model are: $\varepsilon=0$ and $\mu=0.03$. This implies that, according to the equation above, the steady-state rate of growth should be 0.04, which is indeed the case, as can be seen in Figure 2.4.

66. This implementation of disembodied technological change is just one possibility. Another way is to assume that disembodied technological change starts from scratch at the year of installation. This implies that the steady-state growth rate of output is independent of the rate of disembodied technological change (cf. van Zon, 1991).

Appendix 2B. Adjustment Costs and the Shape of the Diffusion Process in Stoneman

Stoneman (1981) defines total returns as:

$$\mu_t = \alpha_t \mu_{nt} + (1-\alpha_t)\mu_{ot} \quad \text{with } 0 \le \alpha_t \le 1 \tag{2B.1}$$

where α is the proportion of output produced on the new technology and μ_{nt} and μ_{ot} denote the returns on the new and old technology, respectively. The variance is equal to

$$\sigma_t^2 = \alpha_t^2 \sigma_{nt}^2 + (1-\alpha_t)^2 \sigma_{ot}^2 + 2\alpha_t(1-\alpha_t)\sigma_{not} \tag{2B.2}$$

where σ_{it}^2, with $i = n,o$, denotes the variance of the returns of the new and old technologies, respectively, and where σ_{not} is the covariance.

The utility function is defined as $U_t = \mu_t - \frac{1}{2}\sigma_t^2 - C_t$ where C_t are the adjustment costs. Without adjustment costs, firms will move to the optimal level of usage (α_t^*) of the new technology instantaneously:

$$\alpha_t^* = \frac{\mu_{nt} - \mu_{ot} + b(\sigma_{ot}^2 - \sigma_{not})}{b(\sigma_{nt}^2 + \sigma_{ot}^2 - \sigma_{not})} = \frac{d_t}{e_t} \tag{2B.3}$$

If there is no learning, i.e., if firms do not update their expectations with respect to the mean and the variance of the returns, the optimal proportion of use of the new technology is constant so that there is no diffusion in the case without adjustment costs and without learning.[67]

In the case of positive adjustment costs, firms will move towards the optimal proportion (α_t^*) at such a speed that the marginal utility of increasing the use of the new technology is equal to the disutility due to the adjustment costs, i.e., the condition

$$\frac{\partial C}{\partial \alpha} = d_t - e_t \alpha_t = d_t \left(\frac{\alpha_t^* - \alpha_t}{\alpha_t^*} \right) \tag{2B.4}$$

should hold. The term at the right-hand side shows that the marginal utility decreases as α reaches the optimal level α^*. This implies that, if the adjustment costs function inhibits the first property only, i.e., if the adjustment costs depend on the change of α irrespective of its level, the rate of adoption $\alpha_t - \alpha_{t-1} = d\alpha / dt$ is positive but will decrease at all points in time such that the diffusion curve is concave.

For example, if the adjustment costs function is defined as $C_t = \frac{1}{2}(\alpha_t - \alpha_{t-1})^2$, the optimal adoption path is:

$$\frac{d\alpha_t}{dt} = d \left(\frac{\alpha_t^* - \alpha_t}{\alpha_t^*} \right) \tag{2B.5}$$

so that the second derivative is negative for all values of $0 \le \alpha \le \alpha^*$, i.e., the diffusion path is not S-shaped in this case.

If, as Stoneman assumes, the adjustment costs function inhibits both properties, the disutility due to adjustment costs will be large in the beginning of the diffusion process, leading to a slow rate of adoption. Adjustment costs decrease for a given change of the production technology as the level of use of the new technology increases and the diffusion process speeds up. At the end, the increase of the marginal utility decreases thus slowing down the diffusion process until the optimal level is reached.

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67. Note that the optimal proportion of use is not just a boundary solution if the variance of the returns is not equal to zero.

For example, if the adjustment costs function is given by:

$$C_t = \frac{1}{2}\left(\frac{\alpha_t - \alpha_{t-1}}{\alpha_{t-1}}\right)^2 \tag{2B.6}$$

the optimal adoption path is:

$$\frac{d\alpha_t}{dt}\frac{1}{\alpha_t} = d\left(\frac{\alpha_t^* - \alpha_t}{\alpha_t^*}\right) \tag{2B.7}$$

The second derivative will therefore change sign from positive to negative at $\alpha = \frac{1}{2}\alpha^*$, which implies that the diffusion path is S-shaped.

PART II

A MACRO ECONOMIC VINTAGE-DIFFUSION MODEL

3 Diffusion in a Putty-Clay Vintage World

In the previous chapter, we argued that the homogeneity of all vintages in the standard vintage models contradicts the general findings within the literature on adoption and diffusion of new technologies. Furthermore, we argued that the introduction of diffusion into a vintage model will endogenize the transmission of embodied technological change. This chapter presents a combined diffusion-vintage model which will provide another view on the transmission of technological change. In standard vintage models, the impact of embodied technological change is determined by the amount of investment and by changes in the age structure. The impact of embodied technological change depends also on the rate of adoption in a combined model. If, for example, the rate of adoption of new technologies slows down, the impact of embodied technological change would decrease, even if (i) the total amount of investment is constant; (ii) the total amount of scrapping remains the same and (iii) the rate of embodied technological change is constant. It is possible that more firms buy previously developed, or older, technologies while the development of new technologies continues. Of course, one could also endogenize the development of new technologies, but since we are interested in the spread of these technologies, we will keep this development constant.

Following the seminal works of Johansen and Salter, we will develop a putty-clay vintage model. Examples in the Netherlands of such models are Kuipers and van Zon (1982), Gelauff, Wennekers and de Jong (1985) and Muysken and van Zon (1987). The reason for using this type of model is threefold: (i) all Dutch vintage models find a significant rate of embodied technological change, which exclude the use of aggregate models; (ii) vintage models can measure technological change more accurately, especially when the age structure changes over time (cf. van Zon, 1991) — this excludes the Solow/Phelps putty-putty approach; (iii) putty-clay models perform better than clay-clay models, especially when the rate of technological change may vary over time.

Thus, if the introduction of the diffusion element into a putty-clay model would result in a variable impact of technological change, and if such model describes the actual data more accurately, we would end up with a model (i) that separately measures the impact of embodied and disembodied technological change; (ii) that gives a more realistic picture of productivity growth and (iii) that is based on an endogenized transmission of technological change which means that the ad hoc elements of the models of Gelauff, Wennekers and de Jong and Muysken and van Zon are overcome. This chapter presents a simple putty-clay vintage model that incorporates the idea of the diffusion of new technologies. As discussed in the previous chapter, we will use a macro-economic-inspired distribution of technologies, i.e., we will take the general ideas of the epidemic diffusion model as a starting point. We also argued that purely epidemic models have some drawbacks (cf. Gold, 1981). First, it is assumed that the profitability of a technology does not change over time and that there is no room for ex-post improvements. This assumption becomes very unrealistic if one recalls the empirical observation that diffusion processes take up to 50 years. Second, the ceiling level has to be known at the beginning of the diffusion process as is the case in standard epidemic models. Although we will use the general ideas of the epidemic model, we will specify our model in such a way that both drawbacks are overcome. But this is not without some costs. Although we will show that the diffusion process is likely to be S-shaped, we cannot prove that this will be the case in a strongly fluctuating environment. The empirical results should give some insights into the shape of the diffusion process if we use actual data. So we assume that the distribution of technologies is based on some epidemic-like model but we do not require the profitability of a technology to be constant, nor do we require the ceiling level to be known in advance. The technologies are embodied in new equipment and it is assumed that a new technology comes onto the market for capital goods each year. Some firms will invest in the newest technology but the majority will buy older equipment, i.e., new equipment but of an older type. The speed of diffusion depends on expected profits and on accumulated knowledge.

In order to highlight the differences between the vintage diffusion model and its standard, non-diffusion, counterpart, we will develop and estimate versions of both types of models. The next section presents a version of the standard putty-clay vintage model. In its core, it is comparable with the above-mentioned Dutch putty-clay models. Subsequently, section 3.2 presents the vintage-diffusion model. This model will relax the assumption of immediate adoption of new technologies and will provide a broader view on the transmission of technological change. The estimation results will be discussed in chapter 4.

3.1 The Non-Diffusion Putty-Clay Model

The basic putty-clay model follows the Dutch vintage-modelling tradition and will rely heavily on the work of Kuipers and van Zon (1982), Gelauff, Wennekers and de Jong (1985) and of Muysken and van Zon (1987), in the remainder of this book referred to as KvZ, GWJ and MvZ, respectively. In these models, it is assumed that the rate of technological progress is given exogenously and that all investment is of the latest type, i.e., that all firms invest in the best-practice technology. Furthermore, firms are assumed to maximize the expected value of future profits of the current investment project only.[68] Although the planning period is assumed to be larger than one, this implies static behaviour since firms do not consider future investment decisions. This section will present a core version of the models of KvZ, GWJ and MvZ. In order to keep the non-diffusion model as simple as possible, we will use the main properties of these models and briefly discuss the points at which we take shortcuts.

First, we will discuss the ex-ante production structure and the objective function of the firm, followed by the ex-post production structure and the expectation formation. Finally, we will present the optimal choice of the firm, the scrapping conditions and the resulting capacity output and aggregate demand for labour.

3.1.1 The Production Structure Ex-Ante

As in KvZ, GWJ and MvZ, it is assumed that the output market is competitive and that output prices are given. The production structure ex-ante is specified as a linear homogeneous CES production function with two factors of input: labour and capital.[69] Furthermore, we allow for labour-augmenting as well as capital-augmenting embodied technological progress. The production function is given by:

$$X_{\tau,\tau} = \left\{(A_\tau N_{\tau,\tau})^{-\rho} + (B_\tau I_{\tau,\tau})^{-\rho}\right\}^{-1/\rho} \quad \text{with: } 0<\rho<\infty \tag{3.1}$$

where $X_{\tau,t}$ stands for the productive capacity of vintage τ in year t, $I_{\tau,t}$ represents the capital input, and $N_{\tau,t}$ stands for the labour input needed to produce $X_{\tau,t}$. The elasticity of substitution between labour and capital is defined as:

$$\sigma = \frac{1}{1+\rho} \tag{3.2}$$

Both capital and labour are corrected for changes in effective working hours, hi_τ and hn_τ respectively, which we include in the next two equations. A_τ is a measure of the effectiveness of the labour force. This measure is defined as being propor-

68. In chapter 6, we will develop a more general vintage model in which entrepreneurs maximize expected profits of the whole firm, i.e., all vintages taken together. This will be done in both a static and an intertemporal setting. In that chapter, we will show that the static model is comparable to the current putty-clay model if the output market is competitive, which is assumed to be the case.

69. GWJ add energy as a third factor.

tional to the embodied labour-augmenting technological progress times the index of effective working hours:

$$A_\tau = A_0(1+\mu_n)^\tau hn_\tau \quad \text{with } A_0>0 \text{ and } \mu_n \geq 0 \tag{3.3}$$

where τ stands for the year of installation. The parameter μ_n describes the rate of embodied labour-augmenting technological progress. This parameter is exogenous and is to be estimated.

Capital-augmenting technological progress, including changes in working hours, is described in an analogous way:

$$B_\tau = B_0(1+\mu_i)^\tau\, hi_\tau \quad \text{with } B_0>0 \text{ and } \mu_i \geq 0 \tag{3.4}$$

where μ_i describes the rate of embodied capital-augmenting technological change. Thus, we allow for both labour and capital-augmenting embodied technological change.

Because of the ex-ante substitution possibilities between labour and capital, firms can choose a combination between both factors of input. We assume that the choice of the labour intensity ($l_{\tau,t} \equiv N_{\tau,t}\ / I_{\tau,t}$) is the result of the producers' wish to maximize the present value of expected future rents over the expected lifetime (θ_τ) of equipment:

$$PV_\tau = \sum_{t=\tau}^{\tau+\theta_\tau-1} \frac{p^e(t)_\tau X_{\tau,t} - w^e(t)_\tau N_{\tau,t}}{(1+r^e(t)_\tau)^{t-\tau}} - q_\tau I_{\tau,\tau} \tag{3.5}$$

subject to the production function, equation (3.1). $p^e(t)_\tau$ stands for the expected output price in year t, where expectations are formed in year τ; $w^e(t)_\tau$ denotes the expected nominal wages per man-year, and $r^e(t)_\tau$ stands for the expected rate of interest. The price of equipment is given by q_τ.

The initial labour intensity follows from the optimizing behaviour of firms. Since we assume a linear homogeneous CES production function, the initial labour productivity ($\lambda_{\tau,\tau}$) and the initial capital productivity ($\kappa_{\tau,\tau}$) are given by equation (3.1) as a function of the initial labour intensity ($l_{\tau,\tau}$):

$$\lambda_{\tau,\tau} \equiv \frac{X_{\tau,\tau}}{N_{\tau,\tau}} = \left\{ (A_\tau)^{-\rho} + \left(\frac{B_\tau}{l_{\tau,\tau}}\right)^{-\rho} \right\}^{-1/\rho} \tag{3.6}$$

and

$$\kappa_{\tau,\tau} \equiv \frac{X_{\tau,\tau}}{I_{\tau,\tau}} \equiv \lambda_{\tau,\tau}\, l_{\tau,\tau} \tag{3.7}$$

Thus, both initial factor productivities follow from the choice of an initial labour intensity of production.

3.1.2 Production Structure Ex-Post

After installation, substitution between capital and labour is no longer possible. The labour productivity ($\lambda_{\tau,t}$) and capital productivity ($\kappa_{\tau,t}$) will change over time due to disembodied technological progress and due to changes in working hours of both labour and capital. These changes can be described by:

$$\lambda_{\tau,t} \equiv \frac{X_{\tau,t}}{N_{\tau,t}} = \frac{hn_t}{hn_\tau}(1+\varepsilon_n)^{t-\tau}\ \frac{X_{\tau,\tau}}{N_{\tau,\tau}} \quad \text{with: } \varepsilon_n \geq 0 \tag{3.8}$$

and

$$\kappa_{\tau,t} \equiv \frac{X_{\tau,t}}{I_{\tau,t}} = \frac{hi_t}{hi_\tau}(1+\varepsilon_i)^{t-\tau}\ \frac{X_{\tau,\tau}}{I_{\tau,\tau}} \quad \text{with: } \varepsilon_i \geq 0 \tag{3.9}$$

where ε_n stands for labour-augmenting and ε_i for capital-augmenting disembodied technological progress. Both are assumed to be constant over time and non-negative. Note again that the disembodied technological change can be labour-augmenting or capital-augmenting. Although there are no substitution possibilities ex-post, the labour intensity may shift over time if the rates of ex-post technological change are not equal to each other, i.e., if disembodied technological change is not neutral in the sense of Hicks.

Apart from the disembodied type of technological change the capital stock is subject to wear and tear. The amount of capital that still exists in year t and which is installed in year τ is equal to:

$$I_{\tau,t} = \Omega_{t-\tau} I_{\tau,\tau} \tag{3.10}$$

where $\Omega_{t-\tau}$ represents the technical survival fraction of vintage τ in year t. We will use an exogenous technical depreciation scheme, and assume a maximum age of capital of 45 years, which is a common assumption in Dutch vintage models.[70]

3.1.3 Expectations

As mentioned above, the optimal labour intensity depends on the expected output prices, the expected wages, the expected discount rate, the expected changes in working hours and on the expected rates of disembodied technological change. Moreover, firms are assumed to maximize the net present value of future rents over the expected lifetime of equipment.

The expectations can be described by:

$$y^e(t)_\tau = y_\tau(1+g^e(y)_\tau)^{t-\tau} \quad \text{for } y = p,\ w,\ hn \text{ and } hi \tag{3.11}$$

70. See for instance Den Hartog (1984), Tables 1 and 2.

where $g^e(y)_\tau$ stands for the expected rate of growth of variable y for $t \geq \tau$. We will denote this expected rate of growth by $\hat{y}^e_\tau$ for short.[71] We assume adaptive expectations so that the expected rate of growth is assumed to be equal to the average of the realized rates of growth over the last $\bar{z}$ years. The expected rate of interest (r^e_τ) is equal to the average value over the last $\bar{z}$ years. In the estimation process, we ran some experiments using different values of $\bar{z}$ (ranging from 3 to 6 years). The results did not vary greatly between these values but $\bar{z}$ equal to 4 gave the best results.[72]

Both KvZ and GWJ assume a constant expected lifetime throughout the whole estimation period. Expected lifetime is incorporated in their models as a parameter which has to be estimated. KvZ find a value of 13 years whereas it is 15 years in GWJ.[73] In KvZ, the actual lifetime decreases from 45 years in the 1950s to 15 years in 1977, which is the end of their estimation period. It is hard to believe that entrepreneurs will apply a constant expected lifetime if the actual lifetime decreases by two-thirds. Muysken and van Zon recognize this shortcoming and assume that the expected lifetime is a constant fraction of the actual lifetime. However, this implies that, if the actual lifetime is for example 20 years, the expected lifetime of the current vintage is based on a vintage that was installed 20 years ago. Furthermore, the rule of Muysken and van Zon can only lead to consistent expectations if the actual lifetime is constant in time, which is not confirmed by the findings of KvZ and GWJ.[74] In our model, we develop an alternative rule which overcomes this problem and in which firms use the latest information. From the expected growth rates of wages, prices, discount rate and disembodied technological change, which are all based on more recent information, each firm is able to forecast the lifetime of equipment in such a way that the lifetime is consistent with their expectations and with the scrapping condition.[75,76] As they are assumed to act rationally, they will

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71. Note that the rate of growth is defined as $\hat{y}_t = \frac{y_t - y_{t-1}}{y_{t-1}}$ in this chapter whereas it is defined as a continuous rate of growth ($\hat{y}_t = \frac{dy}{dt}\frac{1}{y}$) in parts I and III.

72. Kuipers and van Zon (1982) estimated this parameter and found the same value of four years. Muysken and van Zon (1987) assumed $\bar{z}$=4. Gelauff, Wennekers and de Jong used an average based on ten years, which seems to be rather long.

73. Which is its imposed upper boundary.

74. If the expected lifetime is a fraction of the actual lifetime, for instance two-third as found by MvZ, their rule leads to rapidly decreasing expected lifetimes if the expectations are consistent with the actual results.

75. Note that such a rule is also used by Arrow (1962).

76. As will be discussed in section 3.1.5, firms will scrap equipment for two reasons. First, if the quasi-rent becomes zero or negative and second, if there is lack of aggregate demand, leading to underutilization of the installed capacity. When determining the expected lifetime, we assume that scrapping due to underutilization is unforeseen, so expected scrapping is only due to non-positive quasi-rent.

use this lifetime as the planning period which is used to evaluate the expected rents in order to choose the initial labour intensity. We assume that equipment is scrapped if the quasi-rent of that vintage is zero, which is the case if the labour productivity is equal to the real wage rate.[77] This implies that the expected date of scrapping depends on the initial labour productivity, which depends — according to equation (3.6) — on the initial labour intensity. Because the initial labour intensity depends on the expected lifetime we end up with a simultaneous system in which we have to search for the expected lifetime of equipment which is installed in year τ and which solves the following problem:

Find θ_τ such that

$$\lambda^e(\tau+\theta_\tau)_\tau = \frac{w^e(\tau+\theta_\tau)_\tau}{p^e(\tau+\theta_\tau)_\tau} \tag{3.12}$$

in which $\lambda^e(\tau+\theta_\tau)_\tau$ equals the expected labour productivity of vintage τ in year $\tau+\theta_\tau$. So this term equals:

$$\begin{aligned}\lambda^e(\tau+\theta_\tau)_\tau &= \frac{hn^e(\tau+\theta_\tau)_\tau}{hn_\tau}\,(1+\varepsilon_n)^{\theta_\tau}\,\lambda_{\tau,\tau} \\ &= (1+\hat{hn}^e_\tau)^{\theta_\tau}\,(1+\varepsilon_n)^{\theta_\tau}\,\lambda_{\tau,\tau}\end{aligned} \tag{3.13}$$

Substitution of the definition of the expected growth rates gives the expected lifetime of equipment:

$$(1+\hat{hn}^e_\tau)^{\theta_\tau}(1+\varepsilon_n)^{\theta_\tau}\lambda_{\tau,\tau} = \frac{w_\tau(1+\hat{w}^e_\tau)^{\theta_\tau}}{p_\tau(1+\hat{p}^e_\tau)^{\theta_\tau}} \tag{3.14}$$

so:

$$\theta_\tau = \ln\left(\frac{w_\tau}{\lambda_{\tau,\tau}}\frac{1}{p_\tau}\right)\cdot\left(\ln\left[\frac{(1+\hat{hn}^e_\tau)(1+\varepsilon_n)(1+\hat{p}^e_\tau)}{1+\hat{w}^e_\tau}\right]\right)^{-1} \tag{3.15}$$

The expected lifetime increases if the labour productivity increases, and it will decrease if the real wage rate increases.[78] The labour productivity depends on the initial labour productivity, on disembodied technological change and on changes in

77. Below, we will argue that it is impossible to apply the Malcomson scrapping condition to our vintage-diffusion model as an alternative to quasi-rent scrapping. Furthermore, if scrapping is based on the Malcomson scrapping rule, the expected lifetime of the current vintage depends on the total costs per unit of output of its successor. But the total costs per unit of output of that vintage depends on its initial labour intensity, which depends again its the expected lifetime, which depends on the total costs per unit of output of its successor, and so on. The current expected lifetime would therefore depend on the expected lifetime of a vintage which is installed at $\tau=\infty$.

78. Note that the first term within brackets has to be smaller than one, because otherwise, the initial labour productivity would be below the real wage rate so that the newest vintage generates negative quasi-rents.

working hours. The initial labour productivity is the only unknown variable in this equation. We will elaborate the solution of the expected lifetime after the discussion of the choice of the initial labour intensity.

3.1.4 Choice of the Production Technique

Having specified the ex-post production structure and the expectations with respect to lifetime, factor prices, and changes in working hours, we are now able to determine the initial capital intensity by maximising equation (3.5). Substituting equation (3.10) in (3.9) gives the ex-post capacity output in year t of vintage τ in terms of the initial output capacity of that vintage:

$$X_{\tau,t} = \frac{hi_t}{hi_\tau} (1+\varepsilon_i)^{t-\tau} \, \Omega_{t-\tau} \, X_{\tau,\tau} \tag{3.16}$$

And substitution of this equation in equation (3.8) gives the amount of labour input needed to produce $X_{\tau,t}$:

$$N_{\tau,t} = \frac{hn_\tau}{hn_t} \frac{hi_t}{hi_\tau} \left(\frac{1+\varepsilon_i}{1+\varepsilon_n} \right)^{t-\tau} \Omega_{t-\tau} \, N_{\tau,\tau} \tag{3.17}$$

Equations (3.16) and (3.17) can be substituted in equation (3.5), together with equation (3.11), which represents the expectations formation. This results in an equation representing the net present value of the expected rents in terms of initial factor requirements:

$$PV_\tau = p_\tau \, X_{\tau,\tau} \, S_1(\theta)_\tau - w_\tau \, N_{\tau,\tau} \, S_2(\theta)_\tau - q_\tau \, I_{\tau,\tau} \tag{3.18}$$

with:

$$S_1(\theta)_\tau = \sum_{t=\tau}^{\tau+\theta_\tau-1} \left\{ \left[\frac{(1+\hat{p}_\tau^{\,e}) \, (1+\hat{hi}_\tau^{\,e}) \, (1+\varepsilon_i)}{(1+r_\tau^{\,e})} \right]^{t-\tau} \Omega_{t-\tau} \right\}$$

and:

$$S_2(\theta)_\tau = \sum_{t=\tau}^{\tau+\theta_\tau-1} \left\{ \left[\frac{(1+\hat{w}_\tau^{\,e}) \, (1+\hat{hi}_\tau^{\,e}) \, (1+\varepsilon_i)}{(1+r_\tau^{\,e}) \, (1+\hat{hn}_\tau^{\,e}) \, (1+\varepsilon_n)} \right]^{t-\tau} \Omega_{t-\tau} \right\}$$

in which the expected lifetime (θ_τ) follows from equation (3.15). Maximising equation (3.18) with respect to the input factors labour and capital, conditional on the production function, results in the optimum level of the initial labour intensity:

$$l_{\tau,\tau} \equiv \frac{N_{\tau,\tau}}{I_{\tau,\tau}} = \left(\frac{w_\tau \; S_2(\theta)_\tau}{q_\tau}\right)^{\frac{-1}{1+\rho}} \left(\frac{A_\tau}{B_\tau}\right)^{\frac{-\rho}{1+\rho}} \tag{3.19}$$

in which A_τ and B_τ are defined in equations (3.3) and (3.4), respectively. Because the production function is linear homogeneous, the initial labour intensity is independent of total output. The labour intensity depends positively on the costs of capital and negatively on the wage costs. Both depend on the length of the expected lifetime, which depends, as we have shown before, on the initial labour productivity. It is not possible to solve this simultaneous system analytically, however. In the estimation routines we solve this numerically, and Figure 3.1 gives a graphical representation of the solution.

The relation between the optimal labour intensity and the length of the expected lifetime, i.e. equation (3.19), is shown in the south-west quadrant, curve I. The position of this curve is determined by the rates of embodied technological progress, by the current wage rate and by the current price of capital goods. These variables may change over time, but are given for the firm at each point in time. The optimal labour intensity is concave towards the origin due to the concavity of the production function. A short expected lifetime implies that the total costs of capital, which are assumed to be sunk, are spread over a short period which means that the annual costs of capital are high. In that case, a firm will choose a labour-intensive way to produce output. If the expected lifetime increases, the costs of capital will be spread over a longer period so that the annual costs of capital will decrease. This will lead to a less labour-intensive production technique.

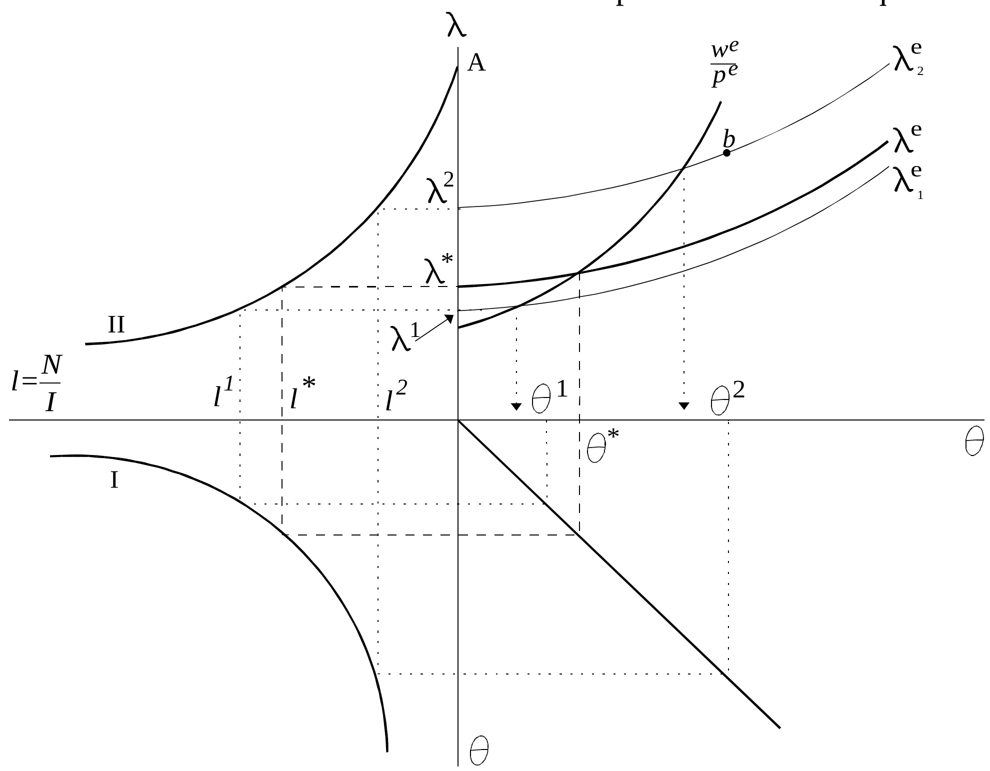

Figure 3.1. Determination of the initial labour intensity and the expected lifetime of equipment

The relation between the optimal labour intensity and the corresponding labour productivity, i.e. equation (3.6), is given in the north-west quadrant, curve II. This relation depends solely on the shape of the CES production function. The point of intersection with the vertical axis, that is the point at which the labour intensity is zero, is determined by the variable A_τ and depends on labour-augmenting technological change, cf. equation (3.6).[79] The labour productivity decreases asymptotically towards zero if the labour intensity becomes infinite.

Finally, the first quadrant shows the determination of the expected lifetime. Equipment is scrapped if the quasi-rents become zero which implies that the expected date of scrapping is determined by the date at which the labour productivity equals to real wage rate. The level as well as the growth rate of the real wage rate are assumed to be given for each firm. The expected growth rate of the labour productivity is also given but the level of the labour productivity is determined by its initial value. The initial labour productivity depends, as we have seen above, on the initial labour intensity.

The optimal labour intensity and the corresponding length of the expected lifetime are determined as follows. The labour intensity is equal to l^* if the initial guess of the expected lifetime is equal to θ^*. The initial labour productivity is then equal to λ^*. From this level, it is possible to forecast the future values of the labour productivity. Given the expected values of the real wage rate, the expected date of scrapping is determined by the point of intersection between the expected labour productivity and the expected real wage rate. This gives the expected lifetime, which is equal to θ^*, the initial guess, in this case which means that this solution is consistent.

If, for example, the initial guess of the expected lifetime was θ^2, the optimal labour intensity would be l^2 and the initial labour productivity λ^2, which is higher than λ^*. The expected date of scrapping is, again, given by the intersection of the expected real wage rate and the expected labour productivity, which has shifted by now. The resulting expected lifetime is below the initial guess, which implies that this guess is inconsistent with the expected lifetime and has to be adjusted downwards. This process will converge to the ‘correct’ expected lifetime θ^*. Note however, that if the initial guess of the expected lifetime is below θ^*, such as θ^1, this will lead to an expected lifetime which is even below the initial guess. If we calculate the expected lifetime according to a recursive procedure, the expected lifetime would go to zero if the initial guess is below the consistent or correct expected lifetime. In the estimation program, we start with the upper boundary of the

79. Note that the CES production function does not satisfy the Inada conditions. If we had used a Cobb-Douglas production function, curve II would not intersect the vertical axis but would approach it asymptotically.

expected lifetime and will determine the correct one by a simple grid search procedure.[80,81]

3.1.5 Scrapping of Equipment

As stated previously, and as done by for instance Muysken and van Zon (1987) and Kuipers and van Zon (1982), we assume that a machine is scrapped if the quasi-rent becomes non-positive. Thus, a machine is scrapped if

$$\lambda_{\tau,t} \leq \frac{w_t}{p_t} \tag{3.20}$$

Both Kuipers and van Zon (1982) and Muysken and van Zon (1987) used the three-year moving average of the real wage rate in this equation. We also adopted this practice, because it is hard to believe that each firm would scrap a vintage as soon as the real wage rate drops below the labour productivity of that vintage. It is more likely that firms will use an average movement of real wage rates to determine the obsolescence of equipment. Gelauff, Wennekers and de Jong (1985) use a smoother scrapping condition with respect to negative quasi-rents. They assume that a vintage is scrapped completely if the variable costs exceed the revenues by 15% or more and that a vintage is not scrapped at all if the variable costs are equal to or below the revenues. Furthermore, they assume a linear scrapping condition if the ratio of the variable costs over the revenues are between 1 and 1.15. The reason for this is to reduce discontinuities which arise in the estimation procedure. The implementation is rather ad hoc, however.

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80. Note furthermore that, at least in principle, multiple solutions are possible. For instance, if the growth rate of real wages is lower than the depicted growth rate and the initial wage rate is higher so that the current solution at θ^* still holds, it is possible that the real wage curve cuts through the line λ_2^e at point b and a second solution is obtained at θ^2. However, notice that the relation between the labour intensity and the length of the expected lifetime depends on the wage rate, which implies that curve I will shift. It is therefore impossible to determine analytically whether multiple solutions are possible. In the estimation procedure, we checked for such possibilities and they never emerged.

81. Moreover, the expected lifetime proved to be highly unstable due to relatively small changes in the growth rate of real wages (the expected lifetime varied more than ten periods per year in some cases). Because it is not likely that firms will adjust the expected lifetime that rigorously, we imposed a restriction on the annual change of the expected lifetime. The largest possible difference between the expected lifetime of a machine with a certain technological age and the expected lifetime of the machine with the same technological age which was installed in the preceding year, is two years. For example, suppose that the expected lifetime of a machine which was installed in 1980 and incorporates a technology from 1975 is equal to ten years. The expected lifetime of a machine which was installed in 1981 and which embodies the technology from 1976 is bounded between eight and twelve years.

Apart from scrapping due to negative quasi-rent, Gelauff, Wennekers and de Jong (1985) introduced scrapping due to severe under-utilisation of the capital stock.[82] Muysken and van Zon (1987) adopt this scrapping condition but they assume that the least productive vintage is scrapped first.[83] In the present model we utilise the latter condition. We assume that a fraction χ of the excess capacity is scrapped if the utilisation rate is below the normal utilisation rate u^n for more than two consecutive years. The productive capacity of the equipment that will be scrapped is equal to:

$$\begin{aligned} X_t^{scrap} &= \chi\,(X_t^c\, u^n - X_t) \qquad \text{if: } (u_t \le u^n) \wedge (u_{t-1} \le u^n) \\ &= 0 \qquad\qquad\qquad\qquad \text{otherwise} \end{aligned} \tag{3.21}$$

where u_t stands for the utilisation rate ($=X_t / X_t^c$), X_t^c for the total productive capacity at time t and X_t for aggregate demand, which is exogenously given. We will employ both u_t and X_t^c before scrapping due to under-utilisation whereas u_{t-1} equals the utilisation rate after scrapping due to under-utilisation has taken place. Note that we will scrap the least productive machines first and that we will continue scrapping until the amount of associated productive capacity equals X_t^{scrap}. In general, the last vintage will be scrapped partially.

3.1.6 Productive Capacity and the Demand for Labour

The total capacity in a year can be derived by aggregating the capacity of all vintages (and parts of vintages) which still exist at that point in time:

$$X_t^c = \sum_{\tau \in V_t} X_{\tau,t} \tag{3.22}$$

In this equation V_t describes the set of vintages which are not scrapped at time t. The capacity demand for labour is derived in the same way:

$$N_t^c = \sum_{\tau \in V_t} N_{\tau,t} \tag{3.23}$$

Similar to Muysken and van Zon (1987), we assume that, if the utilisation rate is below unity, the least productive machines are put aside first. Define a lower bound on the labour productivity, $\bar{\lambda}_t$, so that the actual output can be produced by the machines for which the labour productivity exceeds $\bar{\lambda}_t$. Next we define $\bar{\lambda}_t$ in such a way that:

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82. Gelauff, Wennekers and de Jong (1985: 333-334). It is assumed that some firms will go bankrupt if there is a lack of aggregate demand. GWJ assume that a fraction of the total capital stock is scrapped if the utilisation rate is below a normal rate.

83. Muysken and van Zon (1987: 109-111).

$$\sum_{\tau \in V_t \mid \lambda_{\tau,t} > \bar{\lambda}_t} X_{\tau,t} = X_t \tag{3.24}$$

holds. The minimal demand for labour equals that amount, which is just enough to produce the actual output at any point in time. This minimal demand equals:

$$N_t^- = \sum_{\tau \in V_t \mid \lambda_{\tau,t} > \bar{\lambda}_t} N_{\tau,t} \tag{3.25}$$

Muysken and van Zon (1987) elaborate two reasons for labour hoarding: desired labour hoarding and forced labour hoarding.[84] Because we want to concentrate on the structure of the capital stock we employed a condensed version of their labour demand function. We assume that the amount of labour that is hoarded is equal to a constant fraction of the difference between capacity demand for labour and the minimal demand for labour. So the total demand for labour equals:

$$N_t = N_t^- + \xi \, (N_t^c - N_t^-) \qquad \text{with: } 0 \le \xi \le 1 \tag{3.26}$$

This equation completes the basic non-diffusion vintage model and the next section will combine this basic model with a model of diffusion of new technologies.

3.2 The Vintage-Diffusion Model

In chapter 2, we have shown that the assumption that all firms will invest in the same technology contradicts some common findings of the research into adoption and diffusion of new technologies. Moreover, most a such models do not consider total investment or output decisions. Finally, most of them do not consider replacement effects, i.e., they only consider the first part of the life-cycle of an investment good.[85] The combination of a diffusion model with a vintage model will remove both shortcomings. As pointed out previously, we will introduce a relatively simple diffusion structure, which is based on the epidemic approaches, into a putty-clay vintage model. This implies that the choice of technologies is not determined explicitly as being the result of firm behaviour.[86] The basic vintage model is described above and this section extends this model towards a macro-economic vintage-diffusion model.

We assume that each year, a new technology[87] comes onto the market for capital goods. This new technology will be supplied in addition to the existing, hence

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84. See Muysken and van Zon (1987: 115). The actual level of hoarding in their model is equal to the maximum of desired and forced labour hoarding.

85. Stoneman (1981) is a notable exception, cf. chapter 2.

86. Part III develops a micro-based adoption vintage-diffusion model. However, that model is only partially meant to give micro-foundations of the current macro-oriented model.

87. We will use the term ‘technology’ in the sense of a complete isoquant whereas a ‘technique’ describes a point on an isoquant, i.e., with a given labour intensity.

older, technologies. We will call this new type of equipment the best-practice technology. In their investment decisions, firms may choose equipment which is based on the best-practice technology, but they can also invest in equipment embodying older technologies. Firms will invest in the available technologies, or in machines embodying these technologies, as long as the expected rents are positive. Once the productivity of an investment good in which a certain technology is incorporated is too low relative to its price so that the net present value of the expected future rents associated with that investment good is negative, firms will stop investing in that technology. It will be economically obsolete and be withdrawn from the market for ever.

In the literature on the speed of diffusion of innovations, two explanatory variables dominate: the proportion of firms that already installed the technology and the expected profitability of adopting a technology.[88] It is argued that increases in the proportion of firms that already installed the technology will increase the speed of diffusion. As more information and experience accumulates, it will become less risky to invest in a new technology. It is obvious that as expected profitability of using a new technology relative to other technologies increases, more firms will invest in that technology, ceteris paribus. Following these common findings, we assume that the share of a specific technology in total investment depends first on the expected profitability of that technology relative to the expected profitability of all technologies taken together, and secondly on the knowledge of that type of equipment in relation to the total stock of knowledge. For each profitable technology a firm will choose that labour intensity, i.e., that particular point on the isoquant, that maximizes the net present value of the expected future rents. This is equivalent to the non-diffusion model.

In the recent diffusion literature, the technological expectations become more important in the explanation of a delay in the introduction of new technologies — if firms expect major improvements in the near future, they might postpone investment decisions. Such an approach requires a stochastic specification of the generation of new technologies which complicates the analysis extensively. Although chapter 6 presents a dynamic vintage-diffusion model which pays attention to technological expectations, the present model disregards such an approach to keep the analysis as simple as possible.

The next sections will recapitulate the description of the non-diffusion model. If it concerns only slightly changed definitions, these alternations are discussed very briefly. The main burden is of course the distribution of the capital stock towards different technologies.

88. See for instance the models of Griliches (1957), Mansfield (1961) and Romeo (1977).

3.2.1 The Production Structure Ex-Ante

Since different firms can invest in different types of equipment, we have to add an extra dimension to the production structure. The total capital stock can be subdivided into individual vintages while each vintage itself can be subdivided into individual machines. Each machine embodies a specific technology and is assumed to be homogeneous. Whereas it is sufficient to describe a vintage in the basic, non-diffusion, model with two subscripts, the year of installation and the current year, a further decomposition of the capital stock needs an extra index. A machine is now determined by the incorporated technology, by the year of installation and by the current year. The technology index is given by a superscript i and this index refers to the year in which the technology is introduced into the market for capital goods. The ex-ante production function is given by:

$$X^i_{\tau,\tau} = \left\{(A^i_\tau N^i_{\tau,\tau})^{-\rho} + (B^i_\tau I^i_{\tau,\tau})^{-\rho}\right\}^{-1/\rho} \quad \text{with: } 0<\rho<\infty \tag{3.27}$$

where $X^i_{\tau,t}$ stands for the productive capacity of vintage τ in year t, for a technology which was introduced in year i. $I^i_{\tau,t}$ represents the capital input whereas $N^i_{\tau,t}$ stands for the labour input needed to produce $X^i_{\tau,t}$. So $I^\tau_{\tau,\tau}$ is the amount of investment in the best-practice technology in year τ. We assume that each year, a new technology becomes available on the market for capital goods. The embodied labour-augmenting technological progress, which is related to a certain technology can be described by:

$$A^i_\tau = A_0(1+\mu_n)^i(1+\gamma_n)^{\tau-i}hn_\tau \tag{3.28}$$

$$\text{with: } \mu_n \geq 0;\ 0 \leq \gamma_n \leq \mu_n \text{ and } \tau \geq i$$

The parameter μ_n describes the embodied labour-augmenting technological progress of the best-practice technologies, whereas γ_n stands for the embodied labour-augmenting technological progress of the older technologies. This latter parameter can be viewed as being the result of improvements of the best-practice technology by the suppliers of that equipment without affecting the main characteristics of that technology. Because of the very nature of these improvements we expect this parameter to be smaller than the embodied labour-augmenting technological progress of the best-practice machines.[89,90] We will treat both types of technological progress as being exogenous.

Capital-augmenting technological progress can be described in an analogous way:

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89. Note that if this is not the case, older technologies will become better than the best-practice technology in the sense that they will generate a higher level of output for a given level of inputs.

90. During the estimation of the model, we did not require that $\gamma<\mu$. In chapter 4, we will show that the embodied technological progress of the best-practice technologies is far above the technological progress for the less than best-practice technologies.

$$B^i_\tau = B_0(1+\mu_i)^i(1+\gamma_i)^{\tau-i}\,hi_\tau \tag{3.29}$$

with: $\mu_i \geq 0$; $0 \leq \gamma_i \leq \mu_i$ and $\tau \geq i$

The difference with the reference model is that we now make a distinction between technological change of the best-practice technologies and improvements of such technologies in the course of time. In the non-diffusion model, the parameters μ_n and μ_i describe technological change of all new investments. By the introduction of ex-post embodied technological change, we relax the often criticized assumption of standard epidemic diffusion models that there is no room for ex-post improvements of existing technologies (cf. Gold, 1981).

As before, the choice of a specific labour intensity ($l^i_{\tau,t} \equiv N^i_{\tau,t} / I^i_{\tau,t}$) is the result of the producers' wish to maximize the present value of expected future rents over the expected lifetime (θ^i_τ) of a machine. But now, we assume that not all firms will invest in the same technology. Some firms will buy the best-practice technology whereas others will invest in less advanced technologies. The distribution of firms with respect to technologies is discussed in the next section but at this point we assume that each firm will invest in only one technology at each point in time. The optimal choice of the labour intensity depends, among the variables which have already been introduced in the previous section, on the chosen technology:

$$PV^i_\tau = \sum_{t=\tau}^{\tau+\theta^i_\tau-1} \frac{p^e(t)_\tau X^i_{\tau,t} - w^e(t)_\tau N^i_{\tau,t}}{(1+r^e(t)_\tau)^{t-\tau}} - q^i_\tau I^i_{\tau,\tau} \tag{3.30}$$

in which all variables have been defined in the previous section. The price of equipment at time τ in which a technology from year i is embedded is q^i_τ. Generally, this price differs not only between vintages but also between different machines within a certain vintage. So machines differ from one another in that they embody different technologies and in that their prices are different. The optimal labour intensity will therefore also be different for each machine which will result in a range of labour intensities for each vintage.

In Figure 3.2 we plotted four different isoquants representing four different technologies in a certain year: the one that embodies the best-practice technology (i=t) and some older machines (i=t−1, t−2 and t−3) for which the isoquants are located further from the origin. This figure is comparable with Figure ?, page ?, but in the non-diffusion case, we plotted an isoquant at two different points in time, whereas Figure 3.2 displays several isoquants at the same point in time. Some firms will invest in the newest technology (i=t) while others will invest in new equipment which incorporates older technologies, i.e., technologies which where the best-practice technology one or more years ago.

All firms which invest in the same technology are assumed to be the same. They will choose that point at the isoquant, i.e., that labour intensity, that maximizes their expected discounted profits. Assuming the labour intensity to be the same for each machine, for instance along the line Oa, both the labour productivity and the

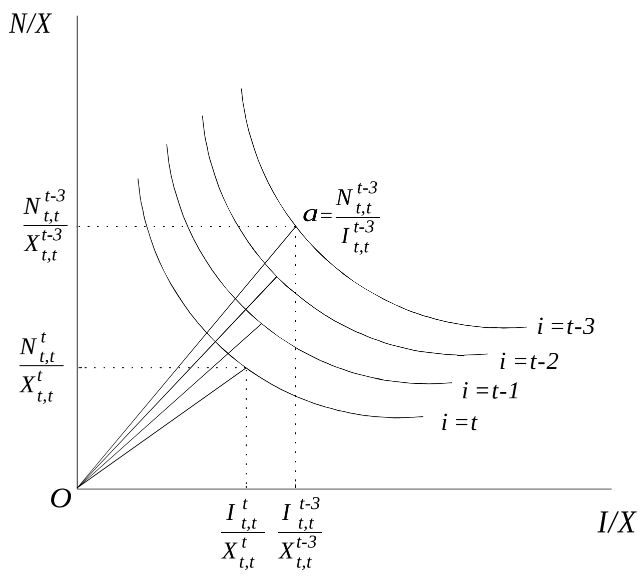

Figure 3.2. Isoquants representing several technologies at one point in time

capital productivity of a newer machine will be higher than the factor productivities of the older types of equipment.[91] Mainly due to differences in the prices of the capital goods as well as due to differences in the expected lifetime of equipment, the optimal labour intensity will be different for each particular machine but not necessarily increasing as the embodied technology becomes older as shown in the figure. Therefore, it is possible that the capital productivity of an older technology will be higher than the chosen capital productivity of a more recent technology. It is not possible, of course, that both factor productivities are higher for an older technology.

The shift of the isoquants depends on the difference between the rates of embodied technological progress of the best-practice technologies (μ_n and μ_i) and the rates of embodied technical progress of the less than best-practice technologies (γ_n and γ_i) as can be seen from equations (3.28) and (3.29). If these are equal for both factors than there is no difference any more between new and old technologies in the sense that the isoquants will be the same for all machines.

To summarize, we assume that there are several different isoquants at the same point in time in the vintage-diffusion model. Each isoquant represents a certain technology. The best-practice technology is determined by the rate of embodied technological change, as in the non-diffusion model. Each year, a new technology becomes available and firms can choose from a range of different technologies. The least advanced technology is determined by the non-negativity constraint on the expected profits. This implies that if the real wage rate becomes high to the extent that the expected profits will be negative, no firm will invest in that technology, which will subsequently be removed from the market.

91. Note that we plotted factor-coefficients on both axes.

As before, the choice of the labour intensity resulting from the maximisation of the net present value of the expected future rents, i.e. equation (3.30), will be discussed after the description of the frequency distribution of different technologies and the explanation of the ex-post production structure of the model.

3.2.2 Distribution of Technologies

Following Mansfield (1961), Romeo (1977) and Soete and Turner (1984), for instance, we assume that the amount of investment in a certain technology depends positively on the expected profitability of installing and using this equipment, as well as on the available information about that technology. As firms are of measure zero, we ignore intra-firm aspects of the diffusion process. Furthermore, we assume that each firm has complete and costless access to all information available about each existing technology, so information is treated as a public good.

We assume that for all existing technologies, the average expected profitability of installing and using these technologies is known by all firms. Without elaborating this in detail we assume that the risk of installing a certain technology is associated with the variance of its expected profitability.[92] It is assumed that the variance of the profitability will decline as more information about the associated technology becomes available.[93] Some firms are less risk-averse than others and will invest in the newest technology as soon as it is introduced onto the market for capital goods. Other firms are more reluctant to take risks and have some threshold value of risk in mind which has to be passed before they will invest in a technology. Until that point they will invest in older technologies for which the threshold has already been passed.[94] Soete and Turner assume that the information about a technology is proportional to the relative size of the capital stock of that technology. In our view, this is not an adequate measure of the experience with an existing technology. If we compare a relatively capital intensive technique with a relatively labour intensive technique on the same isoquant, it is not clear why the former will gener-

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92. A formal derivation would require a stochastic specification of the production function, i.e. equation (3.27). For each technology, the optimal labour intensity is no longer uniquely determined in that case. This would lead to another dimension of the distribution of all technologies. To avoid severe problems with respect to the aggregation of vintages and technologies, we assume that the distribution of the labour intensities can be summarized by its average value. For the impact of uncertainty on the choice of the labour intensity and on the amount of investment, see for instance Kon (1983) and Moene (1985a and 1985b).

93. This is slightly inconsistent with the general ideas of learning by doing because if firms learn from their own experience, or from the experience of others, both the variance and the mean value of the expected profitability would change (cf. Stoneman, 1981). Because of this, we refer to our model as an epidemic diffusion model rather than a probit model.

94. Another possibility is an epidemic explanation. Firms are not informed about the existence of the new technology but this information becomes available as it generates more output. Because we assume that firms compare the profitability of a technology with the profitability of all alternatives, which consequently have to be known, we prefer to use the first interpretation.

ate more experience and consequently more information about that technique than the latter. In our view, the productive capacity of a technique is a more appropriate measure of the experience with a certain technology.

Thus, production with a technology will generate information about that specific technology which will be added to the existing stock of knowledge. The expected risk of the returns on equipment will decline as the stock of knowledge increases. The probability that a piece of information about a technology is already known will increase as the stock of knowledge grows. We therefore assume a decreasing marginal impact of an additional piece of information on the decision to invest in that technology.

Let kn_{τ}^{i} be the stock of knowledge of technology i at time τ, relative to the average of the total stock of knowledge of all technologies taken together at time τ and let π_{τ}^{i} be the relative expected profitability per unit of output of that technology.[95] Then, the relative amount of investment for each technology i, in terms of productive capacity, is equal to:

$$x^{c\,i}_{\tau,\tau} = f(kn_{\tau}^{i}, \pi_{\tau}^{i}) \qquad \text{with: } f_1 > 0,\ f_{11} < 0 \text{ and } f_2 > 0 \tag{3.31}$$

in which $x^{c\,i}_{\tau,t}$ stands for the capacity output of technology i in year t, which is installed in year τ, relative to the total capacity output of all technologies which are installed in the same year. So:

$$x^{c\,i}_{\tau,\tau} \equiv \frac{X^{i}_{\tau,\tau}}{X^{c}_{\tau,\tau}} \tag{3.32}$$

Following Romeo (1977) we assume the following multiplicative relation:[96]

$$x^{c\,i}_{\tau,\tau} = s_{\tau}(kn_{\tau}^{i})^{\alpha_1} (\pi_{\tau}^{i})^{\alpha_2} \qquad \text{with: } 0 \le \alpha_1 \le 1 \text{ and } \alpha_2 \ge 0 \tag{3.33}$$

where s_{τ} is a scale factor so that $\sum_i x^{ci}_{\tau,\tau} = 1$. This equation does not determine the absolute amount of investment in each technology. It defines the distribution of technologies with respect to their relative size in terms of output capacities. The available information as well as the profitability related with each technology are measured relative to the average information and average profitability of all technologies, respectively.[97] We assume that there always exists some knowledge about a specific type of equipment, even if it embodies a new technology, for instance due to direct contact between potential users and suppliers of a new tech-

95. We defined the relative stock of knowledge as well as the relative profitability as being relative to the average values in order to make the weights of both factors in the distribution function invariant for changes in the number of technologies, cf. equation (3.33) below.

96. Romeo uses this relation to explain the rate of adoption of a logistic curve. We use this form in a somewhat different setting.

97. That profitability is measured relative to the profitability of all alternatives is a direct consequence of our assumption that firms compare all alternatives in making their investment decision. We used relative knowledge to avoid scaling problems which occur if total knowledge increases over time. This is likely to happen due to increased aggregate output.

nology or due to advertisements, etc. The initial relative amount of knowledge is assumed to be equal to α_0 which means the initial amount of knowledge (K_0^i) is equal to a fraction α_0 of the average knowledge of all existing technologies taken together. The stock of knowledge of a technology can be written as:

$$K_\tau^i = K_0^i + \sum_{t=i}^{\tau-1} \sum_{j=t}^{\tau-1} X_{t,j}^i \qquad \forall\ i \in \{i_\tau^{\max},\ldots\ldots,\tau\} \tag{3.34}$$

in which $i_\tau^{\max}$ stands for the oldest technology which yields positive expected profits at time τ.[98]

The stock of knowledge is defined relative to the average knowledge of all technologies taken together, i.e., the relative amount of knowledge kn_τ^i is equal to:

$$kn_\tau^i = \frac{K_\tau^i}{\frac{1}{n_\tau} \sum_{i=i_\tau^{\max}}^{\tau} K_\tau^i} \qquad \forall\ i \in \{i_\tau^{\max},\ldots,\tau\} \tag{3.35}$$

where n_τ is defined as the number of technologies with positive expected profits at time τ.[99] This implies that the relative knowledge (kn) of a new technology is equal to α_0. From equation (3.35), it follows that the average relative knowledge of all technologies taken together is equal to one, so that we assume that $0<\alpha_0<1$.

The relative profitability is defined in an analogous way:

$$\pi_\tau^i = \frac{PVX_\tau^i}{\frac{1}{n_\tau} \sum_{i=i_\tau^{\max}}^{\tau} PVX_\tau^i} \qquad \forall\ i \in \{i_\tau^{\max},\ldots,\tau\} \tag{3.36}$$

in which PVX_τ^i is defined as the expected profitability per unit of output of each machine embodying technology i, i.e. $PVX_\tau^i = PV_\tau^i / X_{\tau,\tau}^i$. This profitability will depend, amongst other things, on the initial labour intensity which will be the result of the maximizing behaviour of the firm. Note that if the profitability of a machine becomes zero, or negative, nobody will invest in this technology any more. Note furthermore that $\pi^i = 1$ for that technology for which the profitability is equal to the average profitability of all technologies taken together.

Thus, from the expected profitabilities per unit of output and from the stocks of knowledge of each technology, the distribution of the technologies in terms of output capacities is given by equation (3.33). On the other hand, the optimal labour intensity, and thus the capital productivity, is given from the optimizing behaviour of firms, which is analogous to the determination of the optimal labour intensity in

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98. Note that the amount of information is defined as the aggregate amount of output and that the stock of knowledge is an increasing function of this aggregate amount of information. As stated previously, we will summarize this process by just one equation and we will use the term ‘knowledge stock’ for K_t^i.

99. So n_τ is equal to $\tau - i_\tau^{\max} + 1$.

the non-diffusion model. The distribution of technologies with respect to the output capacities can be transferred to the distribution of technologies with respect to amounts of investment. Given the total amount of investment, we can derive the amount of investment for each technology. This is elaborated in section 3.2.5.

Although the distribution of technologies stems from the epidemic approaches, we do not use a logistic diffusion curve as such. In the previous chapter, we mentioned two shortcomings of the standard logistic diffusion curve: a constant (expected) profitability of each technology and a fixed saturation level which has to be determined in advance. Our diffusion pattern results from the cumulative distribution of technologies in the course of time and the distribution at time t depends on both the expected profitability and the stock of knowledge at that same point in time. Furthermore, we allow for ex-post improvements of existing technologies. The end of the diffusion pattern, i.e. the saturation level, is determined endogenously and may change over time.

But does this specification lead to S-shaped diffusion curves? This question cannot be answered for the general case. Even if we make some restrictive assumptions, the shape of the diffusion pattern still depends on parameter values and on the development of the relative profitability.

The main problem we face is that the number of technologies may change over time which means that the share in total investment also changes, ceteris paribus. Moreover, the distribution with respect to the profitability may change, which also leads to changes in the distribution of technologies with respect to the amount of investment and finally, the total amount of investment may change. Consequently, the accumulated amount of information will change leading to fluctuations of the knowledge distribution, which in turn leads to further reactions because of the path dependency. This implies that the shape of the diffusion curve cannot be determined a priori in a changing environment. This also implies that, in order to answer the above question, we have to make some rather restrictive assumptions. The actual diffusion patterns as generated by the estimated model and by using actual data are discussed in the next chapter.

Assume that the number of different technologies is constant in time and that the expected relative profitability of all investment goods decreases with the age of the incorporated technology. For convenience, we assume that the profitability decreases linearly with the age of the technology here, but this is not required to obtain an S-shaped diffusion path. Moreover, suppose that this distribution of expected profitabilities does not change over time. The relative profitability of all technologies at one point in time, such as given in the figure by line π, is equal to the relative profitability of one technology in the course of time if these assumptions hold. From our definition of the relative profitability and from the assumption that the profitability decreases linearly as the technology becomes older, it follows that the expected profitability of the newest technology is twice as high as the average profitability of all technologies taken together and the expected profitability of the oldest technology is zero. This also implies that the relative profitability of a new technology at time zero is equal to two and that this term is zero if this technology becomes the oldest one.

Starting with an initial knowledge stock (K_0^i), some firms will invest in that technology at time 0. The share of output in total output of all new investments is given by equation (3.33) and denoted by the curve x^c in Figure 3.3. Firms will produce output with this new technology and will generate, publicly available, information which is added to the initial stock of knowledge. Although the relative profitability decreases in the next year, the relative amount of investment will increase due to the increased knowledge stock (kn). Producing output will again generate information which increases the stock of knowledge leading to yet another increase of the amount of investment in the following year. This process will continue until the amount of investment, given by the curve x^c, reaches a maximum. This maximum is determined by two different forces. First, the expected profits will decrease steadily such that this will put a downward pressure on the relative amount of investment. Secondly, it is assumed that new information will duplicate existing information to a larger extent if the stock of knowledge increases. The growth rate of the knowledge stock decreases so that the impact of decreasing profitabilities will finally overrule the impact of the growing knowledge stock. This process continues until the expected profits are equal to or below zero. No firm will invest in such a technology any more, and so the diffusion process stops. In this example, the diffusion process, which is defined as the cumulative amount of investment, is S-shaped.

Mathematically, the diffusion curve is S-shaped if the first derivative of the amount of investment changes sign from positive to negative, i.e., if:

$$\frac{dx_t^c}{dt} \gtreqless 0 \quad \text{for} \quad t \lesseqgtr t^* \quad \text{where } 0 < t^* < T \tag{3.37}$$

Taking the derivative of equation (3.33) and dividing both sides by x_t^c, which is always positive by definition, yields:[100]

$$\hat{x}^c = \alpha_1 \frac{dkn}{dt}\frac{1}{kn} + \alpha_2 \frac{d\pi}{dt}\frac{1}{\pi} \tag{3.38}$$

The initial amount of knowledge (α_0) is assumed to be small. Furthermore, $0 < \alpha_1 < 1$ and the relative profitability exceeds one by definition which means that the initial amount of investment exceeds α_0, cf. equation (3.33). This implies that the relative addition to the stock of knowledge exceeds one. The relative decrease of the profitability cannot exceed one so that the first derivative is likely to be positive in the

100. Note that we assumed that total investments as well as the development of the profitability are constant in time. This implies that the scale factor, s_τ in equation (3.33), is constant. Indeed, the scale factor would vary if these restrictive assumptions do not hold true, which would make the analysis of the shape of the diffusion pattern even more complicated.

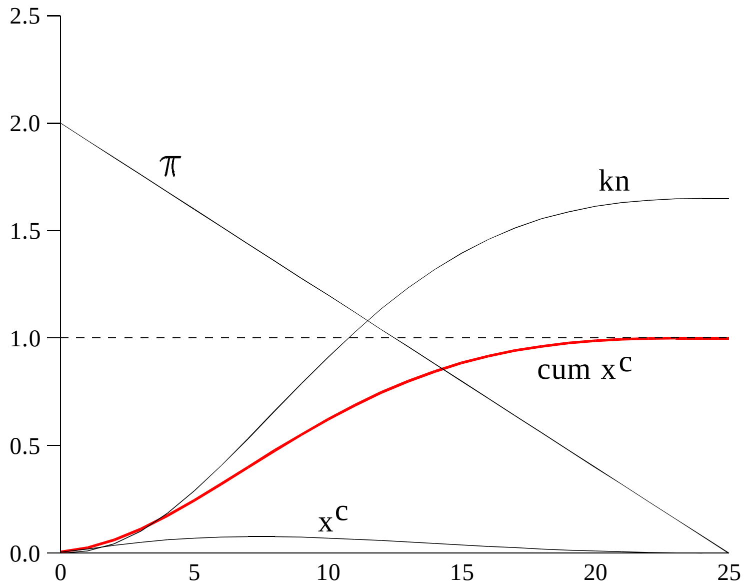

Figure 3.3. Determination of the diffusion process

initial stage of the diffusion process if the importance of knowledge cannot be neglected, relative to the importance of profitability, that is, if α_1 / α_2 is not too small. On the other hand, if the process goes on, the stock of knowledge will grow whereas the profitability will decrease towards zero. At the end of the diffusion process, π will tend to zero whereas kn is equal to some finite number. From that, it is likely that the derivative is negative, leading to an S-shaped diffusion process.

Note that a smooth S-shaped diffusion path, as shown in Figure 3.3, is mainly determined by the smoothly decreasing profits. Note furthermore that the diffusion process is highly path-dependent due to the way knowledge is accumulated. It is likely that the diffusion path will be S-shaped if we use actual data, but it is unlikely that this path will be smooth to the extent shown in the figure. The next chapter will present the diffusion patterns as a result of the estimated model when making use of actual data.

3.2.3 Production Structure Ex-Post

We assume that disembodied technological change is the same for all technologies. In a more sophisticated model we could link disembodied technological progress with the age of the technology or the amount of output as a proxy of the accumulation of technology-specific human capital, but to keep the model simple we will ignore this. As before, the ex-post productivities are given by:

$$\lambda^i_{\tau,t} \equiv \frac{X^i_{\tau,t}}{N^i_{\tau,t}} = \frac{hn_t}{hn_\tau}(1+\varepsilon_n)^{t-\tau}\frac{X^i_{\tau,\tau}}{N^i_{\tau,\tau}} \quad \text{with: } \varepsilon_n \geq 0 \tag{3.39}$$

and

$$\kappa^{i}_{\tau,t} \equiv \frac{X^{i}_{\tau,t}}{I^{i}_{\tau,t}} = \frac{hi_t}{hi_\tau}(1+\varepsilon_i)^{t-\tau}\frac{X^{i}_{\tau,\tau}}{I^{i}_{\tau,\tau}} \quad \text{with: } \varepsilon_i \geq 0 \tag{3.40}$$

where ε_n stands for the labour-augmenting and ε_i for the capital-augmenting disembodied technological progress. Again, both are assumed to be non-negative.

Furthermore, physical deterioration, or scrapping due to wear and tear, is assumed to be independent of the incorporated technology:

$$I^{i}_{\tau,t} = \Omega_{t-\tau} I^{i}_{\tau,\tau} \qquad \forall\ i \in \{i^{\max}_{\tau},\ldots,\tau\} \tag{3.41}$$

3.2.4 *Expectations*

We assume that all firms will have the same adaptive expectations with regard to the price of output, wages, rate of interest and working hours, independent of their choice with respect to the embodied technology. The expectations are described in the non-diffusion model.

As already noted above, it is not likely that the expected lifetime is the same for each technology, but if we employ the concept of consistent expectations, we can derive the expected lifetime endogenously for each individual technology. The way in which the expected lifetime is determined is the same as in the non-diffusion model. The equivalent of equation (3.15), the expected lifetime as a function of the initial labour productivity, is now equal to:

$$\theta^{i}_{\tau} = \ln\left(\frac{w_\tau}{\lambda^{i}_{\tau,\tau}}\frac{1}{p_\tau}\right) \cdot \left(\ln\left[\frac{(1+\hat{hn}^{e}_{\tau})(1+\varepsilon_n)(1+\hat{p}^{e}_{\tau})}{1+\hat{w}^{e}_{\tau}}\right]\right)^{-1} \tag{3.42}$$

The only difference between the diffusion model and the non-diffusion model is that the initial labour productivity depends on the incorporated technology in the diffusion model. In general, the labour productivity will decrease as the incorporated technology is less advanced. This will be elaborated after the presentation of the optimal labour intensity.

3.2.5 *Price and Quantity Indices of Investment*

Although we treat the total amount of investment as an exogenous variable, we are interested in the amount of investment of each technology. Furthermore, the price index of investment for each technology has to be known. The data material contains indices for the volume of invested equipment and means of transport and the corresponding price level for each year. This implies that we have to decompose these data in order to derive the amount of investment and the price level for each individual technology. This leads to three different problems: (i) what is the development of the price of a technology in the course of time, relative to all other technologies; (ii) which method has to be used to decompose the data in such a way that both price indices and quantity indices are consistent, and finally, (iii) how do we treat technological change in this decomposition method?

From the production function, it follows that the capital productivity changes due to embodied technological change. Furthermore, this type of technological change is assumed to proceed at a constant rate. This implies that succeeding technologies are more productive, ceteris paribus.[101] It seems reasonable to assume that the price of an investment good, relative to the price of all other investment goods, will fall over time as its incorporated technology becomes older. On the other hand, it is likely that prices of equipment are related to the development of the aggregate price level of all investment goods taken together. This implies that the price of equipment can be written as:

$$q_\tau^i = f(Q_\tau, \tau - i) \quad \text{with } f_2 < 0 \text{ and } f_{22} > 0 \tag{3.43}$$

i.e., the price of a technology depends on the general price index (Q_τ) and on the age of the incorporated technology ($\tau - i$). Furthermore, it seems plausible that the rate of decline with respect to the age is constant, given a constant rate of embodied technological change.

The answer to the second question, as to which method has to be used to decompose the data, is straightforward as we know that the Central Bureau of Statistics, CBS for short, uses Paasche price and Laspeyres quantity indices to aggregate the micro-data. The best we can do is to use the same methods in order to decompose these data.

The answer to the last question is less obvious, however. CBS uses two distinct methods to handle technological change, i.e., if new investment goods are introduced. The first one is to wait one year with the introduction of the new good into the indices. After one year, prices and quantities of that new good are known for two consecutive years so that it can be incorporated in the indices. The second method is to ignore quality changes and to treat all investment goods as if they did not change. Although we think that the first method is the most correct one, CBS uses the second method more frequently and we will use the latter method to decompose our data.

In appendix 3A, we show that equation (3.43) is consistent with the Paasche index if it can be written as:

101. Note that factor productivities are not only determined by the shift of the production function but also by the initial capital-labour ratio. But the capital intensity depends, amongst other things, on the price of capital so that we would end up with a simultaneous system if we take this ratio into account.

$$q_\tau^i = Q_\tau f(\tau - i) \tag{3.44}$$

which simply says that the price of equipment, relative to the price of all other technologies, depends on the age of the incorporated technology whereas the (absolute) prices of all technologies are proportional to the aggregate price index. Above, we assumed that the rate of decline of the prices with respect to the age of the technology is constant. This implies that equation (3.44) can be written as:

$$q_\tau^i = Q_\tau \exp^{(-\beta(i-\tau-\bar{l}))} \quad \forall \ i \in \{i_\tau^{\max},...,\tau\} \tag{3.45}$$

in which Q_τ describes the (exogenous) aggregate price index for investment goods and $\bar{l}$ denotes the average number of technologies.[102] The parameter β describes the sensitivity of the price with respect to the incorporated technology and is to be estimated.

The amount of investment for each technology can be easily derived from the Laspeyres quantity index as is shown in appendix 3A. Total capacity output of the entire new vintage, i.e., all technologies taken together, is equal to:

$$X_\tau^c = \frac{Q_\tau \ I_\tau}{\sum_{i=i_\tau^{\max}}^{\tau} q_\tau^i \ \frac{x_\tau^{c\,i}}{\kappa_\tau^i}} \tag{3.46}$$

in which I_τ denotes the (exogenous) aggregate amount of investment. The amount of investment in each technology is given by the capacity output of that technology divided by the capital-output ratio. So we find for $I_{\tau,\tau}^i$:

$$I_{\tau,\tau}^i = \frac{x_\tau^{c\,i} \ X_\tau^c}{\kappa_\tau^i} \qquad \forall \ i \in \{i_\tau^{\max},...,\tau\} \tag{3.47}$$

The amount of investment in each technology is determined as follows. The total amount of investment (I_τ) and its price index (Q_τ) are exogenous. Furthermore, given the optimal choice of labour intensities, which is presented in the next section but which is comparable with the choice in the non-diffusion model, both the expected profitability per unit of output and the capital productivity can be determined. Whether the expected profits are negative is also determined by this optimal which determines the oldest technology ($i_\tau^{\max}$). The stock of knowledge was determined in the past which means that the distribution of technologies with respect to their output capacity ($x_\tau^{c^i}$) can be determined according to equation (3.33). Substitution of these variables into equation (3.46) yields the total output capacity of the whole vintage (X_τ^c), that is, of current investment in all technologies

102. We added this average number of technologies in order to ensure that prices of individual machines move around the aggregated price level. Note that this will not be the case if the number of machines fluctuates very significantly. From our estimates it followed that the average number of technologies in the period 1960-1988 is equal to about 7.

together. The amount of investment in each technology is finally determined by equation (3.47).

This implies that, given the relative prices between the technologies, we can determine a price index for each individual technology according to the Paasche price index rule. Furthermore, given the initial distribution of technologies in terms of invested capacity output, we can derive the amount of investment as well as the total capacity output of all newly installed technologies taken together according to the Laspeyres quantity index rule. This is, we think, the most close we can get to the aggregation methods of the CBS, without introducing many ad hoc elements into our analysis.

3.2.6 Choice of the Production Technique

The solution of the optimal labour intensity is analogous to the determination of the labour intensity in the non-diffusion model. The net present value of the expected rents in terms of initial factor requirements is:

$$PV^i_\tau = p_\tau \; X^i_{\tau,\tau} \; S_1(\theta^i)_\tau - w_\tau \; N^i_{\tau,\tau} \; S_2(\theta^i)_\tau - q^i_\tau \; I^i_{\tau,\tau} \tag{3.48}$$

with:

$$S_1(\theta^i)_\tau = \sum_{t=\tau}^{\tau+\theta^i_\tau-1} \left\{ \left[\frac{(1+\hat{p}^e_\tau)\;(1+hi^e_\tau)\;(1+\varepsilon_i)}{(1+r^e_\tau)} \right]^{t-\tau} \Omega_{t-\tau} \right\}$$

and:

$$S_2(\theta^i)_\tau = \sum_{t=\tau}^{\tau+\theta^i_\tau-1} \left\{ \left[\frac{(1+w^e_\tau)\;(1+hi^e_\tau)\;(1+\varepsilon_i)}{(1+r^e_\tau)\;(1+\hat{hn}^e_\tau)\;(1+\varepsilon_n)} \right]^{t-\tau} \Omega_{t-\tau} \right\}$$

in which the expected lifetime (θ^i_τ) follows from equation (3.42). The terms S_1 and S_2 depend on the technology only through the expected lifetime. All other variables are assumed to be the same for all technologies and/or firms. Maximising equation (3.48) with respect to the input factors labour and capital, conditional on the production function, results in the optimum level of the initial labour intensity:

$$l^i_{\tau,\tau} \equiv \frac{N^i_{\tau,\tau}}{I^i_{\tau,\tau}} = \left(\frac{w_\tau \; S_2(\theta^i)_\tau}{q^i_\tau} \right)^{\frac{-1}{1+\rho}} \left(\frac{A^i_\tau}{B^i_\tau} \right)^{\frac{-\rho}{1+\rho}} \tag{3.49}$$

which is equivalent to the optimal labour intensity in the non-diffusion model.

The main difference between both models is that the terms A_τ, B_τ and q_τ are technology-dependent and that the expected lifetime may differ between different technologies. As we have done before, we will present the graphical solution of the optimal labour intensity and the expected lifetime, but now for two different technologies.

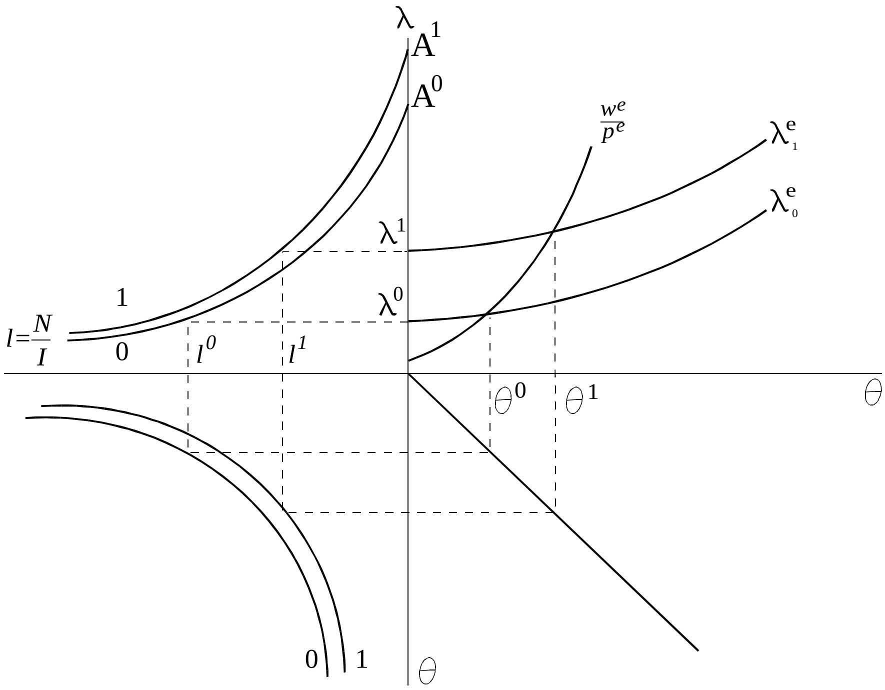

Figure 3.4. Determination of the expected lifetime at time τ in the case of two different technologies

In Figure 3.4, it is assumed that technological progress is mainly labour-augmenting. The measure of the effectiveness of the labour force of the least advanced technology, A^0, is below A^1, the equivalent measure for technology 1. As is shown in the north-west quadrant, the labour productivity, related with the new technology, is above the labour productivity of the older technology, given the same labour intensity. The optimal labour intensity of the new technology, curve 1 in the south-west quadrant, is assumed to be below the labour intensity of the older technology, for a given length of the planning period. This is the case if the contribution of a relative change in the price of capital goods is below the impact of the relative change of embodied technological progress.[103] The consistent expected lifetime of the newest technology is larger than the expected lifetime of the older technology. This will be the case unless technological change is merely capital-

103. Cf. equation (3.49). In this equation, the wage rate as well as the term $S_2(\theta)_\tau$ are the same for both technologies for a given length of the planning period. Both the price of the capital good (q_τ) and the embodied technological change measures (A_τ and B_τ) will be different for different technologies. In this particular example, technological change, from technology 0 to technology 1, is merely labour-augmenting whereas the price of technology 1 is higher but not high enough to offset the influence of technological change on the labour intensity. Otherwise, the labour intensity of technology 1 would be higher than the labour intensity of technology 0, for a given length of the planning period.

augmenting and the difference between the price of the capital goods is relatively high.[104]

3.2.7 Scrapping of Equipment

We did not introduce the Malcomson scrapping condition in our non-diffusion model by arguing that this rule cannot be applied to the vintage-diffusion model. The Malcomson scrapping rule says that a vintage is scrapped if the total (variable plus fixed) costs per unit of output of a new vintage are below the variable costs of the older one. In that case, a firm could increase profits by replacing the old by the new, even if the old vintage yields positive quasi-rents. If we use a representative firm, i.e., if all firms would be the same so that the vintage structure would be the same, one could apply this rule. But in our vintage-diffusion model, some firms will invest in newer types of equipment whereas other buy older technologies. Furthermore, the distribution of investment with respect to the technologies is not related to firm characteristics, which implies that we cannot assign technologies to firms. This implies that we do not know which new technology should be compared with which existing technology, so that we cannot apply the Malcomson rule in our vintage-diffusion model.[105]

In the diffusion model, the quasi-rent of each individual machine is evaluated. Because vintages are subdivided into several machines it is likely that parts of vintages are scrapped at one point in time, instead of complete vintages as is the case in the non-diffusion model. More smooth scrapping will reduce the discontinuities due to the scrapping condition and will reduce the severe estimation problems of the standard vintage models.[106] As in the non-diffusion model, we

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104. Cf. footnote 103. Note that the labour productivity for a given value of the labour intensity, will always be higher for a more advanced technology (cf Figure 3.2). This implies that the labour intensity of the older technology has to be considerably below the labour intensity of the newest technology, given the same length of the planning period, to obtain a higher initial labour productivity for the less advanced technology. The expected lifetime proves to be longer for more advanced technologies from the estimation results so that the latter case does not emerge in our results.

105. A competitive output market is an alternative argument to avoid the Malcomson scrapping condition — the output price is then equal to the total costs per unit of output of the newest vintage so that the quasi-rent condition, which says that variable costs per unit of output of the oldest vintage is equal to the output price, coincides with the Malcomson scrapping rule. But in our model, it is not guaranteed that total costs per unit of output on the newest vintage are equal to the (observed) output price. This notion is used in Meijers and van Zon (1991). They assume a competitive output market whereas they apply the Malcomson condition to determine scrapping behaviour.

106. GWJ apply a smooth quasi-rent condition to solve estimation problems. They assume that a fraction of a vintage is scrapped if the quasi-rent becomes negative. This fraction depends in their model on the magnitude of the quasi-rent which implies that, on average, firms will scrap equipment if the variable costs per unit of output are about 7% below the returns. This loss-making behaviour is not justified, however. As noted before, MvZ assume a distribution of firms along each isoquant. This reduces discontinuities in their model.

also allow for scrapping due to underutilisation, next to scrapping due to negative quasi-rents.

The difference of the amount of scrapping due to negative quasi-rents between the standard vintage models and the diffusion-vintage model can be made clear by the use of a Salter diagram.[107] Such diagrams are given in Figure 3.5 in which the standard vintage model is displayed at the top. The amount of output of all existing vintages is given on the horizontal axis. The labour costs per unit of output are displayed on the vertical axis. In the top figure, we plotted six different vintages. The newest vintage, which is installed at time 7, bears the lowest labour costs per unit of output. The total labour costs of that vintage are given by rectangle number 7. If the output price at that moment is equal to p_7, the total returns of that vintage are given by the rectangle $oabp_7$ and the quasi-rent is equal to the difference between total labour costs and total returns.

All older vintages bear higher labour costs per unit of output, or, given the fact that the wage rate is the same for all vintages, older vintages are less productive. The vintage-diffusion model is given in the lower figure. A vintage contains several different technologies which differ from each other with respect to the labour productivity. The upper number denotes the time of installation, i.e., the vintage, and the number at the bottom denotes the time at which the incorporated technology is introduced. The capital good which is installed at time 7, and which contains the most recent technology is the most productive and bears the lowest labour costs per unit of output. This is the best-practice technology at time 7. The most productive but one machine is again installed at time 7 but contains the technology which stems from year 6.

Note that the machines are sorted with respect to the labour productivity and that vintages are mixed. Machine ${}^{6}_{6}$, for example, is more productive than machine ${}^{7}_{5}$. The least productive machine in this figure is indexed by ${}^{3}_{0}$.

Suppose that, at time 6, the output price is above the unit labour costs of the oldest vintage and of the least productive machine and that this price falls relative to the wage rate towards p_7 at time 7. In the non-diffusion model, vintage number 2 yields negative quasi-rents and will be scrapped completely. In the vintage-diffusion model, however, only machine ${}^{3}_{0}$ will be scrapped, which is much smaller in terms of productive capacity. Suppose that in the next year, the relative price declines towards p_8. In the non-diffusion model, no vintage will be scrapped at that point in time but in the vintage-diffusion model, machines ${}^{2}_{1}$ and ${}^{3}_{1}$ will be scrapped.[108]

107. Cf. Salter, 1960.

108. Note that we de not consider new investments. These new vintages and new machines would be added at the left-hand side of the figure. This does not influence the amount of scrapping and is not displayed.

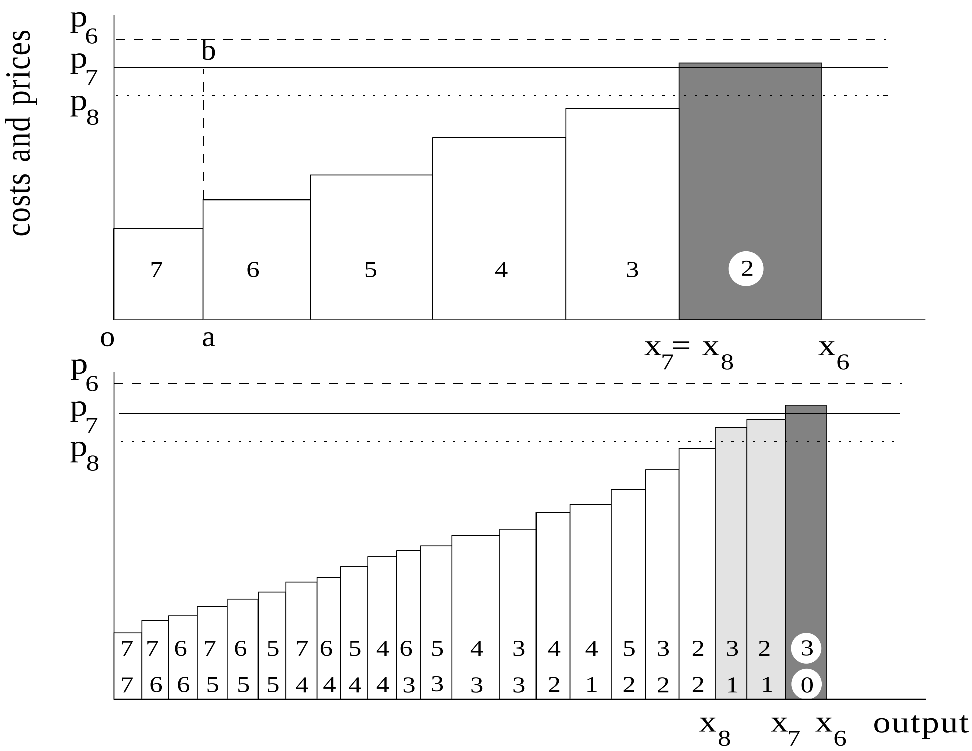

Figure 3.5. Scrapping in the non-diffusion and in the diffusion vintage model

This implies that scrapping due to negative quasi-rents will lead to larger fluctuations in the standard vintage model than in the vintage-diffusion model. The estimation problems due to severe discontinuities are partly solved by further decomposition of the capital stock. The smaller these discontinuities, the larger the number of different technologies within each vintage. Scrapping due to severe underutilisation is assumed to decrease the total output capacity, leading to the same result in both models, at least in terms of reduction of output.

3.2.8 Productive Capacity and the Demand for Labour

The total capacity in a year can be derived by aggregating the capacity of all machines (and parts of machines) which still exists at that point in time:

$$X_t^c = \sum_{\tau \in V_t^1} \sum_{i \in V_{\tau,t}^2} X_{\tau,t}^i \qquad (3.50)$$

In this equation $V_{\tau,t}^2$ describes the set of machines embodying technology i which belongs to vintage τ which are not scrapped at time t. V_t^1 is equal to the set of those vintages for which the set $V_{\tau,t}^t$ is not empty. The capacity demand for labour is derived in the same way:

$$N_t^c = \sum_{\tau \in V_t^1} \sum_{i \in V_{\tau,t}^2} N_{\tau,t}^i \qquad (3.51)$$

As before, we assume that if the utilisation rate is below unity, the least productive machines are disposed of first. The lower bound on the labour productivity, $\bar{\lambda}_t$, is defined in such a way, that:

$$\sum_{\tau \in V_t^1} \sum_{\{i \in V_{\tau,t}^2 \mid \lambda_{\tau,t}^i > \bar{\lambda}_t\}} X_{\tau,t}^i = X_t \qquad (3.52)$$

holds. The minimal demand for labour which is just enough to produce the actual output at any point in time is equal to:

$$N_t^- = \sum_{\tau \in V_t^1} \sum_{\{i \in V_{\tau,t}^2 \mid \lambda_{\tau,t}^i > \bar{\lambda}_t\}} N_{\tau,t}^i \qquad (3.53)$$

We assume, as before, that the amount of labour which is hoarded is equal to a constant fraction of the difference between capacity demand for labour and the minimal demand for labour. So the total demand for labour equals:

$$N_t = N_t^- + \xi \, (N_t^c - N_t^-) \qquad \text{with: } 0 \leq \xi \leq 1 \qquad (3.54)$$

which completes the vintage-diffusion model.

3.2.9 Summary and Implementation of the Vintage-Diffusion Model

In the vintage-diffusion model, it is assumed that each year a new technology comes onto the market for capital goods. The nature of the improvement of this new technology with respect to the older technologies can be both labour- and/or capital-augmenting. Furthermore, it is assumed that the price of an investment good, relative to the prices of all other existing technologies at that point in time, increases as the technology incorporated is more advanced, i.e., if it is based on a more recent design. Firms are assumed to be distributed with respect to risk aversion and it is assumed that the relative amount of investment in a certain technology depends on the expected profitability of that technology and of the knowledge about that technology.[109]

The newest technology is determined exogenously whereas the oldest technology is determined on economic grounds. It is assumed that firms will not invest in a technology if the expected profits are negative, i.e, if factor prices are too high relative to the productivity. This implies that there is a range of different technologies, graphically represented as a range of different isoquants. This range of isoquants will move towards the origin in the course of time.

The choice of the optimal initial labour intensity is the result of maximizing behaviour and is the same in both the non-diffusion and the diffusion model and depends, among other things, on the expected lifetime of equipment. We know

109. Note that risk does not enter the model in a formal way. Without elaborating this in detail, the distribution is assumed to be the result of firm behaviour under risk aversion. Although this will be done in another setting, part III presents a model in which the relation between the choice of technologies and risk aversion is considered explicitly.

from other studies, such as KvZ and GWJ, that the actual lifetime of equipment has decreased to a large extent within our estimation period. Furthermore, the rule of MvZ cannot lead to consistent expectations if the actual lifetime falls over time. But from the model, we can determine the expected lifetime endogenously. This solves two problems, the inconsistency of the MvZ rule and the problem of how the expected lifetime would differ between different technologies.

There are several differences between the diffusion and the non-diffusion model but the most important is that the transmission of technological change is partly endogenized by the vintage-diffusion model. If, for instance, the relative expected profitability of new technologies decreases, fewer firms will invest in these technologies. This will shift the distribution as a result of which firms will invest in older technologies, decreasing the impact of technological change. An example of such a shift is given in Figure 3.6. Assume that at time t, the distribution of capacity output with respect to the existing technologies is skewed to the left so that the (weighted) average labour productivity of the whole new vintage is equal to *av* in the figure at the top. At time $t+1$, a new technology comes onto the market for capital goods and we assume that the least productive technology at time t yields negative expected rents so that the number of technologies is not changed from t to $t+1$.[110] If the relative profitability of older technologies increases, for instance due to a decrease of the wage rate so that differences between technologies in terms of labour costs are reduced, more firms will invest in less advanced technologies and the distribution skews to the right. This can imply that the average productivity of the newest vintage, i.e., all technologies taken together, decreases from time t to $t+1$. In other words, the profitability distribution can alter the average productivity of the newest vintage in the diffusion-vintage model, even if the productivity of all individual technologies does not change.[111]

Moreover, if firms invest less in the new technology, they will accumulate less information so that the stock of knowledge for the newer technologies will decrease, relative to the stock of knowledge of older technologies. This will again drift the distribution towards older technologies even if the profitability distribution would not change any more. The model inhibits path dependencies through the generation of knowledge.[112]

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110. For simplicity, we also assume that the impact of substitution is small leaving labour productivities of existing technologies unchanged.

111. Of course, if the growth rate of wages decreases, firms will choose a more labour-intensive way to produce output, leading to a decrease in labour productivity due to substitution. But this effect will be about the same in the vintage-diffusion model as well as in the non-diffusion vintage model.

112. Note that the Malcomson scrapping condition can also explain variation in growth rates of (labour) productivity to some extent. If the total costs per unit of output of new equipment decreases, due to increased productivity for instance, firms will replace old but still profitable machinery by new equipment so that the productivity of the total capital stock increases. Yet if the profitability of newer equipment declines, there will be fewer replacement investments but scrapping is bounded from below by the negative-quasi rent condition which implies that the growth rate of labour productivity is bounded from below. Moreover, there are no path dependencies which are equival-

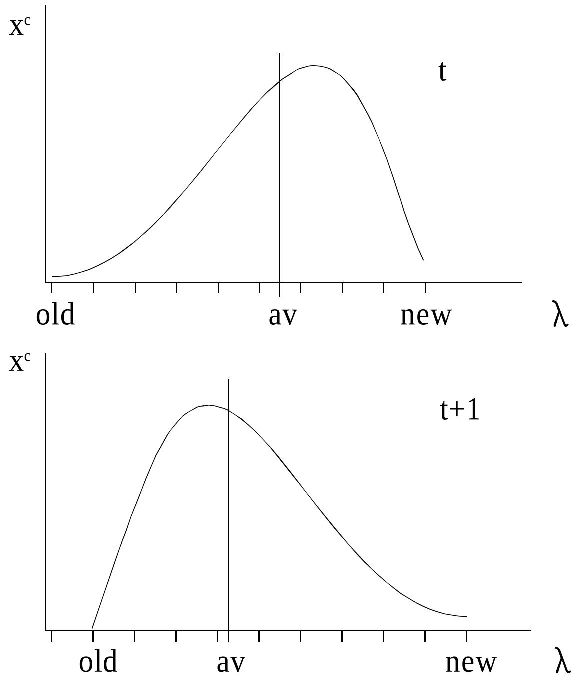

Figure 3.6. Effect of changes in the distribution on labour productivity of the newest vintage

Furthermore, the scrapping condition will lead to fewer discontinuities because a vintage is no longer homogeneous. Changes in the output capacity due to scrapping as well as changes in the aggregate demand for labour will be less sensitive to changes in the real wage rate in the vintage-diffusion model. This will remove some of the estimation problems of the standard vintage models.

With respect to the models on adoption and diffusion of new technologies, we included both the investment stage and the scrapping stage in our model thus covering the complete life-cycle of equipment. Moreover, we relaxed the restrictive assumption that supplying industries do not improve the technologies once they have been invented. We also relaxed the assumption that the profitability of each technology is fixed over time, which may occur due to changes in the wage rate or due to changes in the price of investment goods, for instance, even if there are no ex-post improvements. Finally, we do not impose an a priori ceiling level of the diffusion process.

Before discussing the estimation procedure and the estimation results, we will briefly summarize the model and the way it is implemented in an estimation procedure. For each year, the initial labour intensity is calculated for all available technologies, according to equation (3.49). This includes the determination of the length of the planning period (equation (3.42)). Given the optimal labour intensity, we are able to calculate the expected net present value of future rents per unit of

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ent to the generation of knowledge.

output for each technology. All technologies for which the expected net present value is negative are excluded. For the remaining technologies, we know the stock of knowledge from previous output as well as the expected profits. From this, we can determine the distribution of the technologies according to equation (3.33). Although, at least in principle, the amount of investment could be made endogenous, we follow the Dutch vintage modelling tradition and assume exogenous investment.[113] Moreover, part III will take endogenous investment decisions into account.

Given the exogenous total amount of investment, we can determine the capacity output of the whole vintage, thus all technologies together, according to equation (3.46), and the amount of investment for each technology (equation (3.47)). This new vintage, which incorporates several technologies, will be added to the existing capital stock. This concludes the investment stage of the model.

Next, all existing machines are updated with respect to disembodied technological progress and changes in working time according to equations (3.39) and (3.40). After that, we determine which vintages and/or machines have to be scrapped. Scrapping due to wear and tear, including a maximum lifetime of 45 years, will be employed first. Subsequently, we determine for which machines the quasi-rent is negative. This equipment is also scrapped. Finally, we determine the rate of capacity utilisation. If this rate is below the normal rate and if this was also the case in the two preceding years, we will scrap a fraction of the capital stock according to equation (3.21), which also holds for the vintage-diffusion model. The least productive machines are scrapped first. This concludes the scrapping procedure.

Finally, the output capacity of all individual machines and the corresponding demand for labour are aggregated, which results in aggregate capacity output and in aggregate capacity demand for labour. Given the exogenous actual output, we determine the demand for labour which is needed to produce this amount of output. The difference between capacity demand and minimal demand is used to determine the amount of labour hoarding. This results in the aggregate demand for labour. The whole procedure is repeated for all subsequent years to generate time series for the output capacity and for the demand for labour. The parameters of the model will be estimated by confronting these series with actual data. Chapter 4 presents the estimation results. We will compare the results of the diffusion model with the results of the non-diffusion model. Moreover, we will compare our results with the results of Gelauff, Wennekers and de Jong (1985) and those of Muysken and van Zon (1987).[114] Finally, we will examine to what extent the productivity slowdown and the productivity paradox can be explained by our vintage-diffusion model.

113. Muysken and van Zon (1987) describe an investment function in the theoretical part of their model, but treat them, mainly due to estimation problems, exogenous in their empirical part.

114. See also footnote 61 on page 59.

Appendix 3A. Price and Quantity Indices Regarding Investment

In the main text, we stated that the Central Bureau of Statistics (CBS) does not incorporate quality changes in their aggregation methods. As we use the same method to decompose the data, we compare the best-practice technology at time τ with the best-practice technology at time $\tau-1$, the one year old technology at time τ with the one-year old technology at time $\tau-1$ and so on.

According to the Paasche chain index, the index for the price of investment is given by:

$$\frac{Q_\tau}{Q_{\tau-1}} = \frac{\sum_{i=i_\tau^{\max}}^{\tau} q_\tau^i \, I_{\tau,\tau}^i}{\sum_{i=i_\tau^{\max}}^{\tau} q_{\tau-1}^{i-1} \, I_{\tau,\tau}^i} \tag{3A.1}$$

where Q_τ stands for the exogenous price index of total investments in year τ. It is easy to verify that the price function (equation (3.45)) is consistent with this Paasche chain rule.

Given the prices of all individual machines, we can derive the amount of investment for each technology. From equation (3.33) we know the distribution of technologies in terms of their productive capacity, and from the optimization behaviour of firms we can obtain the initial capital productivity (cf. equation (3.6)). The amount of investment for each machine is equal to the capacity output divided by capital productivity by definition. The capacity output of an individual machine equals the relative capacity output, which originates from the diffusion process, multiplied by the total capacity output of the entire vintage. So we find for $I_{\tau,\tau}^i$:

$$I_{\tau,\tau}^i = \frac{X_{\tau,\tau}^i}{\kappa_\tau^i} = \frac{x_\tau^{c\,i} \, X_\tau^c}{\kappa_\tau^i} \qquad \forall \; i \in \{i_\tau^{\max},...,\tau\} \tag{3A.2}$$

We know that the value of total investments has to be equal to the sum of the values of investments in all technologies:

$$Q_\tau \, I_\tau = \sum_{i=i_\tau^{\max}}^{\tau} q_\tau^i \, I_{\tau,\tau}^i \tag{3A.3}$$

where I_τ refers to the exogenous amount of total investments in year τ. By substituting equation (3A.2) into equation (3A.3) we find:

$$Q_\tau \, I_\tau = X_\tau^c \sum_{i=i_\tau^{\max}}^{\tau} q_\tau^i \, \frac{x_\tau^{c\,i}}{\kappa_\tau^i} \tag{3A.4}$$

From this equation, we can obtain an expression for the capacity output of the entire vintage:

$$X_\tau^c = \frac{Q_\tau \, I_\tau}{\sum_{i=i_\tau^{\max}}^{\tau} q_\tau^i \, \frac{x_\tau^{c\,i}}{\kappa_\tau^i}} \tag{3A.5}$$

Thus, we transformed the capacity distribution into a distribution of investments using the optimal capital productivity and scaled the distribution of investments in such a way that the sum of investments in terms of their money value equals the aggregated value of total investments.

The total capacity output of the entire vintage follows from equation (3A.5) and the amount of investment for each technology can be easily obtained by using equation (3A.2).

4 Estimation Results

This chapter presents the estimation results of both the non-diffusion and the diffusion vintage model.[115] These models are estimated using Dutch data of the enterprise sector for the period 1960 until 1988. The first section describes the data and the employed estimation methods. The parameter estimates and the estimation results are presented in section 4.2, together with the results on the diffusion process. That section also presents some other results of both models, such as the amount of scrapping, the expected and the realized lifetime of equipment. The initial factor coefficients will be analyzed in order to determine the magnitude of technological change versus substitution. Finally, section 4.3 presents the development of labour productivity in the Netherlands. Figures on productivity growth are compared with the results of Gelauff, Wennekers and de Jong (1985). Moreover, a relation between changes in productivity growth and changes in the speed of diffusion is considered. This will provide some new insights in the productivity slowdown.

4.1 Data and Estimation Procedure

The model is estimated for the period 1960-1988 using Dutch data for the whole enterprise sector excluding natural gas and housing. The time series of the exogenous variables we used are data on investment and value added (both prices and quantities), the wage rate, the long-term interest rate, an index for the number of hours worked per year and a technical survival scheme of capital which covers scrapping due to wear and tear. The endogenous data are the demand for labour and the rate of capacity utilisation from which the output capacity can be obtained, given the actual, exogenous, output in terms of value added. All data and their sources are given in appendix 4A.

115. Parts of this chapter draw on Meijers (1994).

Between 1915 and 1924 the data show a sharp rise in the wage rate, both in nominal and in real terms. Assuming positive expected rents for all vintages, the parameters describing technological progress, especially the labour-augmenting technological progress, are heavily influenced by this shock in factor prices. Similar to Gelauff, Wennekers and de Jong (1985), we replaced the data for the wage rate, the interest rate, the price levels of output and investments between 1915 and 1924 by data computed from the average growth during that period.[116]

The objective function which we used to estimate the parameters of the model have been derived from a maximum likelihood approach, cf. Smallwood (1972) and Gelauff (1987). The objective function is (cf. appendix 4B):

$$F = \sum_{t=1960}^{1988} \left\{ \left(\frac{X_t^c}{\hat{X}_t^c} - 1 \right)^2 + \left(\frac{N_t}{\hat{N}_t} - 1 \right)^2 \right\} \tag{4.1}$$

or, given the exogenous level of output:

$$F = F_u + F_n \quad \text{with:} \quad F_u = \sum_t \left(\frac{\hat{u}_t}{u_t} - 1 \right)^2 \quad \text{and} \quad F_n = \sum_t \left(\frac{N_t}{\hat{N}_t} - 1 \right)^2 \tag{4.2}$$

in which variables with a hat denote estimated values. u_t denotes the rate of capacity utilisation. This function is also used by Kuipers and van Zon (1982), Gelauff, de Jong and Wennekers (1984) and Muysken and van Zon (1987). This objective function is based on the assumption that the residuals on the output capacity and on the demand for labour are independently distributed and have the same variance, i.e., the variance-covariance matrix is written as the variance times the unity matrix. Gelauff (1987) suggests that the complete variance-covariance matrix of the residuals should be estimated, which is done by for instance Gelauff, Wennekers and de Jong (1985). We also employed an objective function which is based on this assumption but this did not change the results dramatically. The alternative objective function as well as the estimation results are presented in appendix 4C.

The vintage-diffusion model contains 16 parameters. Seven parameters describe technological change (μ_n, μ_i, γ_n, γ_i, ε_n, ε_i and $f_{\mu n}$) and three parameters describe the distribution of technologies (α_0, α_1 and α_2). Furthermore, one parameter describes the difference in prices of capital goods between several technologies (β) and the production function contains two scale parameters (A_0 and B_0) and the elasticity of substitution between labour and capital (σ). Finally, we included labour-hoarding (ξ) and scrapping due to underutilisation (χ). The reference model, i.e. the non-diffusion model, does not distinguish between technological change of best-practice and older technologies. This implies that this model is

116. Gelauff, Wennekers and de Jong did not mention this point in their paper, but their data 'available upon request' proved to have this property.

based on 10 parameters. The excluded parameters are the embodied technological change of less than best-practice technologies (γ_n and γ_i), the price difference between several technologies (β) and the distribution parameters (α_0, α_1 and α_2). In all other respects, both models are identical.

Our first estimation experiences showed that the objective function is still discontinuous with respect to changes in the parameters. Therefore, we experimented with some alternative estimation routines: a complex method, a random search method, a simple grid search and a quasi-Newton method. Because the complex method and the random search method are not very sensitive for discontinuities, we used these methods to find starting values for the parameters. Thereafter, the grid search and the quasi-Newton methods are used to find the minimal value of the objective function.[117] In general, the complex method proved to be superior to the random search method, whereas the grid search method improved the objective function which was found by the complex method. The quasi-Newton method did not find a lower objective function, neither when it was initialized with the parameters from the complex method nor when it was initialized with the grid-search results. From this, we may conclude that a combined estimation strategy of the complex and the grid-search method performed the best.

In order to speed up the conversion process, we included penalty functions in the first stage of the estimation process. Penalties are given if the rate of capacity utilisation is above 1.05 or below 0.85. Furthermore, a penalty is given if the capacity demand for labour is below 0.98 times the actual demand for labour. These penalties are assumed to be a quadratic function of the deviation of the computed values and the boundaries and is added to the computed value of the objective function. After the first stage, the estimated values for the capacity utilisation and the capacity demand for labour no longer reached these boundaries so that the penalty function became inactive.

The gradient, computed in the optimum, is not equal to zero for all parameters due to discontinuities and due to computational problems. This implies that the parameter vector is not minimizing the objective function. To check whether or not we are close to this point, we computed the gradient on both sides of the estimated parameter vector using very small deviations in the parameters. The left and the right gradients changed sign for all parameters, which implies that the parameter vector we found is at least very close to the ‘true’ parameter vector which minimizes the objective function. Although the gradients changed sign, their size appeared to be highly dependent on the chosen stepsizes.[118] A further implication of the fact that the gradient is not equal to zero is the impossibility to compute the

117. Further details on both the complex method and the random search method are given in Appendix 4D.

118. Although all variables are programmed as double precision reals, the computed gradients sometimes changed by a factor of more than 1000 for a small change in the stepsizes employed.

Hessian and hence the standard errors of the parameters.[119] In appendix 4E, we plotted the value of the objective function against small deviations for some parameters of the vintage-diffusion model. Furthermore, we plotted the value of the objective function as a function of two parameters (μ_n and σ) to obtain a more dimensional picture of the objective function. These figures, which are representative of almost all parameters, show that the objective function is far from smooth, which explains the bad performance of the quasi-Newton method. Furthermore, it is shown that the objective function contains many local minima so that the grid-search routine should be carried out with varying step sizes. Since the three-dimensional pictures in particular illustrate that the objective function is rather freakish with many ridges and gorges, robust estimation routines like the complex method should be used to find the minimal value of the objective function (cf. page 153).

Before discussing the estimation procedure and the its results, some remarks have to be made on the construction of the initial capital stock. The maximum lifetime of equipment equals 45 years. This implies that in 1960, the first year for which we estimated the model, the oldest possible vintage dates from 1916. To construct the distribution of the capital stock in this year, we started with a lognormal distribution of the productive capacity in 1916.[120] The available data on investment start from 1904 onwards. These data are used to calculate the stock of knowledge in 1917, which implies that the number of technologies in 1916 is bounded to 13. From this distribution we calculate the stock of knowledge of all technologies using the investment data in which a constant distribution of investments with respect to the distribution of technologies is assumed from 1904 until 1916.

Furthermore, the number of technologies (n_t) is kept within a reasonable range, i.e., range from 2 to 25. Finally, we assume that war damage on vintages installed before 1946 equals 40% and that the embodied labour-augmenting technical progress on best-practice machines before 1948 is equal to a fraction, $f_{\mu n}$, of its post-war value. This is common practice in Dutch vintage models.

119. An alternative would be to estimate the model many times on randomly changed time series (Monte-Carlo experiments). One should notice, however, that the full estimation procedure takes more than 24 hours real CPU-time on a mainframe computer (a VAX 8650). A reliable estimate of the standard errors would take more than one year real CPU-time and has therefore not been performed.

120. This lognormal distribution of the initial distribution of the productive capacity is based on a previous version of our model (cf. Meijers 1989). It is assumed that all technologies are captured by the 95% interval of the distribution. Furthermore, we assumed a linear relation between the number of technologies and the mean of the distribution. We adopted the estimated value of the distribution of that model, which results in a mean of 3.9 year of the lognormal distribution in 1916. Using the 95% interval, the value of standard deviation equals 0.54. Furthermore, we investigated the sensitivity of the final results to changes in the mean of the distribution. The results did not change significantly unless we imposed large values of the mean (above 7 years with 13 technologies in total).

4.2 The Estimation Results

First we will compare the results of the diffusion and the non-diffusion model. We will present the resulting time series on the rate of capacity utilisation and the demand for labour, and we will discuss the parameter estimates. Previously, we mentioned that the scrapping of equipment is smoother in the diffusion model. The next section will investigate whether this is true. Finally, that section compares both models with respect to the development of the labour productivity. Section 4.2.2 presents the diffusion process which results from the vintage-diffusion model. Subsequently, we compare our model with the results of Gelauff, Wennekers and de Jong (1985) and Muysken and van Zon (1987). Finally, section 4.2.4 examines the nature of technological change in the vintage-diffusion model.

4.2.1 The Diffusion Model and the Non-Diffusion Model Compared

The results with respect to the utilisation rate of capital and the demand for labour for the diffusion model as well as the non-diffusion model are presented in Figures 4.1 and 4.2, respectively. We will concentrate first on the results of the diffusion model. Figure 4.1 shows that the utilisation rate between 1964 and 1969 is under-estimated, and that fluctuations in the estimated rate are comparable in size to the ones in the actual data. With the exception of an outlier in 1976, we observe a smoother fluctuation after 1976 compared to the actual utilisation rate. Both turning points in 1982 and 1987 show up in our results.

The estimated demand for labour follows the actual data quite well. Although the model seems to be one period ahead, the fall in the demand for labour after 1980 and the increase from 1983 onwards, can also be observed in our estimates.

On average, the estimated rate of capacity utilisation of the non-diffusion model is slightly worse than the one generated by the diffusion model.[121] The fluctuations are stronger due to the fact that complete vintages are scrapped rather than parts of them. The estimated demand for labour in the case of the non-diffusion model is unsatisfactory in comparison with the results of the diffusion model. Before 1969 one encounters an underestimation and between 1970 and 1980 an overestimation of the demand for labour. The first deviation does not appear in the diffusion model while the second is more severe than the overestimation in the diffusion model. The movement of the demand for labour after 1984 points in the opposite direction of the actual data. From these figures, we may conclude that the diffusion model performs better than the non-diffusion model, especially where the demand for labour is concerned. One of the main reasons for this difference is that

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121. Compare the contribution of the residuals of the rate of capacity utilisation in the objective function (F_u=0.0070 and F_u=0.0129 for the diffusion model and the non-diffusion model, respectively, cf. Table 4.1 below).

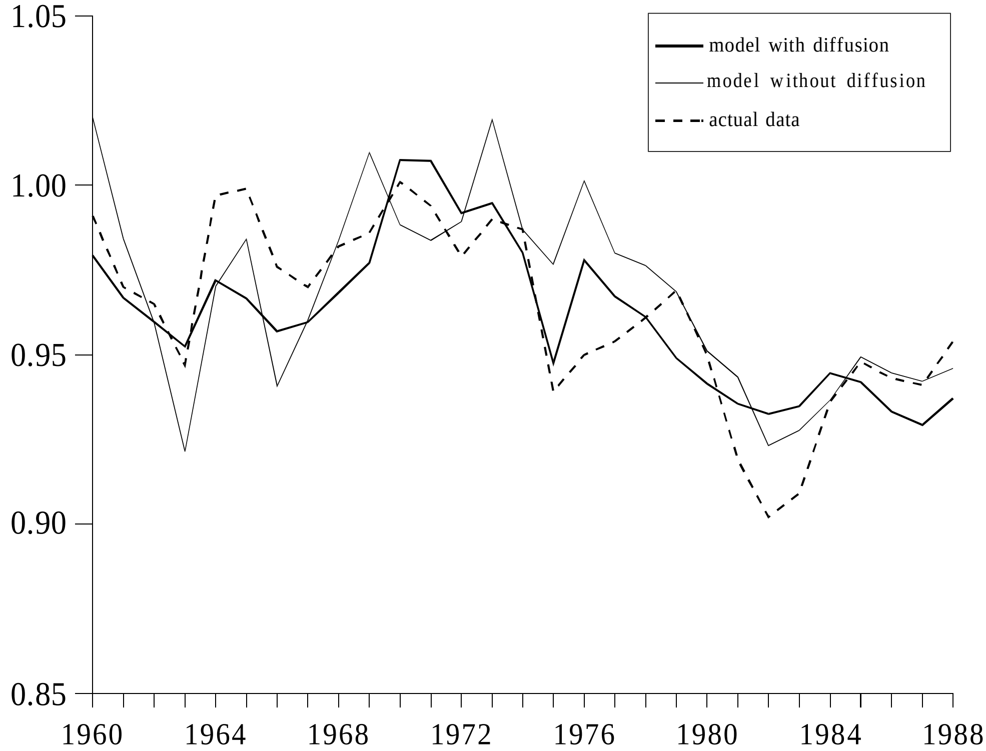

Figure 4.1. Estimation results on the rate of capacity utilisation

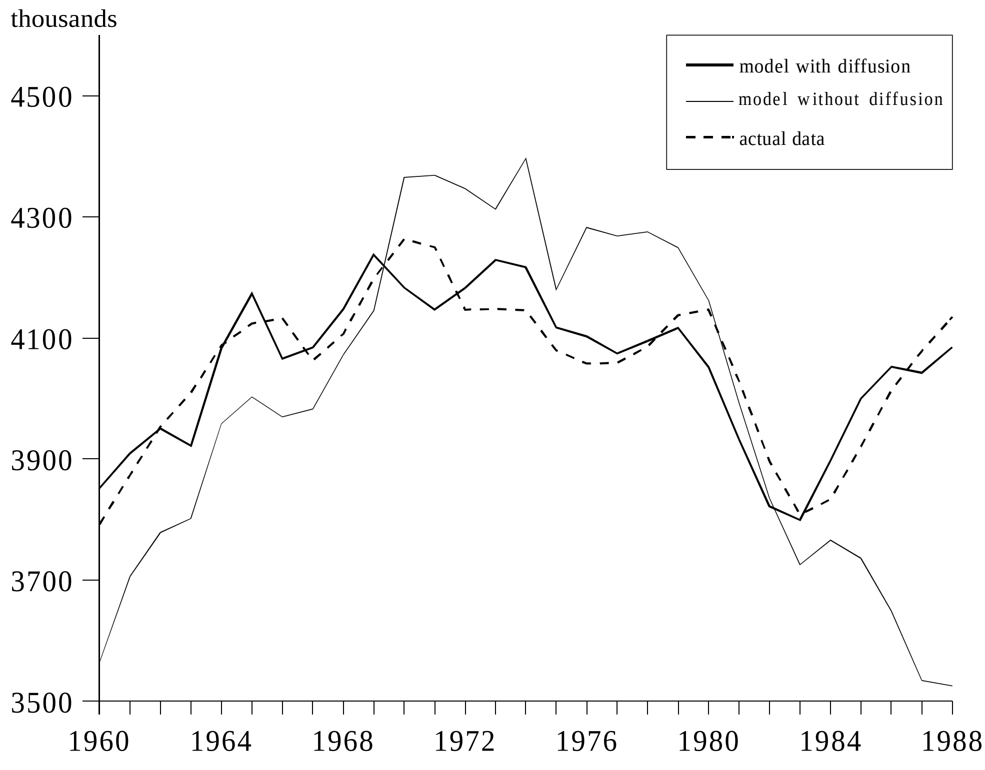

Figure 4.2. Estimation results on the demand for labour

the impact of technological change is endogenized through the diffusion process. This is elaborated in section 4.3.

The values of the estimated parameters are presented in Table 4.1. Again, we will first concentrate on the results of the diffusion model. Of most interest are the parameters which describe the production structure, which show a relatively high value of the embodied labour-augmenting technological progress of the best-practice technology ($\mu_n = 3.4\%$). The embodied labour-augmenting technological progress of the less than best-practice technologies (γ_n) is about zero. The capital augmenting technological progress for the best-practice technology is equal to about 1% per year, which is rather different from the labour-augmenting one. The value of the embodied capital-augmenting technological progress for the less than best-practice technologies is about equal to zero. Thus the model predicts that the development of new technologies tends to be labour-augmenting, whereas there are almost no improvements of these new technologies after their introduction onto the market for equipment. However, with respect to the latter finding one should realize that the way in which technologies are embedded in the model differs from the notion of technologies as being physical equipment, such as computers, which are often classified as being the same technology. This is not the case in the present model, in which a technology represents equipment in a more general sense. Thus, a computer introduced in 1979 (an 'XT') may be captured within another technology than a computer that was introduced in 1994 (a 'Pentium'), whereas one would characterize it as being the same, but improved, technology in 'standard' diffusion literature.

Comparing the estimated parameters with the model without diffusion, one encounters a corresponding value of the embodied labour-augmenting technological progress but an almost vanishing influence of capital-augmenting technological progress. Looking at the disembodied part, one observes an opposite shift. The non-diffusion value of the disembodied labour-augmenting technological progress is almost zero — as in the diffusion model — while the parameter describing the capital-augmenting disembodied technological progress rises towards about 1.8% a year. So, whereas capital-augmenting technological change is merely embodied in the vintage-diffusion model, it is disembodied in the non-diffusion vintage model. Another notable difference between the two models is the amount of labour hoarding, which in the diffusion model is about three times as high as the value in the non-diffusion model. One may wonder whether the good performance of the diffusion model is due to this high value of labour hoarding and whether the differences between the models in terms of parameter values are due to the difference in labour hoarding. But suppose that the amount of labour hoarding is reduced to 0.35 in the diffusion model, what would happen to the other parameters?[122] Such

122. Recall that the demand for labour is equal to the amount which is needed to produce the actual amount of output, which we called minimal demand for labour, plus the amount of labour hoarding. The amount of labour hoarding is assumed to be a fraction of the difference between the

	with diffusion	without diffusion		with diffusion	without diffusion
μ_n	3.39%	4.06%	ξ	0.90[123]	0.35
μ_i	1.04%	0.12%	χ	0.60	0.62
γ_n	0.007%	--	β	0.015	--
γ_i	0.000%	--	α_0	0.0003	--
ε_n	0.036%	0.08%	α_1	0.56	--
ε_i	0.080%	1.83%	α_2	1.76	--
A_0	9.65	9.93	F	0.0115	0.1123
B_0	5.97	12.11	F_u	0.0070	0.0129
σ[124]	0.55	0.60	F_n	0.0045	0.0994
$f_{\mu n}$	0.50	0.26			

Table 4.1. The parameter estimates

a decrease implies that the demand for labour is reduced, given the capacity demand for labour. This implies that both the capacity demand for labour and the minimal demand for labour should be increased to obtain about the same demand for labour. Consequently, the labour productivity will decrease, ceteris paribus. However, if the labour productivity decreases, the quasi-rents will also decrease resulting in more scrapping due to economic obsolescence. This induces two effects: first, the labour productivity will increase due to scrapping, and secondly, the output capacity will be reduced, given unchanged capital productivities and given the exogenous amount of investment. As a result, the capital productivity should be increased to fill the capacity gap and one would expect capital-augmenting technological change to increase whereas the movement of labour-augmenting technological change is ambiguous. Furthermore, the effect of the reduction of labour hoarding on the performance of the model is unknown. Therefore, we estimated the vintage-diffusion model again, but now with a boundary on the amount of labour hoarding of 35%. The results are presented in Table 4F.1, on page 154. This table shows that all parameters describing capital-augmenting technological change (μ_i, γ_i and ε_i) are increased by about 0.5%-point whereas the parameters describing labour-augmenting technological change are about the same as in the

capacity demand for labour and the minimal demand for labour.

123. This parameter equals its imposed upper limit.

124. The elasticity of substitution between labour and capital: $\sigma = \frac{1}{1+\rho}$.

unbounded estimate. Furthermore, the value of the objective function is increased by about 38%, which is much higher than in the unbounded case, but is still far better than the objective function of the non-diffusion model. The estimated demand for labour is shown in Figure 4F.1, page 154, which shows that the results are about the same. A lower percentage of hoarding implies that the capacity demand for labour is increased. As a result, the structural labour productivity, measured as the output capacity divided by the capacity demand for labour, should be decreased. This is indeed the case, but since this is mainly obtained by higher values for the scale parameters (A_0 and B_0), the growth rate of labour productivity is about the same for both the bounded and the unbounded model.

The diffusion model deviates from the non-diffusion model in the way in which embodied technological change enters the model and in the way in which vintages, or parts of them, are scrapped. These differences will be discussed in the next section, but first we will examine the residuals of the vintage-diffusion model.

The relative residuals of the estimated output capacity and the demand for labour are given in Figure 4.3. Given the structure of the model, one would expect a strong correlation between the two residuals. An overestimate of the output capacity will lead to an overestimate of the capacity demand for labour. Because the labour demand depends positively on the capacity demand for labour, labour demand is correlated with output capacity. For some periods this correlation is indeed visible, for instance, for the positive outliers in 1963 and 1971, and the negative outlier in 1965. However, the correspondence disappears, and even reverses, after 1974. Until 1982, we see a clear opposite movement of the residuals

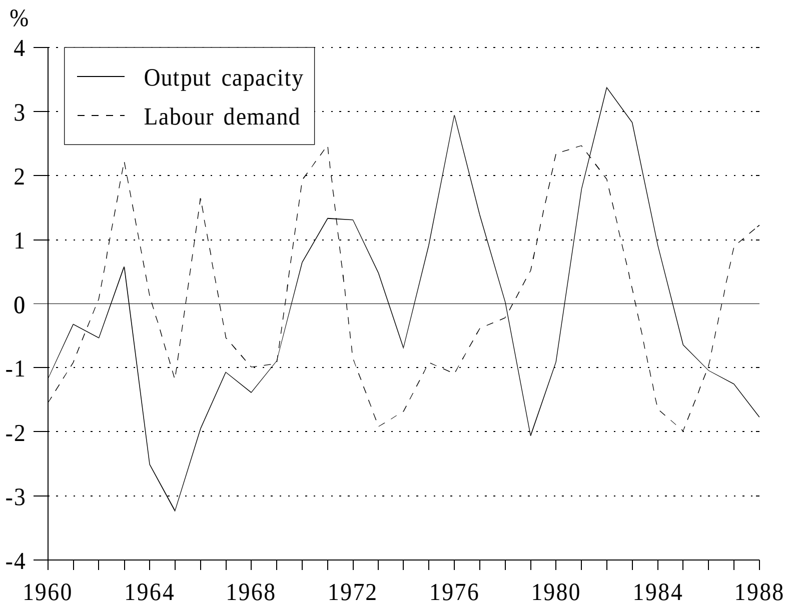

Figure 4.3. Relative residuals of the diffusion model

whereas there appears to be a lag between the two residuals after 1982.[125]
Finally, note that almost all residuals are located within the 3% interval. Appendix 4C presents some simple statistics on the residuals and there it is shown that the residuals on capacity output in particular, autocorrelation appears to be present.[126] We also estimated the residuals on a trend term, but for both the residuals on the capacity output and the demand for labour. Both appeared to be positive but non-significant.

The presence of autocorrelation also biases the estimators and points into the direction of a misspecification of the model. However, due to the strong non-linearity and due to discontinuities of the model, it is not clear in advance how to adjust for autocorrelation. The insignificance of the trend terms suggest that there are no structural misspecifications with respect to the way in which technological change is introduced in the model. The source of autocorrelation is likely to be found in the scrapping condition and in the labour hoarding function. Although this needs attention in further research, we did not search for such corrections.

Scrapping of Equipment
The relative capacity output of scrapped equipment in the case of the vintage-diffusion model is shown in Figure 4.4. In this figure, we distinguish two reasons for scrapping: scrapping due to negative quasi-rents and scrapping due to severe underutilisation. Scrapping due to wear and tear has a nearly constant effect on the capacity output and is not shown in the figure. This type of scrapping decreases the capacity output by about 2.5% per year. In Figure 4.4, the line at the bottom denotes scrapping due to underutilisation while the upper line denotes scrapping due to underutilisation plus scrapping due to negative quasi-rents. The parameter which describes the amount of scrapped equipment which had already been put aside, (χ in Table 4.1), is equal to 0.6. This implies that, if the rate of capacity utilisation is below its normal rate of 0.98 for at least two consecutive years, 60% of the excess capacity is scrapped.[127] Scrapping due to underutilisation is relevant to the periods 1960-1968 and 1977-1988. Note, however, that equipment which is scrapped due to this reason might be scrapped during the next year due to negative quasi-rents. A simulation of the same model, with no scrapping due to under-

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125. This explains the slight differences between the estimation results obtained with the original objective function and those obtained with the alternative objective function. The covariance between the residuals is accounted for in the latter procedure (cf. Appendix 4C). That appendix also presents some correlation coefficients between the residuals.

126. Cf. Table 4C.1, page 148.

127. MvZ find a value of 0.46 for this parameter. GWJ use a varying scrapping rate. They find a rate of scrapping between 0.3 and 0.5, which are based on imposed upper limits, however. Note furthermore that scrapping due to underutilisation is especially relevant in the last period, from 1977 and onwards. Both, GWJ and MvZ estimate their model until 1982. It is likely that the additional years in our estimation period influence these results. The value of 0.62 in the non-diffusion model confirms this notion.

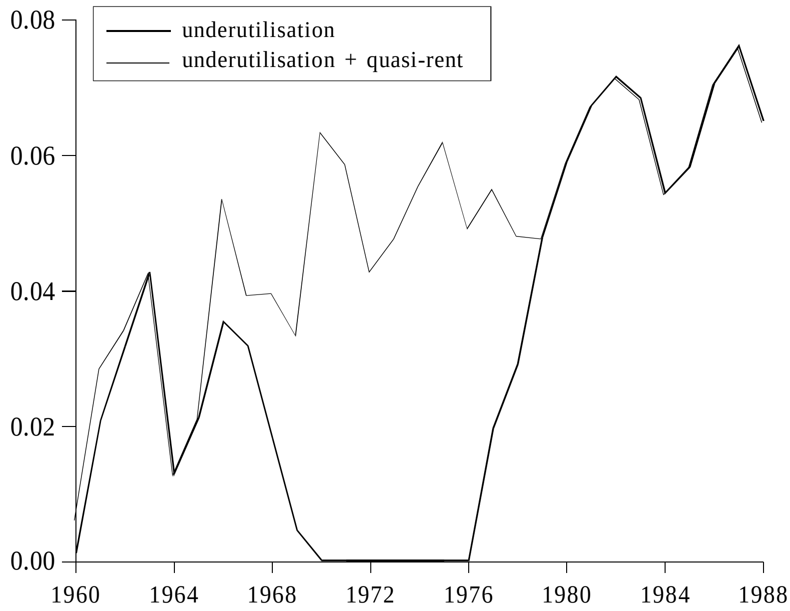

Figure 4.4. Percentage of production capacity scrapped due to various reasons (vintage-diffusion model)

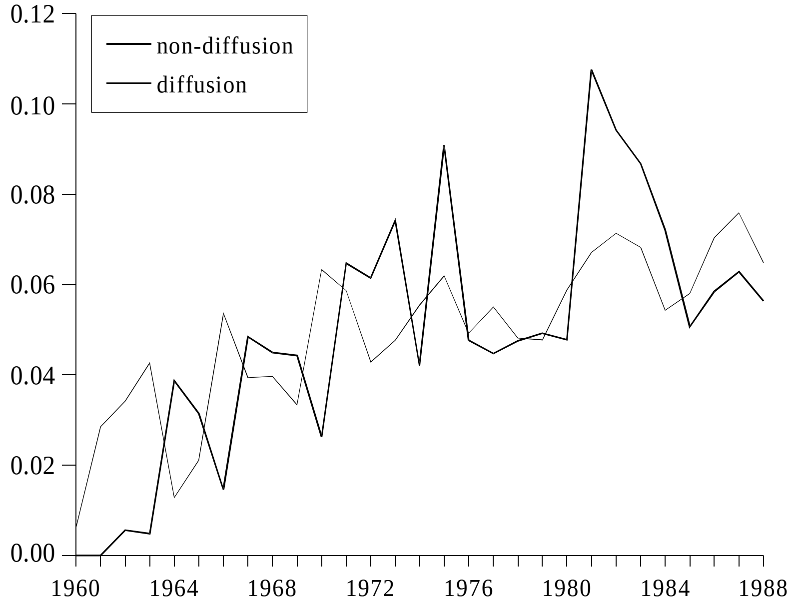

Figure 4.5. Total scrapping (in % of capacity output) in both models

utilisation shows that this is indeed the case in the first period (1960-1968). The total amount of scrapping remains about the same in this period. This is not the case in the last period (1977-1988), in which there is almost no scrapping due to negative quasi-rents, even in the $\chi = 0$ experiment. There are two reasons for this finding. First, due to rapid increases of the real wage rate in the early seventies, the capital stock is rationalized to a large extent as a result of which the remaining equipment is relatively productive. Secondly, the growth rate of real wages decreased sharply after 1974 and became even negative in the early eighties (cf.

Figure A4.1 in appendix 4A). Consequently, the capital stock is relatively productive whereas the growth rate of real wages is very moderate, after 1975. The quasi-rents of all equipment remain positive and no machines are scrapped, except for wear and tear and underutilisation.

In the previous chapter, we already noted that smoother scrapping would be one advantage of the vintage-diffusion model. Now, after estimating both models, we are able to examine whether this is true. Figure 4.5 shows the relative amount of scrapping in both models. The graph of the vintage-diffusion model is redrawn from Figure 4.4. Figure 4.5 demonstrates that, especially from 1972 onwards, scrapping fluctuates heavily in the non-diffusion model whereas it is smoother in the diffusion model. The mean of both series is about the same (both 0.049) whereas the standard deviation of the non-diffusion model (0.027) exceeds the standard deviation of the diffusion model (0.017). From this, we can conclude that the scrapping behaviour in the diffusion model is indeed less turbulent than in the non-diffusion model.

Labour Productivity Compared

We already pointed out that the rate of labour-augmenting technological change is about the same for both the diffusion and the non-diffusion model. Furthermore, the elasticity of substitution is about the same so that we might expect the development of the labour productivity between both models to be comparable. However, one main difference is that the impact of embodied technological change depends on the distribution of technologies in the diffusion model. In the previous chapter, we mentioned the possibility that the labour productivity of the newest vintage decreases, even if the labour productivity of the individual technologies does not change (cf. Figure 3.6, page 102). In Figure 4.6, we plotted the labour productivity of the newest vintage for the diffusion model and for the non-diffusion model. For the diffusion model, we made a distinction between the labour productivity of the best-practice technology, of the 'least' practice technology and the labour productivity of the complete vintage, i.e., all technologies taken together, in which we weighted the productivities with the share of each technology in total capacity output.

If we compare the labour productivity of the non-diffusion model with the average productivity of the diffusion model, we observe that the productivity of the non-diffusion model is slightly above the diffusion model between 1960 and 1964. From 1965 to 1979, the opposite is the case while after 1980, we see that the productivity of the non-diffusion model is far above the labour productivity of the diffusion model. Although we are only discussing the newest vintages here, this development is consistent with the estimation results on the demand for labour, in which all vintages are considered. If we compare the development of the labour productivity of the non-diffusion model with the productivity of the best-practice technologies, then we see fewer differences, with the exception of a deviation in the

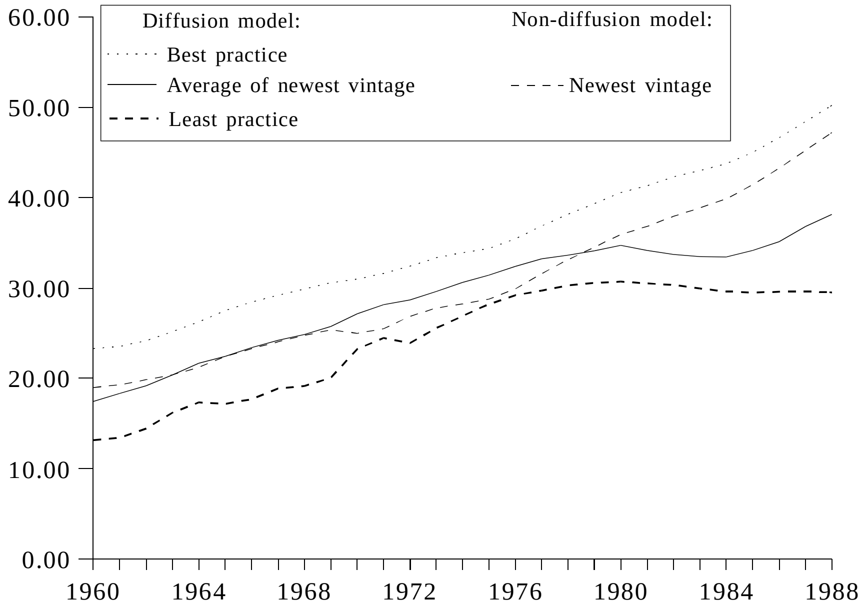

Figure 4.6. Labour productivity of the newest vintage;
The diffusion model and non-diffusion model compared

levels of course. Particularly after 1980, when the non-diffusion model performed badly for the estimated demand for labour, we see comparable movements of both patterns, whereas the development of labour productivity of the total vintage in the case of the diffusion model deviates sharply from these patterns and is even negative between 1980 and 1984. This points to changes in the speed of diffusion in this period, which shows that situations as pointed out in Figure 3.6 are indeed relevant. In section 4.3, we will examine the development of the labour productivity in the diffusion model in more detail, but now we will take a closer look at the diffusion process.

4.2.2 The Diffusion Process

In Figure 4.7, we plotted the cumulative amount of investment per technology against time to get an impression of the diffusion process. The diffusion paths of the technologies introduced between 1947 and 1971 are all clearly S-shaped. The ceiling level, i.e., the level for which the diffusion stops, is raised due to increased investment and due to an increase in the speed of diffusion. The time between the date of introduction and the date at which the ceiling is reached decreases from 17 years for the 1947 technology towards 6 years for the technology introduced in 1971. This phenomenon can mainly be explained by the increase in the wage rate. Investing in older technologies becomes uneconomic in an earlier stage of the diffusion process as the growth of the real wage rate increases. The opposite holds true for the technologies introduced after 1971. The development of the 1972 technology is about the same as the 1971 technology for the first 6 to 7 years. As the growth in real wages slows down after 1976, investing in this technology continues to be profitable until 1988, the end of the estimation period. As our estimation only runs until 1988, the shape of the diffusion paths of the technologies from 1972 and onwards cannot be examined definitely, but the first phase of the diffusion process is not as smooth as it is for the pre-1971 technologies. However, the first stage of the process of the technologies introduced after 1979 looks like the pre-1971 diffusion paths.

In the whole estimation period, almost all technologies are more profitable than their predecessors and the levels of the cumulated amount of investments overtake the older technologies in spite of the fact that the stock of knowledge about these technologies are initially larger than the stock of knowledge of their successors. This is especially the case for the 1973 technology, which overtakes the 1971 technology in 1976. The 1973 technology is overtaken by the 1974 technology at the end of the estimation period. Thus after the mid-seventies, firms continue to invest in all technologies. This implies that the labour productivity of the newest vintage, i.e., all technologies taken together, declines relative to the development of the best-practice technologies. This explains why the labour productivity of the newest vintage in the diffusion model is far below the labour productivity in the non-diffusion model after 1979 (cf. Figure 4.6 above).

Another way to present the diffusion process is to plot the relative output of each technology against time. This is done in Figure 4.8. For each technology we observe an increase in its share of total output in the first years of its existence. After a couple of years a maximum is reached and that particular technology is overtaken by its successors. Its contribution declines after that point due to the fact that parts of that technology will be scrapped and due to the fact that productivity of newer machines rises and will have a larger share in total output, given the exogenous amount of investments which has increased over time. As the speed of diffusion increases, the new vintage will include fewer technologies, which leads to an increase of the proportion of output produced by each technology, ceteris paribus. The speed of diffusion of newly installed machines increases in the early and mid-seventies and decreases afterwards, which explains the bell shape of the envelope of all shares.

One remark should be made on the short period between the introduction of a technology and the moment at which it produces the maximum amount of output. In the 1960s, this period was about seven years, and in the 1970s it was only four years. With respect to the general findings within the diffusion literature, these periods seem rather short. However, the assumption that a new technology becomes available on the market for capital goods each year is important here, and the generalization towards a macro-economic diffusion pattern also plays an important role. Most of the diffusion literature studies the spread of one single technology with the potential users being concentrated mainly within a particular sector of industry. The introduction of new technologies useful for a particular firm is likely to take more time than one year. The generalization of technologies and the yearly

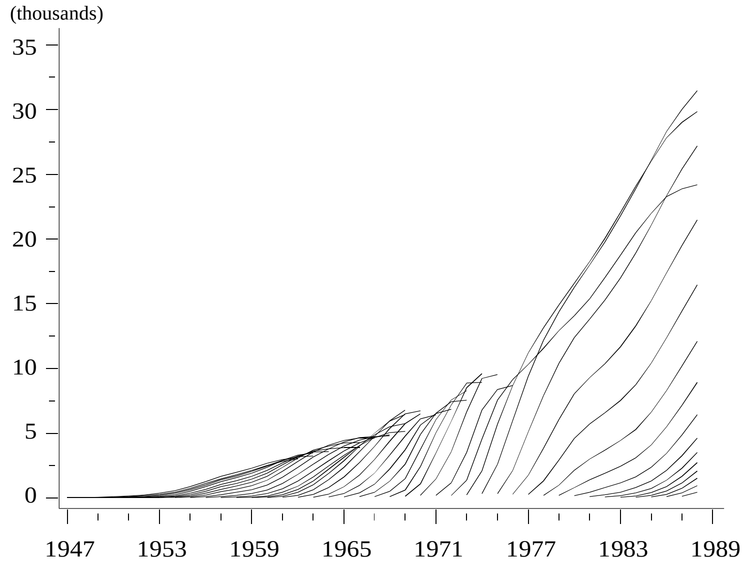

Figure 4.7. The diffusion of technologies in terms of cumulative amount of investment

Figure 4.8. Fraction of output produced with each technology

introduction of a new technology are likely to cause diffusion patterns to be short. Therefore one should take care of translating the concept of technologies in the model into the concept of technologies as it is generally used in the diffusion literature. Moreover, this point shows that more work must be done concerning the aggregation of single technologies into a macro-economic concept.

The technologies introduced after 1970 do not disappear completely. Although most of the previously installed capacity is scrapped, firms continue to invest in these technologies. The expected profits of new equipment in which older technologies are embodied are still positive due to the ex-ante substitution possibilities whereby the labour intensity is adjusted for new information about the development of factor prices. The lifetime of these machines is rather short, however.[128] The share in total output of some technologies increases in the eighties due to two different effects. First, firms continue to invest in these technologies and secondly, the amount of investment falls as a result of which older equipment becomes more important in the production process.

The number of technologies in which firms invest in each year (n_τ) increases from 13 in 1916 towards 25 in 1928, cf. Figure 4.9.[129] After 1960 this number decreases towards 5 in 1975, and after 1976 we see an increase to 17 in 1988. The mean of the distribution, i.e., the age of the newly installed equipment weighted by its productive capacity, shows a similar development, as can be seen in Figure 4.9. The ratio between n_τ and the mean varies between 0.66 in 1946 and 0.33 in 1962 with an average of 0.51 for the period 1919-1988. The mode of the distribution, i.e., the age of the technology in which the biggest amount is invested, rises from 2 in 1916 to 25 in 1940, persists around that high level for a couple of years, and falls sharply to 8 in 1954. After that, we see a convergence towards the mean of the distribution. The rise of the mode shows the persistence of investing in a certain type of equipment. The stock of knowledge dominates in the investment decision if the difference of the expected profitability between technologies is small, which is the case before 1950. Now, we will take a closer look at this development.

The relative difference between the expected net present value of future rents of the best-practice technology and the 5-year-old technology is about 5% in that period. Before 1940, the difference ranges between 10% and 20% while after 1950, we see a sharp rise towards a level of 97% in 1975, followed by a decline to a level of about 25% from 1983 and onwards. In 1975, the 5-year-old technology is the oldest technology which generates positive expected future rents. Thus, before 1950 the diffusion process is mainly dominated by differences in relative knowledge and as new information is cumulated through investments, the stock of knowledge of a particular technology remains high, thereby inducing high investments in the next year. This explains the increase in the mode of distribution as discussed above. After 1950, and especially in the late sixties and early seventies, the diffusion process is dominated by differences in relative profitability. In this period both real wages and the labour share of income increased sharply in the Netherlands. After the mid-seventies, the growth rate of real wages is very moderate, so differences in the profitability becomes less important in the diffusion process (cf. Figure A4.1, on page 145). Note furthermore that in this case, more technologies become profitable, which again reduces the speed of diffusion. So both the number of technologies, n_τ in Figure 4.9, and the model of the distribution increases after 1975.

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128. The lifetime for the least-practice machines installed after 1980 equals 1 to 5 years. These machines are scrapped due to underutilisation. Note that we do not account for scrapping due to underutilisation in the choice of the production technique. This implies that actual lifetime will be smaller than the perceived lifetime if scrapping due to underutilisation matters.

129. Note that this is equal to the upper bound we imposed.

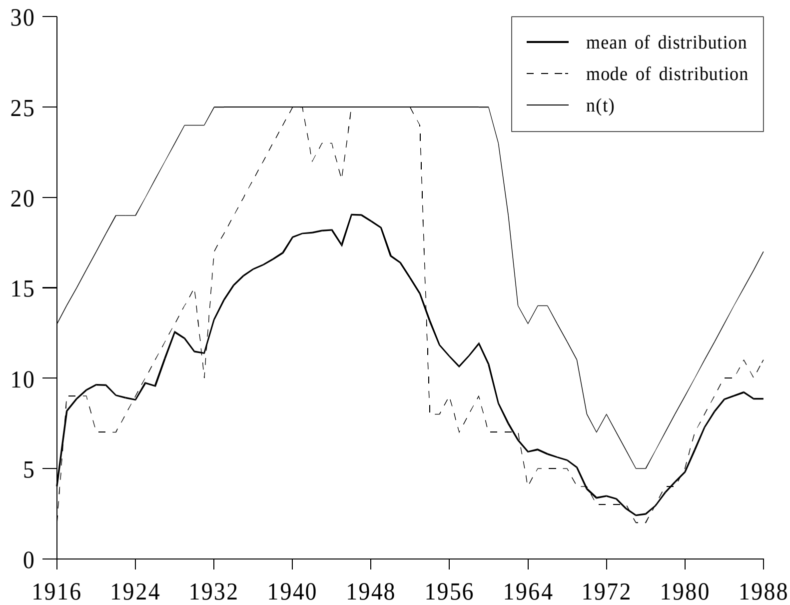

Figure 4.9. Some characteristics of the distribution of technologies

4.2.3 Our Results Compared with Gelauff, Wennekers and de Jong and with Muysken and van Zon[130]

As mentioned before, GWJ introduced partly endogenous technological progress in a rather ad hoc way. Comparing their results on the rate of capacity utilisation and on the demand for labour with our diffusion model, it is obvious that we obtain a more satisfactory fit, especially on the rate of capacity utilisation.[131] MvZ introduced two dummy periods to obtain a satisfactory fit of their model. Their estimation results on the rate of capacity utilisation are slightly better than our results but the results on the demand for labour are comparable.

In Table 4.2, we compare our estimation results with the results of Gelauff, Wennekers and de Jong (1985) and Muysken and van Zon (1987).[132] Notice that our model without diffusion is a reduced version of the models of GWJ and MvZ. The main difference with the model of GWJ is that they partly endogenize the technological change parameters. This implies that the labour productivity in their

130. Because their estimation period differs significantly from our estimation period, we do not compare our results with Kuipers and van Zon (1982).

131. In GWJ, the Root Mean Squared Error of the rate of capacity utilisation is equal to 2.4 whereas we find a value of 1.5. The RMSE of the demand of labour in their model is equal to 0.8 while we find a value of 1.2. Note that they estimate their model, including the demand for energy, for the period 1960-1982 with 19 parameters while our model is estimated for 1960-1988 with 16 parameters.

132. GWJ nor MvZ present t-statistics of the parameters due to severe discontinuities of their models. As pointed out in section 4.1 and in appendix 4E, the same applies to our models.

model falls after 1973 due to a decreased rate of technological change. Although MvZ assume that firms differ with respect to the future — they assume that firm behaviour results in a distribution with respect to the initial labour intensity — they cannot describe the fall in labour productivity without introducing dummies for the technological change parameters. So whereas GWJ partly endogenize technological change, their estimates are less satisfactory than our results in the case of the vintage-diffusion model. Our results, in terms of value of the objective function, is comparable to the results of Muysken and van Zon, but they had to introduce several dummy-variables as a result of which they estimate their model for the period 1960-1982 with 19 parameters, whereas our model contains 16 parameters and is estimated for the period 1960-1988. Moreover, we introduced variability of technological change in a very natural way in contrast with GWJ, who introduce endogenous technological change rather ad hoc.[133] Moreover, they also introduced an innovation possibility curve in which the direction of technological change is ruled by relative factor prices, but this did not improve their results, mainly due to identification problems. In our diffusion model, the development of new technologies is assumed to be constant but the choice of the technology depends on profitability and on the stock of knowledge. The expected profitability is related to relative factor prices which means that we are able to relate the transmission of technological change with the development of factor prices.

Due to their specification, GWJ find that embodied and disembodied labour-augmenting technological change are almost equally important, whereas they find no capital-augmenting technological change, cf. Table 4.2. MvZ used dummy-parameters for embodied labour-augmenting and disembodied technological change. Comparing their results with the results of GWJ, we can conclude that GWJ overestimate the impact of disembodied technological change (cf. Muysken and van Zon, 1987:123-124). In the vintage-diffusion model, we find about the same values for technological change as MvZ. We find slightly less labour-augmenting technological progress for both the embodied and the disembodied component, but notice that changes in the speed of diffusion alters the impact of technological change on the entire capital stock. As shown above, by introducing diffusion in our model we allowed for more variability in the development of total labour productivity. The value for embodied labour-augmenting technological progress found by MvZ for the period 1975-1981 confirms our results at this point. So whereas MvZ had to introduce several dummy-variables in their model, we are able to describe nearly the same movements with the vintage-diffusion model.

133. Recall that embodied technological change depends on the structural rate of change in the export share whereas disembodied technological change is assumed to depend on the sum of growth of export and national product, both apart from an autonomous term. As already noted by Muysken and van Zon (1988:119), these specifications are hardly justified.

	Gelauff, Wennekers and de Jong	Muysken and van Zon	Meijers, with diffusion	Meijers, without diffusion
estimation period	1960-1982	1960-1982	1960-1988	1960-1988
elasticity of substitution	0.44	0.38	0.55	0.60
embodied techn progress				
labour-augmenting %	2-3[a]	4.77 (5.38,0.50)[b]	3.38, 0.00[c]	4.06
fraction in pre-war period ($f_{\mu n}$)	0.1-1[a]	0.20	0.50	0.26
capital-augmenting %	0.0	1.13	1.04, 0.00[c]	0.12
disembodied techn progress				
labour-augmenting %	2-3[a]	0.40 (0.0, 0.0)[b]	0.04	0.08
capital-augmenting %	0.0	1.25 (0.0, 0.0)[b]	0.01	1.38
expected lifetime (planning period)	15	25-8[d]	15-8,15-4[de]	15-6[d]

Table 4.2. Estimation results compared to Gelauff, Wennekers and de Jong (1985) and Muysken and van Zon (1987)

Notes

a) approximate range of variation of endogenous technological progress in the post-war period.

b) values for the periods 1964-71 and 1975-81 respectively.

c) values for the best-practice technology and the less than best-practice technologies, respectively.

d) range of variation of expected lifetime.

e) expected lifetime for the best-practice and the least-practice technologies, respectively.

The elasticity of substitution between capital and labour is rather high in our model. As we find the same result of our model without diffusion, which is more or less comparable with the other models, the difference in the elasticity of substitution can be attributed to a difference in the estimation period or due to a difference in the way the planning period is modelled. As the expected lifetime is completely endogenous in our model, a change in the real wage rate will cause a change in the expected lifetime, thereby influencing the choice of the production technique.

In section 4.3, we will relate the speed of diffusion with the growth rate of labour productivity. Furthermore, we will also take a closer look at the vintage-diffusion model and at the model of GWJ with respect to the sources of labour productivity growth.

Expected and Realized Lifetime

In contrast to the models of GWJ and MvZ, we apply consistent expectations with respect to the length of the planning period. The planning period is assumed to be equal to the expected lifetime of equipment if this lifetime does not exceed an upper boundary of 15 years. If the expected lifetime exceeds this boundary, firms are assumed to apply a maximum planning period of 15 years. After estimation, we are able to confront the length of the planning period with the expected lifetime. This is only possible for equipment which is scrapped at or prior to the end of the estimation period. First, we will compare the expected and realized lifetimes of our model with the results of the model of Muysken and van Zon. Because the vintage-diffusion model contains several different technologies, we will compare the results of the non-diffusion model with the results of MvZ. After that, we will take a closer look at the results of our diffusion model.

In Figure 4.10, we plotted the expected lifetime of each vintage (solid lines) against the realized lifetime (dashed lines). Moreover, both MvZ and we impose upper limits on the expected lifetime. If we release these limits, we obtain expected lifetimes as described by the ‘structural part’ of the model (dotted lines). First, we will examine the results of our non-diffusion model. The realized lifetime of the vintage which is installed in 1950 is equal to 19 years and the lifetime of more recent vintages decreases until about 14 years. The expected lifetime is bounded to an upper limit of 15 years in the fifties and early sixties. After that, the expected lifetime decreases towards about 6 years in 1975. Note that the expected lifetime is based on the expected real wage rate and on expectations with regard to changes in working hours and on disembodied technological change. These expectations are based on the average realized growth rate of the preceding 4 years. Figure A4.1, on page 145, shows that the growth rate of real wages falls from about 6% in the late sixties and early seventies towards about -2% in the early eighties. This implies that the expected lifetime is based on too high growth rates of real wages causing firms to underestimate the actual lifetime in these circumstances. If the expectations with regard to the growth rate of real wages is almost equal to the actual rate, such as in the early sixties, the actual and the realized lifetimes are about the same.

In the model of MvZ, the expected lifetime is equal to its upper limit of 25 years between 1950 and 1962. After that, it falls towards about 9 years in 1975. The realized lifetimes are about the same as those found in our non-diffusion model. This implies that MvZ overestimate the expected lifetime in the fifties whereas their model predicts the actual lifetime slightly better at the end of the estimation period.

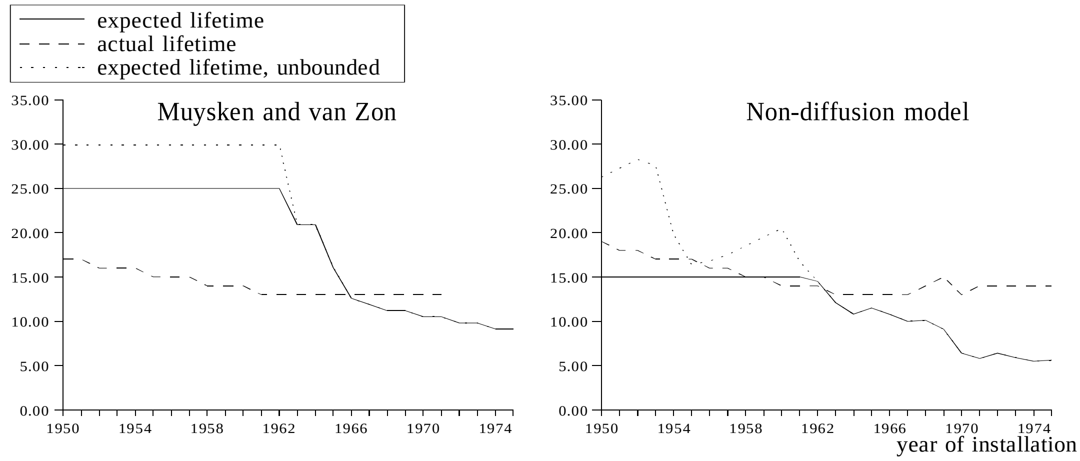

Figure 4.10. Expected and actual lifetimes
The model of Muysken and van Zon and our non-diffusion model compared

Note furthermore that our model overestimates the lifetime in the fifties in the unbounded case but that the model of MvZ predicts even higher values. From this, we may conclude that our prediction of the expected lifetime is slightly better than that of MvZ and that the performance of our model is determined by the prediction of the real wage rate.[134]

Let us now take a brief look at the results with respect to the vintage-diffusion model. In Figure 4.11, we plotted the expected and realized lifetimes of all machines from vintages 1960, 1965 and 1970. The age of technologies are shown along the horizontal axis. These three figures illustrate that the expected lifetime is overestimated in 1960 and is underestimated in 1970. In 1965, both the expected and actual lifetime are about the same. At the vintage level, the diffusion model shows about the same pattern as the non-diffusion model. Within each vintage, the decrease of the expected lifetimes is about the same as the realized lifetimes for different technologies.

Finally, the expected as well as the realized lifetime of equipment within each vintage decreases as the technologies become older. This holds true not only for the displayed vintages, but also for the other vintages in the estimation period, which implies that the labour productivity of older technologies must be below the labour productivity of more recent technologies. Because the ex-post changes are assumed to be the same for all technologies, this implies that the initial labour productivities are lower for older technologies. This is discussed below.

134. The lifetimes would have been predicted more correctly if we has used another expectations model for the real wage rate, for instance a higher order function instead of adaptive expectations allowing for a more accurate prediction of the cycle.

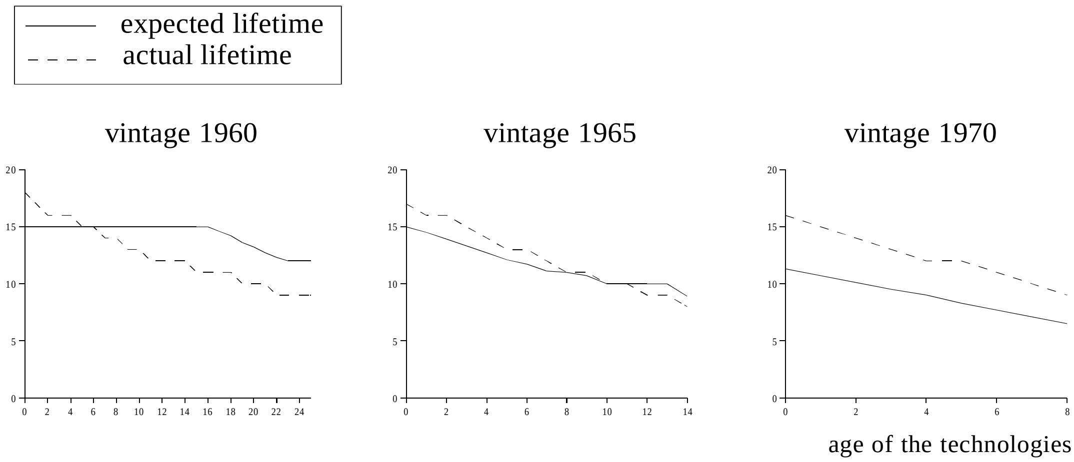

Figure 4.11. Expected and actual lifetimes (diffusion vintage model)

4.2.4 Technological Change Versus Substitution in the Vintage-Diffusion Model

In Figure 4.12, we plotted the initial factor coefficients of all machines installed between 1960 and 1988. Some vintages are labelled in which the number after the minus sign denotes the age of the technology, i.e., 1988–0 refers to the best-practice technology in 1988 and 1960–25 refers to the machine installed in 1960 and in which a 25-year-old technology in incorporated. This technology was the best-practice technology in 1935. Both factors are corrected for changes in working time which means that the coefficients are displayed in working/operating hours.

From this figure, it follows that changes between vintages are mainly labour-augmenting whereas changes within a vintage are almost equally labour- and capital-augmenting, at least in the early sixties and in the eighties. The movement between vintages can be explained by the estimated parameter values on embodied technological change. The annual rate of labour-augmenting technological change is about 3.4%, whereas capital-augmenting change is 1.0% (cf. Table 4.1). This implies that, at a constant wage rental ratio, the production techniques should move mainly in a horizontal direction.[135] Calculating technological change from the initial factor productivities shows that the labour productivity of the best-practice technologies increased from 23.3 in 1960 towards 60.9 in 1988, i.e., an annual growth rate of 3.4%, which is consistent with the parameter estimate of μ_n.[136] The annual growth rate of capital-augmenting technological change is 0.5% if we calculate this growth rate from 1960 until 1988. But notice that the capital productivity decreases from

135. Note that there is almost no embodied technological change of the less than best-practice technologies. This implies that the isoquants of all technologies are almost fixed in time as a result of which, for instance, the factor coefficients of a 15-year-old technology in 1988 denote a point on the same isoquant as the best-practice technology in 1973. This is elaborated in Figure 4.14 below.

136. The labour coefficient decreased from 0.0430 to 0.0164.

1984 until 1988. If we calculate the annual growth rate from 1960 until 1984, it is equal to about 1%, which is again consistent with the parameter estimate.

Consequently, we can conclude that the movement of the initial factor coefficients of the best-practice technologies along the connecting line between 1960-0 and 1984-0 can be attributed to technological change. The turbulent movements in and after this period can be attributed to substitution effects. This will be elaborated below.

The envelope of all initial factor coefficients narrows in the middle of the figure due to different effects. The number of technologies decreases from 25 in 1960 to 6 in 1975 and 1976 and increases to 17 in 1988 (cf. Figure 4.9). This might explain the shape of the envelope if all technologies within each vintage evolved along the same lines as the 1960 and 1988 vintages. However, this is not the case, as can be seen from Figure 4.13. In this figure, we have redrawn the factor coefficients from the previous figure for some vintages. Next to the coefficients, we plotted some construction lines (the dotted lines). Lines marked with (a) denote labour intensities at a constant wage rental ratio, i.e., these lines denote a 3.4% labour-augmenting and 1.0% capital-augmenting technological change without any substitution effects. The two other lines, which are marked by the letter (b), denote Hicks neutral technological change, i.e., the labour intensity is constant along these lines.

In Figure 4.13 we can distinguish two different groups of vintages. The technologies of vintages installed in 1960, 1980, 1984 and in 1988 are distributed in a more or less Hicks neutral fashion, i.e. parallel to lines (b).

The second group of machines belong to vintages 1965, 1970 and 1975. The machines from the 1965 vintage evolve almost parallel to line (a) whereas the factor

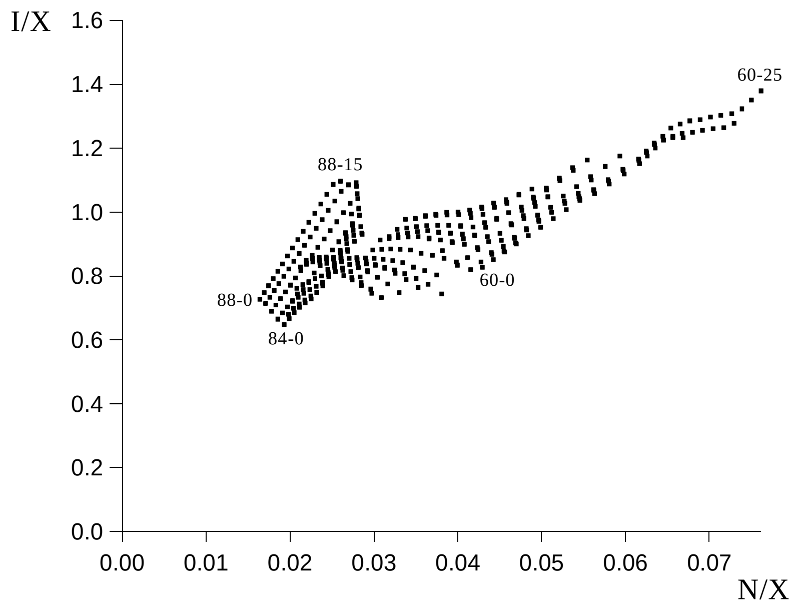

Figure 4.12. Initial factor coefficients of all machines which are installed after 1960 (labour and capital in working/operating hours)

coefficients of machines from vintage 1975 move almost perpendicular to this line. The evolution of the 1965 vintage can be described as a result of technological change, whereas substitution effects play a major role in the relative position of the machines which belong to the 1975 vintage.

To explain this difference, we have to evaluate the difference of labour intensities within a vintage. It is easy to verify that, if we apply the parameter estimates to the optimal labour intensity equation, the relative change of the labour intensity depends mainly on the change of the discounted expected growth rate of future labour costs (the term $S_2(\theta^i)$ in equation (3.48), page 95).[137] This latter term depends only on the technology index through the expected lifetime which implies that, if the expected lifetime is the same for two succeeding technologies, the relative change of the labour intensity is equal to 0.1%. In this case, the influence of the relative change of the price of equipment (β) on the labour intensity is about equal to the influence of embodied technological change. Furthermore, the term $S_2(\theta^i)$ depends mainly on the ratio of the expected growth of nominal wages and the expected interest rate (cf. equation (3.48), page 95).[138] Figure A4.2, page 146, shows that the expected growth rate of nominal wages exceeds the expected interest rate to a large extent in the late sixties and early seventies. This implies that a longer planning period involves higher (integral) wage costs relative to the costs of capital at a constant labour productivity. The opposite is true for the period after 1979, where the expected growth rate of nominal wages is below the expected interest rate, implying that a longer planning period increases the integral wage costs at a diminishing rate.

From Figure 4.11, the expected lifetime of equipment in 1960 is at its upper boundary of 15 years for almost all technologies. This implies that the $S_2(\theta^i)$-term is the same for those technologies, which explains the constant labour intensity for these machines. After 1980, a change in the expected lifetime influences the integral wage costs to a lesser extent so that the technologies evolve along the same labour

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137. From equation (3.49) in the previous chapter, the relative change of the optimal labour intensity between two successive technologies at the same point in time is:

$$\frac{dl^i}{di}\frac{1}{l^i} = \frac{1}{1+\rho}\left(-\frac{dS_2(\theta^i)}{d\theta^i}\frac{d\theta^i}{di}\frac{1}{s_2(\theta^i)} + \frac{dq^i}{di}\frac{1}{q^i} - \rho\left[\frac{dA^i}{di}\frac{1}{A^i} - \frac{dB^i}{di}\frac{1}{B^i}\right]\right)$$

in which we dropped the time indices. If we apply the estimated values of the parameters we obtain:

$$\frac{dl^i}{di}\frac{1}{l^i} = \frac{1}{1+\rho}\left(-\frac{dS_2(\theta^i)}{d\theta^i}\frac{d\theta^i}{di}\frac{1}{S_2(\theta^i)} + \beta - \rho\left[\mu_n - \gamma_n + \mu_i - \gamma_i\right]\right)$$

$$= 0.65\left(-\frac{dS_2(\theta^i)}{d\theta^i}\frac{d\theta^i}{di}\frac{1}{S_2(\theta^i)}\right) + 0.001$$

138. The other terms in this equation are about equal in both the numerator and the denominator and cancel out.

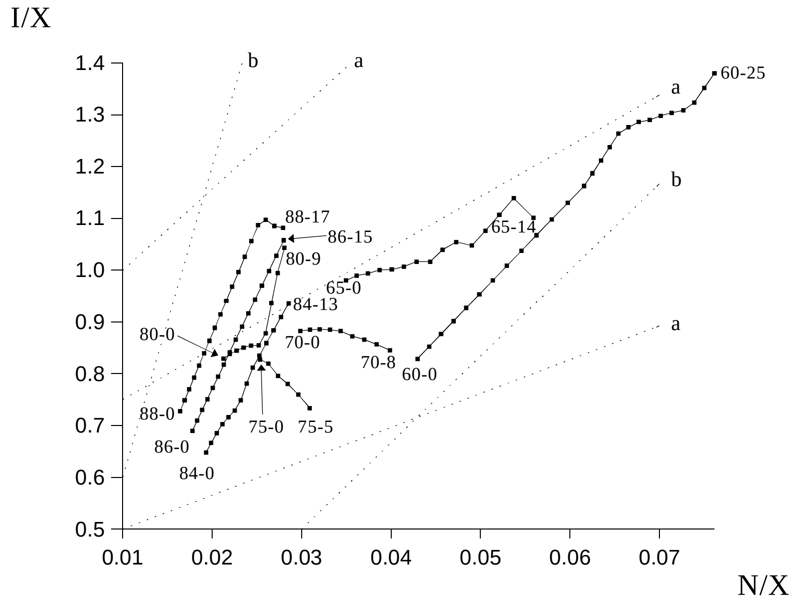

Figure 4.13. Initial factor coefficients of all technologies from several vintages (labour and capital in working/operating hours)

intensity for these vintages. Furthermore, the expected lifetime of the most recent technologies is bounded to 15 years which implies that the integral wage costs are the same for these technologies, as is the case with the 1960 vintage. Finally, the huge difference between the expected wage rate and the expected interest rate in the late sixties and early seventies leads to a considerable difference in integral wage costs for a slight extension of the planning period. The relative costs of capital between succeeding technologies is constant, causing firms to choose a more labour extensive way to produce output in this period. This explains the change in the relative movement of the labour intensities within vintages and the shape of the envelope of all factor coefficients.

Above, we subtracted several vintages from Figure 4.12 in order to highlight the movement of the labour intensity within each vintage. Another way to disentangle Figure 4.12 is to examine the movement of the labour intensity of some technologies. This is done in Figure 4.14, where the technologies developed in 1960, in 1971 and in 1980 are displayed. In the 1960 technology, for example, a 0 denotes the vintage 1960, 1 denotes the same (1960) technology installed in 1961, and so on. Both number 17 of the 1971 technology and number 8 of the 1980 technology are installed in 1988. The factor coefficients effectively move along an isoquant because there are almost no ex-post improvements of the technologies.

The movement of the labour intensities along an isoquant is the result of changes in the wage rate, the interest rate, prices of equipment, etc. Furthermore, the expected lifetime plays an important role, as we have seen before. It is difficult to give a decisive explanation of changes in labour intensities, but changes in the expected growth rate of real wages can explain this movement to a large extent.

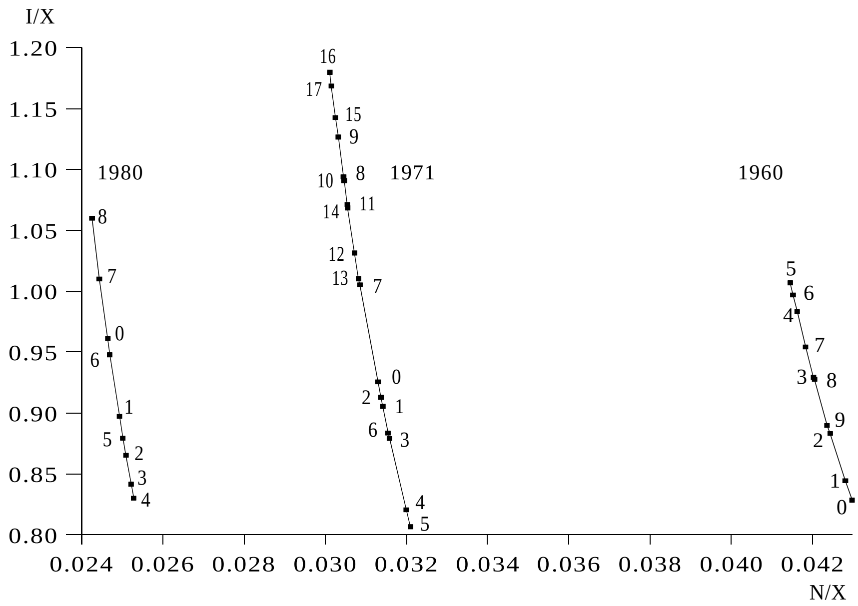

Figure 4.14. Initial factor coefficients of several technologies (labour and capital in working/operating hours)

From the 1960 technology, we observe that the labour intensity decreases from 1960 until 1965 and increases afterwards. This implies that the wage rental ratio increases in the first stage and decreases in the second stage. The expected growth rate of real wages increases in the first period from about 3.5% to 5.5% and fluctuates around 6% afterwards. The price of equipment decreases very slightly in the first years but increases afterwards.[139] Together, this can explain the movement of the labour intensity of the 1960 technology.

The movement of the labour intensity of the technology from 1980 is opposite to the movement of the 1960 technology. The labour intensity increases in the first stage and decreases afterwards. This movement can also be explained to a large extent by changes in the expected growth rates of both nominal and real wages which decreases until 1984 and increases after that. Finally, the movement of labour intensities of the technology from 1971 is hard to explain in detail. However, the general movement is that labour intensity increases in the first stage and decreases in the second stage, which can be explained by movements of the expected wage rates.

139. Note that the general price level of aggregate investment increases in time. However, the relative price of capital decreases as the technology becomes older, which can imply that the price of a certain technology, which becomes older and older, decreases in time.

4.2.5 Conclusions

Compared to the non-diffusion model, the estimates of the vintage-diffusion model yield a much better fit, especially on the demand for labour. This holds true, even if we limit the amount of labour hoarding to 35%, the percentage which we have found in the non-diffusion model. The amount of scrapping is more smooth in the vintage-diffusion model than in the traditional non-diffusion vintage model. The model behaves in line with our expectations, and situations as put forward in Figure 3.5 on page 99 are indeed relevant. Furthermore, we found that the amount of scrapping has increased over time between 1960 and 1988. This holds for both the diffusion and the non-diffusion model and corresponds to the findings of Gelauff, Wennekers and de Jong and of Muysken and van Zon. Finally, by comparing the development of labour productivity of the newest vintage in both models, we showed that the diffusion model is able to vary the productivity to a larger extent. This difference is very significant in the eighties and the turbulent movements of the demand for labour can be described more accurately by the vintage-diffusion model.

We showed that the diffusion process is S-shaped for most technologies and that the speed of diffusion changes over time. The shape of the diffusion process is dominated by differences in the stock of knowledge before 1950 and after about 1980, whereas it is dominated by differences in profitability in the late sixties and early seventies. Furthermore, we are able to examine the complete life-cycle of all technologies. One interesting point is that in the eighties, older technologies are productive for a longer period and we showed that this can be explained by two different forces: decreasing investments and decreasing differences between technologies with respect to expected profits as a result of which knowledge becomes a more important factor in the determination of the adoption process.

By comparing our results with the results of Gelauff, Wennekers and de Jong and of Muysken and van Zon, we showed that our results are more satisfactory if compared with the results of GWJ and we obtain approximately the same results as MvZ. Whereas GWJ introduced endogenous technological change in a rather ad hoc way, we introduced an endogenous transmission of technological change by introducing the main findings of the literature on adoption and diffusion of new technologies within a vintage framework. Due to their specification, GWJ overestimate the role of disembodied technological change whereas we find about the same value for disembodied labour-augmenting technological change as MvZ.

With respect to the expected lifetime, we find that our results for the non-diffusion model are slightly better than the results of MvZ. If we compare the realized and the expected lifetimes in the diffusion model, we see a similar pattern of over- and underestimates if we consider them at the vintage level. The differences of actual and expected lifetimes between several technologies within each vintage are about the same. Although some more research has to be done to improve these results, the concept of consistent expectations seems to work well.[140]

Finally, changes in the production techniques are merely labour-augmenting in the period 1960-1988. The developments within a vintage changes dramatically within this period. Whereas the labour intensity of several technologies within each vintage is about the same in the early sixties and in the eighties, this is certainly not true in the late sixties and seventies. Many forces are responsible for this, but the development of real wages and the development of the difference between the nominal wage rate and the interest rate can explain these changes to a large extent. Furthermore, the choice of the production technique depends highly on the expected lifetimes.

Although the development of total labour productivity of the total capital stock depends heavily on the initial production techniques of all individual machines, the amount of investment, and thus the weight of the individual technologies in the total newest vintage, depends on the diffusion process. Moreover, total labour productivity depends on the amount of scrapping. This is elaborated in the next section.

4.3 Development of the Structural Labour Productivity[141]

In order to highlight the results of the vintage-diffusion model with respect to the productivity slowdown, this section investigates the origins of structural labour productivity growth. First, we will decompose total labour productivity growth into its individual components, including the contribution of the newest vintage to the development of labour productivity growth. We will concentrate on the influence of scrapping of capital goods and the influence of the investment in new vintages on labour productivity growth. Second, we will investigate the contribution of the diffusion process to the productivity growth of the newest vintage by decomposing this newest vintage into its underlying technologies. This will lead to a new explanation of the productivity slowdown. Furthermore, we will show that the labour productivity of the best-practice technology developed at an almost constant rate whereas the labour productivity growth of the new vintage decreased until 1981. This implies that the vintage-diffusion model is able to describe the productivity slowdown as well as the productivity paradox.

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140. Although the realized lifetimes are still the results of our model, the decline of the age of the capital stock until 1975 and its small increase afterwards is consistent with the findings of some other (non-vintages) approaches, e.g., the Commission of the European Communities, Directorate-General for Economic and Financial Affairs (1992).

141. In this section, the term ‘labour productivity’ will be used to indicate the structural labour productivity, i.e., labour productivity as measured at full utilisation of both labour and capital.

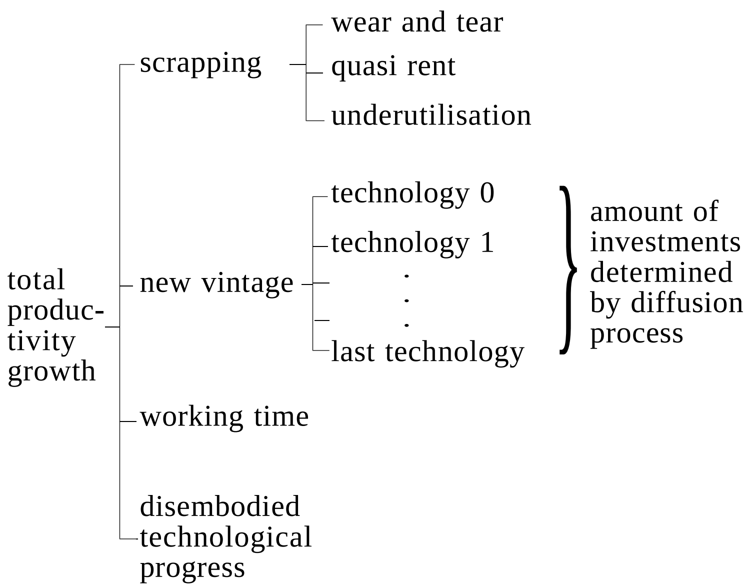

Figure 4.15. Decomposition scheme of total labour productivity growth

The sources of changes in the labour productivity are listed in Figure 4.15. This figure is used as a guideline to examine the importance of each component. The contribution of each component to labour productivity is measured at the margin, which means that the productivity is measured before and after the installation of the newest vintage, after scrapping, after corrections for working/operating hours, etc. The difference between these measures are contributed to the several components.

In Figure 4.16, we plotted the annual total labour productivity growth (top figure) and the productivity growth for several five-year periods (last bar in the bottom figure). In the sixties, the productivity growth rises from 3.5 percent towards about 4.5 percent a year, followed by a decrease in the seventies and early eighties. In the period 1981-1985, the annual growth rate of the labour productivity is equal to 1.4 percent. At the end of our estimation period we see a slight improvement of the productivity growth. Looking at the several components underlying this development, one observes a huge impact of the installation of new vintages (bar no. 4) on total productivity growth. The new vintages account for about 75% percent in total productivity growth in the sixties and early seventies. The impact of newly installed vintages declines somewhat after 1975 but remains above 50%. Below, we will take a closer look at the development of labour productivity growth of the new vintages.

The influence of scrapping on the total labour productivity growth is small in the early sixties but increases afterwards (bar no. 3). From the early seventies until the end of the estimation period, the influence of scrapping is comparable to the influence of the installation of new machinery on the total labour productivity

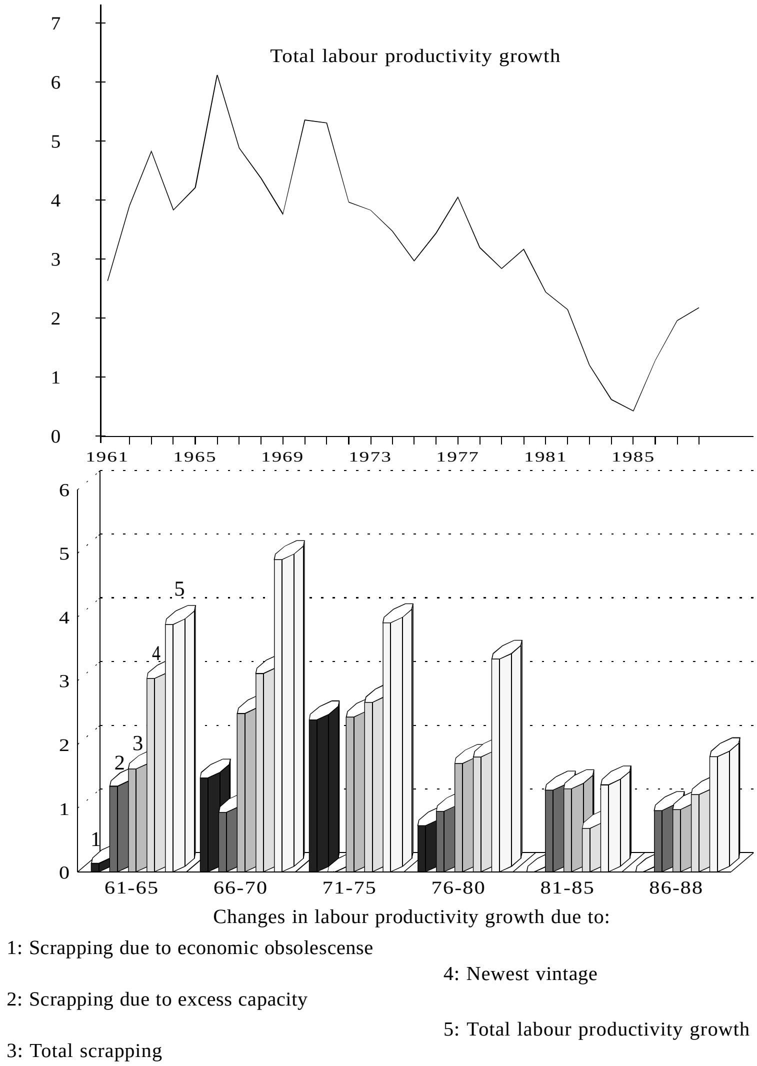

Figure 4.16. Decomposition of structural labour productivity growth (annual percentage change)[142]

growth.[143] Examination of the components of total scrapping we see that the impact of scrapping due to negative quasi-rents and of scrapping due to severe underutilisation switch during the estimation period. In the early sixties, almost all scrapping is due to underutilisation but this type of scrapping declines in favour of the scrapping due to economic obsolescence in the late sixties and early seventies.

142. For sake of clarity, we did not include influence of working time, disembodied technological change and scrapping due to wear and tear on productivity growth in this figure. These components are included in the total labour productivity growth, however. Note furthermore that the contributions of several components are not corrected for working/operating hours. This implies that the levels should be corrected downwards. The relative importance of these factors remain constant however. We did not correct for changes in working hours in order to make our results comparable with the results of GWJ.

143. Note that both are related to each other if embodied technological change is not constant over time. Investing in a relatively highly productive vintage now, for example, implies that labour productivity will change to a lesser extent if this vintage is scrapped, ceteris paribus.

	our model			Model of GWJ	
	1961-1973	1974-1988	1974-1982	1960-1973	1974-1982
Newest Vintage	3.0	1.4	1.7	2.4	1.7
Scrapping, total	2.1	1.5	1.9	0.7	0.8
Technical Decay	0.1	0.02	0.03	0.2	0.2
Economic Obsolescence	1.2	0.6	0.9	0.5	0.6
Excess Capacity	0.9	0.9	0.9	0.0	0.0
Disemb. Technol. Progress	.04	.04	.04	2.6	1.3
Working Time	-0.8	-0.6	-0.5	-1.3	-0.6
Total	4.4	2.4	3.1	4.3	3.1

Table 4.3. Decomposition of structural labour productivity growth (annual percentage changes)

After 1975, the opposite holds true, at the end of the estimation period we observe only scrapping due to underutilisation. Note that both scrapping reasons are not independent of each other. If scrapping due to underutilisation matters, the least productive machines are scrapped first. The labour productivity of the least productive machine will increase which leads to fewer machines being scrapped due to economic obsolescence in the next period.

The Solow / Phelps approach disregards the effect of scrapping. As the influence of scrapping is not directly related to the amount of investment, the contribution of scrapping to changes in the labour productivity growth will be attributed to disembodied technological progress rather than embodied technological change. This is the main reason why approaches based on the Solow / Phelps model underestimate the impact of embodied technological change and, consequently, undervalue the role of vintage models. In Table 4.3, we compare our results concerning the labour productivity growth with the results of Gelauff, Wennekers and de Jong (1985). In order to do so, we divided the average growth into periods before and after the 1973 oil price shock, and calculated the average growth for the period 1974-1982. The development of the total labour productivity growth is identical for both models if we consider the same periods. The growth in the period 1974-1988 is slightly less than the average growth between 1974 and 1982 due to the modest growth in the mid eighties. The impact of newly installed capacity on the labour productivity growth is the same in the last period for both models (1.7%) while the growth in the first period is higher in our model. This can be explained to a large extent by the introduction of the diffusion into our model as we will see below.

Major differences can be found in the effect of scrapping and the impact of disembodied technological progress. In their model, GWJ use partly endogenous disembodied technological progress, which results in a variable impact on the development of the labour productivity with a *"peak of 3.2% a year in the period*

1971-1973 and a decline to 0.9% a year in 1979-1982.[144] In our model we applied constant disembodied technological progress, i.e., with a constant impact on the development of the labour productivity growth of 0.04% per year. This corresponds with the findings of MvZ, and we showed above that GWJ overestimate the role of disembodied technological change. The difference in the effect of scrapping on the development of labour productivity can be explained to a large extent by the impact of scrapping due to severe underutilisation. GWJ assume that this type of scrapping affects the entire capital stock without making any difference between vintages. This has no impact on the growth rate of labour productivity. In our model we assume that the least productive machines are scrapped first, so labour productivity increases as some less productive equipment is scrapped. Note furthermore that, although the contribution of the newest vintages to the growth of structural labour productivity is equal in size for both models, we endogenized the influence of technological progress by introducing diffusion of process innovations while GWJ endogenized technological progress in a rather ad hoc way.

Before we discuss the impact of the diffusion process on labour productivity growth, we will develop a quantity to measure the speed of diffusion. For an individual technology, we can relate the speed of diffusion to the time needed between introduction and reaching the ceiling level — for instance, we can define the speed of diffusion as the inverse of this interval. But during this interval of, let's say, n years, n-1 new technologies will come onto the market for capital goods. Thus, the total number of technologies at that point in time will be n. At the macro level, the speed of diffusion then is equal to the inverse of the number of technologies, i.e., the speed of diffusion is equal to $1/n_t$.

Now, we will discuss the impact of the diffusion process on the development of structural labour productivity growth. As we did above, we will examine first-order effects only. The impact of the diffusion process on productivity growth can be examined by comparing the productivity growth of the best-practice technologies with the average growth of the new vintage. This is done in Figure 4.17. The annual growth of the labour productivity of the best-practice technologies fluctuates between 1 and 4.5 percent without a clear trend. The slowdown in labour productivity growth of the total capital stock as shown in Figure 4.16 does not apply to the best-practice machines. Contrary to the best-practice technologies, the productivity growth of the new vintage, including all technologies, shows a downward sloping trend from 1960 until 1981. In the early eighties, the growth rate of labour productivity is even negative. This can be explained by shifts in the distribution of output with respect to technologies, which is described in the previous chapter (cf. Figure 3.6 on page 102). After 1981, the labour productivity growth of

144. Gelauff, Wennekers and de Jong (1985: 338).

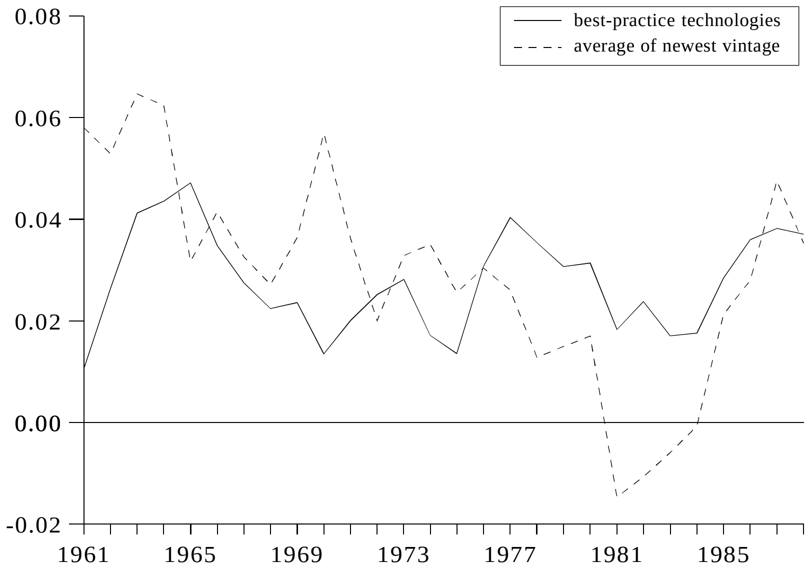

Figure 4.17. Labour productivity growth of the best-practice technologies and of the newest vintage

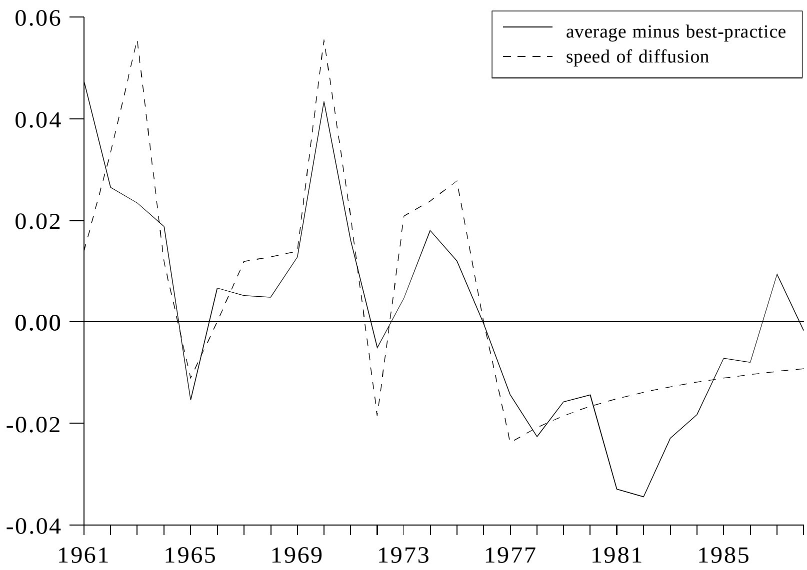

Figure 4.18. Difference of labour productivity growth within the newest vintage and the speed of diffusion

the new vintage increases to about 4 percent in 1988.[145] The deviation of the productivity growth of the new vintage from the productivity growth of the best-practice technology can be attributed to the changes in the speed of diffusion.[146] This is shown in Figure 4.18, which demonstrates that the difference between the

145. Note that we are now discussing the development of labour productivity growth of the new vintage while in relation with figure 4.16, we discussed the influence of the newest vintage on total labour productivity growth.

146. The growth rates of labour productivity of older technologies are very similar to the development of the productivity growth of the best-practice machine, for both the variation and the level.

growth rate of the labour productivity of the new vintage and the growth rate of labour productivity of the best-practice technology can be attributed to the changes in the speed of diffusion.[147]

Note that the difference in labour productivity growth increases sharply from -1.5% towards +4% during the period 1964-1970. For this period, Muysken and van Zon (1987) found a high value for embodied labour-augmenting technological progress (first dummy variable in Table 4.2). They introduced another dummy period (1975-1981), for which they found an almost vanishing value of embodied labour-augmenting technological progress. In our model, the difference of labour productivity growth between the newest vintage and the best-practice machine decreases from +1.5% towards -3.5% during the second dummy period of MvZ. So both the points in time for which they introduced dummies, as well as the estimated values for those dummy periods, can be identified in our model, in which those differences can be attributed to changes in the speed of diffusion.

Total labour productivity growth slowed down from 4.4 percent in the period 1961-1973 towards 2.4 percent in the period after 1974, as is shown in Table 4.3. The impact of the newest vintage on the total labour productivity growth declined with 1.6 percent between those two periods and accounts for about 75% for the slowdown of total productivity growth. We can therefore conclude that the decline of annual total structural labour productivity growth can be attributed for a large extent to the slowdown in the speed of diffusion. In the previous paragraph, we argued that the decline in the growth rate of real wages decreases the differences in expected profitability between new and older technologies. Next to the increase of the nominal wages in the late 1960s, the increase of oil prices increased the general price level whereas it was not entirely compensated in the wages. Both led to a decrease in the growth rate of real wages. This will shift the distribution of investments with respect to the technologies to the left so that the growth rate of the average labour productivity all technologies taken together declines. Furthermore, if the growth rate of real wages decreases, less productive technologies will remain profitable for a longer period, leading to yet another decrease in the growth rate of the average productivity of the newest vintage. Both forces will decrease the speed of diffusion.

Our overall conclusion is that a decline in the growth of real wages and a decline of the nominal wages compared to the nominal interest rate results in a decline of structural labour productivity in two ways. First through the reduction in the amount of scrapping which increases the lifetime of equipment increases so that the average labour productivity decreases. Secondly, through the diffusion effect as described above.

147. The change in the speed of diffusion is divided by 6 in order to make the change in the speed of diffusion comparable to the difference in growth rate of labour productivity.

4.4 Conclusions

In chapters 3 and 4, we developed and estimated a simple vintage model incorporating the idea of the diffusion of technologies. The estimation results show that the model with diffusion performs much better than the model without diffusion. Furthermore, the results suggest that embodied technological change for the best-practice technologies is largely labour-augmenting, whereas we found no embodied improvements of the best-practice technologies after their introduction onto the market for capital goods.[148] Disembodied technological progress is rather small and largely capital-augmenting in nature.

As expected, scrapping in the vintage-diffusion model is less turbulent as compared to the non-diffusion model. But the objective function is still far from smooth, as is shown in appendix 4E. This leads to severe estimation problems if a quasi-Newton method is used. The use of other methods, such as the complex and the random search algorithms, is more appropriate in such a case. Furthermore, the Hessian cannot be computed in the optimal point because of these discontinuities, which means that we cannot compute the variance of the estimated parameters.

One way to reduce these discontinuities could be the use of an alternative scrapping condition. Gelauff, Wennekers and de Jong (1985) use a smooth negative quasi-rent scrapping method in which the amount of scrapping is a linear function of the ratio of the variable costs over the revenues.[149] Although this reduces the discontinuities in their model, their alternative scrapping condition is ad hoc. An alternative could be the use of a mixture of the quasi-rent and the Malcomson scrapping routine, at least in the situation in which the output market is not competitive.[150] The Malcomson scrapping routine can be described as active profit-maximizing behaviour whereas the quasi-rent scrapping is characterized by loss-avoiding behaviour.[151] A functional relation between these two alternatives could lead to a smooth scrapping condition which is less ad hoc than the condition as used by GWJ. Note furthermore that such a relation increases scrapping as compared to the negative quasi-rent condition whereas the GWJ condition reduces the amount of scrapping. The influence of alternative scrapping conditions on the estimates of technological change cannot be determined in advance and should be examined by some estimation experiments.

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148. Recall the difference between the general notion of technologies and the way they are modelled in this thesis (see the discussion on page 111).

149. Cf. chapter 3, page 79.

150. Meijers and van Zon (1991) use a scrapping condition which is based on both the quasi-rent and Malcomson scrapping behaviour. On the base of French data for three different sectors of industry, they find that Malcomson scrapping is more relevant. However, scrapping is still a zero-one decision and this does not reduce discontinuities.

151. Cf. footnote 106 on page 97.

As expected, we find an S-shaped diffusion path for all technologies before 1975. The diffusion patterns of more recent technologies are not that clear S-shaped but the diffusion process is not finished at the end of the estimation period. If the relative profitability of a technology reduces in time in a smooth fashion, we indeed observe diffusion paths as expected in Figure 3.3 (page 91). The shape of the diffusion patterns are less obvious if the relative profitability evolves less smoothly, for instance due to turbulent movements of factor prices after the first oil price shock.

We see an increase in the speed of diffusion if factor prices rise sharply, which happened in the Netherlands in the late sixties and early seventies. The difference in expected profitability between succeeding technologies increases so that more firms will invest in relatively new technologies. Furthermore, fewer technologies are profitable, so firms will invest in the few types of machines that are still profitable. Both reactions speed up the diffusion process. A similar effect can be obtained by using the Malcomson scrapping condition. If the total costs per unit of output of new equipment decreases, due to increased productivity for instance, firms will replace old but still profitable machinery by new equipment, resulting in an increase in the productivity of the total capital stock. Notice, however, that an opposite direction is less clear. If the profitability of newer equipment declines, there will be fewer replacement investments but scrapping is bounded from below by the negative quasi-rent condition, which implies that the growth rate of labour productivity is also bounded from below. Moreover, the Malcomson condition cannot explain such negative growth rates of the labour productivity as we found in the early eighties.

Total structural labour productivity growth shows a slowdown after about 1973 whereas we assumed constant embodied and disembodied technological change. It is shown that the slowdown in total labour productivity growth can be attributed to the slowdown in the speed of diffusion for about 75%. Furthermore, the model solves the productivity paradox; the labour productivity growth of the best-practice machines is more or less constant between 1960 and 1988 whereas the average labour productivity declines steadily between 1973 and 1985.

If we compare our results with the explanations of Romer (1987) and Scott (1989), a number of similarities catch the eye. Romer argues that a lower wage rate decreases labour-augmenting innovations, leading to a decline in labour productivity. In our model, a reduction in the growth rate of real wages decreases the speed of diffusion and consequently reduces the growth of labour productivity. Scott argues that labour hoarding, changes in the lifetime of equipment, and scrapping due to bankruptcies can explain the fall of the investment opportunities followed by a decrease in the growth rate of labour productivity. Our model includes all these terms into the vintage-diffusion framework. Next to changes in the speed of diffusion, we see that a fall of the lifetime of equipment before 1973 has economized the capital stock to a large extent. After 1973, the lifetime is almost constant, so that the scrapping effect on labour productivity growth declines. Thus, whereas Scott argues that equipment is scrapped after 1973, we see that the lifetime of equipment declined much earlier. Our findings are consistent with an international study of the EC, which shows that for most countries, the lowest point of the age structure falls in the period 1971-1975.[152] Furthermore, Dutch non-diffusion vintage models find similar results. Effects due to labour hoarding are also included in our model. Although we find that a reduction of the amount of labour hoarding mainly alters the level of labour productivity, resulting in almost identical growth rates, it is clear that it has some effects on the growth rate of labour productivity if the rate of capacity utilisation declines as rapidly as in the Netherlands between 1973 and 1982.

Thus, whereas Romer and Scott have to make additional assumptions to explain the productivity slowdown in their models, our model is able to describe the data quite well. Their main arguments are included in our model through diffusion effects as well as typical vintage effects.

Finally, from the initial factor productivities, we observe that the productivity of more recent vintages can be below the productivity of older ones. From this, it follows that the hypothesis of Gregory and James (1973) — are more recent vintages more productive? — does not test the embodiment effect. They find that there is some relation between the age of the capital stock and the corresponding productivity, at least on average, but that there are many individual cases in which this is not true. These findings can be explained by our model, in which the embodiment effect is the main source of technological change but where new equipment may be of an older design.

The way in which we integrated the diffusion process within a vintage structure is somewhat artificial. To avoid serious conceptual problems we had to assume a distribution of the technologies within each vintage. Although this distribution depends on the relative expected profitability and the relative stock of knowledge, the underlying behaviour of the firms is not explained, especially with respect to the distribution of risk aversion. In part III of this thesis, we will pay attention to possible underlying mechanisms in order to explain the choice of technologies by firm behaviour more explicitly. In order to keep the model manageable in an analytical way, we will develop a reduced version of the vintage-diffusion model. On the other hand, we will relate firms characteristics to the investment behaviour, thus making the capital stock traceable for each individual firm. This enables us to apply the Malcomson scrapping condition in a vintage-diffusion framework.

152. Cf. Commission of the European Communities, Directorate-General for Economic and Financial Affairs (1992). The countries for which the age profile does not decrease in the mid seventies are Ireland and the UK.

Appendix 4A. Data and Sources

The data used are presented in the tables below. The index for working hours, equal for both labour and capital, is given by $hn_t = hi_t = h_t^{0.75}$ in which h_t denotes the number of working hours.

t	X_t	u_{xt}	N_t
1950	31.639	1.000	3411
1951	32.956	0.978	3442
1952	33.822	0.938	3397
1953	36.472	0.962	3457
1954	39.628	0.980	3561
1955	42.959	0.999	3645
1956	44.532	0.986	3627
1957	45.995	0.980	3715
1958	45.425	0.939	3632
1959	47.738	0.938	3689
1960	52.338	0.991	3792
1961	53.912	0.970	3873
1962	56.246	0.965	3953
1963	58.147	0.947	4009
1964	63.970	0.997	4088
1965	67.826	0.999	4124
1966	69.512	0.976	4133
1967	73.418	0.970	4063
1968	78.423	0.982	4107
1969	83.774	0.986	4198
1970	89.521	1.001	4264
1971	93.440	0.994	4250
1972	96.588	0.979	4147
1973	101.651	0.990	4148
1974	103.551	0.987	4146
1975	101.091	0.939	4080
1976	107.088	0.950	4058
1977	109.599	0.954	4059
1978	113.033	0.961	4086
1979	115.549	0.969	4138
1980	116.483	0.950	4147
1981	115.135	0.919	4029
1982	113.958	0.902	3896
1983	114.861	0.909	3808
1984	119.647	0.936	3833
1985	122.985	0.948	3920
1986	125.173	0.943	4013
1987	126.829	0.941	4079
1988	131.942	0.954	4135

t-τ	$\Omega_{t-\tau}$
1	1.000
2	0.986
3	0.955
4	0.929
5	0.906
6	0.889
7	0.874
8	0.855
9	0.837
10	0.819
11	0.788
12	0.763
13	0.740
14	0.716
15	0.695
16	0.670
17	0.647
18	0.617
19	0.587
20	0.550
21	0.508
22	0.456
23	0.408
24	0.365
25	0.324
26	0.284
27	0.248
28	0.219
29	0.192
30	0.166
31	0.143
32	0.123
33	0.103
34	0.087
35	0.071
36	0.056
37	0.047
38	0.037
39	0.031
40	0.026
41	0.022
42	0.018
43	0.013
44	0.009
45	0.004

t	h_t	p_t	w_t	Q_t	r_t	I_t
1900	1.341	16.246	0.564	16.959	3.17	--
1901	1.336	17.230	0.564	16.017	3.00	--
1902	1.331	16.738	0.564	14.761	3.03	--
1903	1.325	16.738	0.567	14.290	3.12	0.984
1904	1.320	17.230	0.622	14.604	3.16	0.984
1905	1.314	17.230	0.636	14.290	3.17	1.028
1906	1.309	17.230	0.639	14.447	3.20	1.028
1907	1.304	17.476	0.646	15.703	3.32	1.076
1908	1.298	17.969	0.643	15.703	3.30	1.076
1909	1.293	17.723	0.654	14.447	3.21	1.135
1910	1.288	18.215	0.665	15.075	3.34	1.135
1911	1.264	18.461	0.676	15.546	3.52	1.135
1912	1.241	18.707	0.694	16.645	3.68	1.227
1913	1.218	18.953	0.714	17.587	3.79	1.285
1914	1.196	18.953	0.760	17.744	3.79	1.228
1915	1.174	19.666	0.818	18.119	4.05	1.285
1916	1.152	20.405	0.881	18.501	4.09	1.335
1917	1.131	21.173	0.949	18.891	4.13	1.226
1918	1.110	21.969	1.021	19.290	4.42	1.135
1919	1.089	22.795	1.100	19.697	4.85	1.438
1920	1.069	23.652	1.184	20.112	5.73	1.495
1921	1.050	24.541	1.275	20.537	5.07	1.594
1922	1.030	25.464	1.373	20.970	4.86	1.456
1923	1.029	26.421	1.478	21.413	4.63	1.138
1924	1.028	27.415	1.591	21.864	4.70	1.288
1925	1.027	27.076	1.584	21.703	4.18	1.422
1926	1.026	26.092	1.584	21.171	4.00	1.573
1927	1.025	26.092	1.584	21.042	4.01	1.682
1928	1.024	26.338	1.612	21.702	3.88	1.904
1929	1.023	26.092	1.653	22.909	3.94	1.897
1930	1.022	25.107	1.667	22.177	3.81	2.309
1931	1.021	23.630	1.640	21.414	3.86	1.643
1932	1.019	21.907	1.542	18.177	3.89	1.002
1933	1.018	21.661	1.487	16.843	3.68	1.092
1934	1.017	21.661	1.445	16.510	3.35	1.089
1935	1.016	20.922	1.376	16.313	3.43	0.937
1936	1.015	20.430	1.348	16.219	3.32	1.051
1937	1.014	20.922	1.376	19.174	3.13	1.412
1938	1.013	21.415	1.389	20.678	2.99	1.731
1939	1.012	21.661	1.397	21.280	3.56	1.908
1940	1.011	25.107	1.456	25.676	3.98	1.064
1941	1.010	28.553	1.566	26.863	3.58	0.768
1942	1.009	29.045	1.669	26.734	3.21	0.436
1943	1.008	29.784	1.801	27.009	3.11	0.346
1944	1.006	31.014	1.809	30.974	3.09	0.001
1945	1.005	32.491	2.020	33.039	3.00	0.001

t	h_t	p_t	w_t	Q_t	r_t	I_t
1946	1.004	42.337	2.277	52.293	2.99	0.955
1947	1.003	44.799	2.557	53.961	3.06	2.043
1948	1.002	46.029	2.658	55.197	3.09	2.547
1949	1.001	46.466	2.746	56.954	3.12	2.767
1950	1.000	48.458	2.937	59.086	3.12	3.101
1951	1.000	52.757	3.243	66.919	3.94	2.889
1952	1.000	53.803	3.417	74.121	3.95	2.620
1953	1.000	53.328	3.561	73.316	3.30	2.993
1954	1.000	54.595	3.889	71.973	3.22	3.844
1955	1.000	57.121	4.235	73.064	3.33	4.692
1956	1.000	60.024	4.600	76.564	3.99	5.462
1957	1.000	63.646	5.098	79.999	4.95	5.640
1958	1.000	64.869	5.322	80.920	4.45	4.513
1959	1.000	65.545	5.448	80.205	4.33	5.116
1960	0.994	66.802	5.892	80.733	4.35	6.124
1961	0.964	67.854	6.318	80.686	4.12	6.716
1962	0.948	69.475	6.690	80.842	4.28	7.132
1963	0.942	72.474	7.289	83.599	4.32	7.116
1964	0.942	77.164	8.378	86.824	5.12	7.508
1965	0.942	80.854	9.312	89.134	5.53	7.948
1966	0.942	84.702	10.334	91.749	6.60	8.692
1967	0.939	87.275	11.239	91.581	6.17	9.005
1968	0.928	89.819	12.237	90.822	6.47	10.207
1969	0.916	95.954	13.881	93.177	7.52	10.233
1970	0.897	100.053	15.716	100.00	8.20	12.219
1971	0.885	107.378	17.781	107.819	7.38	12.088
1972	0.877	116.464	20.023	111.804	6.94	10.999
1973	0.865	126.614	23.147	111.707	7.80	12.602
1974	0.847	137.212	26.772	123.624	9.67	13.048
1975	0.827	149.152	30.207	138.084	8.52	11.770
1976	0.823	160.416	33.538	148.795	8.72	10.859
1977	0.823	168.535	36.326	152.900	7.96	12.812
1978	0.820	177.114	38.950	156.731	7.65	13.366
1979	0.816	183.725	41.374	162.474	8.59	13.861
1980	0.816	190.926	43.818	171.936	9.90	12.998
1981	0.813	198.326	44.630	186.270	11.52	11.372
1982	0.811	210.862	45.876	196.817	9.93	11.388
1983	0.803	214.935	46.014	201.825	8.24	12.778
1984	0.794	216.723	46.316	205.905	8.10	13.921
1985	0.781	218.368	48.145	208.950	7.32	16.031
1986	0.774	228.629	50.465	207.998	6.36	18.069
1987	0.770	231.130	52.209	204.611	6.35	18.278
1988	0.768	236.658	54.187	209.723	6.10	19.053

All series are based on two databases. The main source is the database of Gelauff, Wennekers and de Jong (1985), whose data until 1982 are used. Data from 1983 and onwards are used from the FK'88 database, obtained from the Central Planning Bureau. Expansion of the time series from 1982 is obtained by using the growth rates from the FK'88 database. Note that, as in GWJ, data of p_t, Q_t and r_t between 1915 and 1925 are based on the average growth rate in that period.

Description of the data:

- X_t Gross value added enterprise sector at factor costs, excluding natural gas and housing
- p_t Price level value added
- I_t Investment in equipment and means of transport of enterprise sector minus gas
- Q_t Price level investments
- r_t Long-term interest rate
- h_t Index of labour time, hours worked per year
- N_t Demand for labour in the enterprise sector
- u_t Rate of capacity utilisation
- w_t Wage rate enterprise sector
- $\Omega_{t-\tau}$ Technical survival fractions

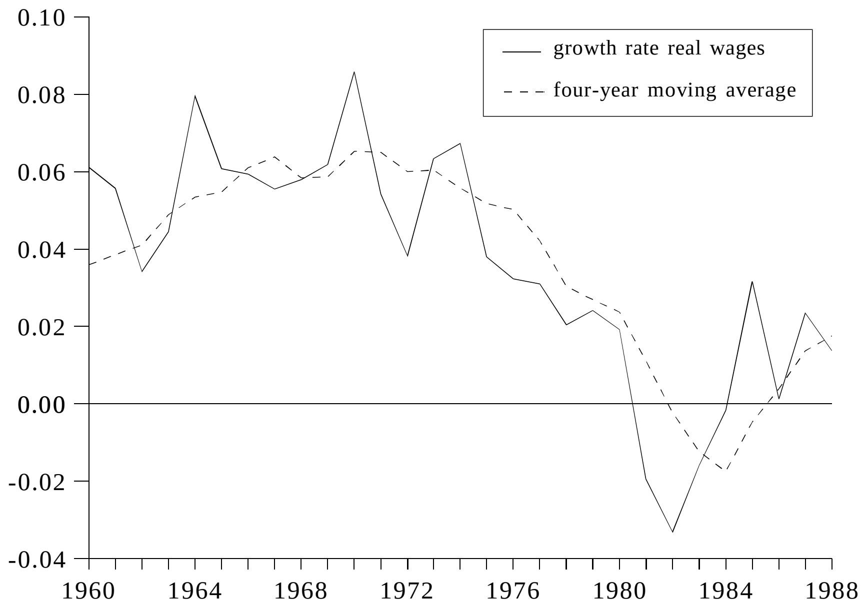

Figure A4.1. Actual and four-year moving average rate of growth of real wages

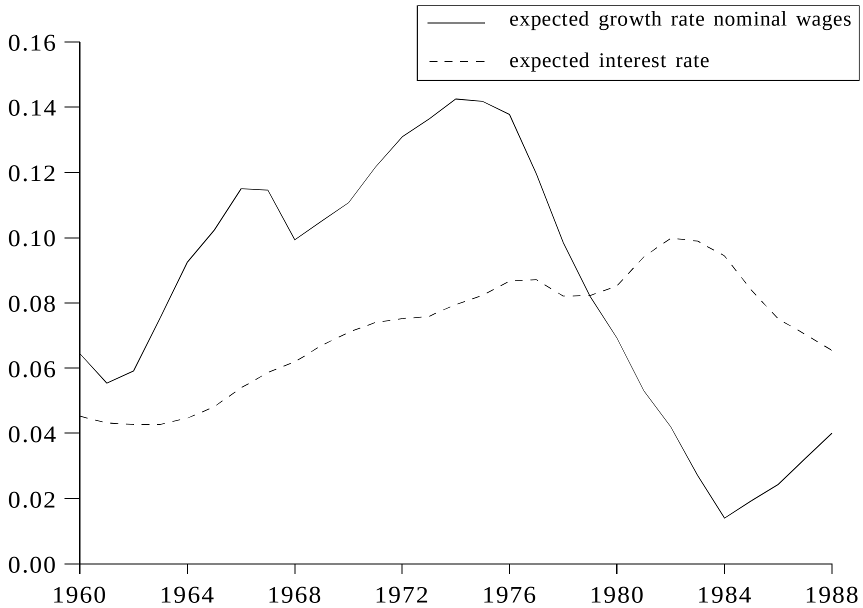

Figure A4.2. Expected growth rate of (nominal) wages and expected interest rate

Appendix 4B. Derivation of the Objective Function[153]

The objective function, equation (4.1), is based on a maximum likelihood approach in which it is assumed that the residuals have the same, constant, variance and that they are independently distributed.

The residuals are taken as relative errors in order to remove scale differences between errors in the capacity output and in the demand for labour. Thus:

$$e_x = \frac{X_t^c - \hat{X}_t^c}{\hat{X}_t^c} \quad \text{and} \quad e_n = \frac{N_t - \hat{N}_t}{\hat{N}_t} \tag{4B.1}$$

in which hats denotes estimated values.[154] Assume that the vector of residuals ($e = (e_x, e_n)'$) is distribution with mean zero and variance-covariance matrix S. Furthermore, it is assumed that the residuals of the output capacity are independent of the demand for labour. This implies that the determinant of the transformation-correction matrix is equal to one, so that the likelihood function can be written as (cf. Meijers 1989):

$$\ln L = \tfrac{1}{2} T \ln |S^{-1}| - \tfrac{1}{2} \sum_t e' S^{-1} e \tag{4B.2}$$

in which T denotes the number of observations. Assume furthermore, that the residuals are independently distributed with variance σ^2, which implies that the variance-covariance matrix can be written as σ^2 times the identity matrix. The likelihood function is then equal to:

$$\ln L = -T \ln \sigma^2 - \frac{1}{2\sigma^2} \sum e' e \tag{4B.3}$$

An estimator of the variance can be obtained by maximizing the likelihood function:

153. This appendix draws heavily on Tjan (1983), Gelauff (1987) and Meijers (1989).

154. An alternative is to define the errors relative to the actual data or to define the errors as the difference between the logarithm of actual and the logarithm of generated data. These changes do not influence the values of the objective function to a large extent.

$$\frac{\partial \ln L}{\partial \sigma^2} = -\frac{T}{\sigma^2} + \frac{1}{2\sigma^4}\sum e'e = 0 \tag{4B.4}$$

thus:

$$\hat{\sigma}^2 = \frac{1}{2T}\sum e'e \tag{4B.5}$$

Substitution of equation (4B.5) in (4B.3) gives:

$$\ln L = -T\,\ln\left(\frac{1}{2T}\sum e'e\right) - T \tag{4B.6}$$

which should be maximized. Ignoring constant terms and the logarithm operator and taking the negative of this function yields:

$$F = \sum (e_x)^2 + \sum (e_n)^2 \tag{4B.7}$$

which should be minimized. Using definitions in (4B.1) gives the objective function as shown in the main text (equation (4.1)).

Appendix 4C. Analysis of the Residuals and Results of an Alternative Objective Function

In appendix 4B, it is assumed that the residuals are independently distributed with variance σ^2. The objective function employed to estimate the parameters is based on this assumption. The resulting residuals are plotted in Figure 4.3, where we stated that the capacity output is independent of the labour demand, but that labour demand is positively correlated with the estimated output capacity. Furthermore, we stated that the residuals of labour demand are stationary whereas the residuals on the output capacity show a slightly increasing trend, which turns out to be autocorrelation rather than a pure trend. A short view on the residuals confirms this. We determine the correlation between the two residuals by means of a simple least square estimate. Furthermore, we estimate the trend of the residuals, together with a lagged structure to get some insights in the size of autocorrelation. The results are shown in Table 4C.1.

From the first row, it follows that both residuals are not significantly correlated with each other. From the second row, it follows that the relative residuals on the output capacity (e_x) are not correlated with the (lagged) residuals on the demand for labour (e_n). Row number III shows that this is not true for the opposite, i.e., the demand for labour is correlated with the (lagged) output capacity. Rows IV and V show that the residuals of the output capacity are correlated, but not significantly, with a positive trend whereas the residuals of the demand for labour are not correlated with a trend term. Rows VI and VII show that the trend terms disappear if the lagged residuals are incorporated. This points into the direction of autocorrelation which is confirmed by the Durbin-Watson statistics (which is equal to 0.67 for the residuals on the output capacity and equal to 1.1 for the demand for labour). Finally, the standard deviation of the residuals of the output capacity (σ_{ex}=0.016, not in the table) is almost equal to the standard deviation of the residuals of the demand for labour (σ_{en}=0.015). The correlation between the demand for labour and the output capacity is discussed below, whereas the presence of autocorrelation is discussed in the main text.

In his paper, in which he compares several objective functions, Gelauff (1987) concludes that one should estimate the variance-covariance matrix. Because of the correlation between the demand for labour and the output capacity, we also estimated the model with an alternative objective function. This implies that the estimator of S in equation (4B.3) should be replaced by:

$$\hat{S} = \frac{1}{T}\begin{bmatrix} \sum \hat{e}_x\hat{e}_x & \sum \hat{e}_x\hat{e}_n \\ \sum \hat{e}_n\hat{e}_x & \sum \hat{e}_n\hat{e}_n \end{bmatrix} \tag{4B.8}$$

Substitution of this equation in (4B.2) gives the objective function:

$$F = \frac{T}{2}\ln\left\{\frac{1}{T}\sum (e_x)^2 \ \frac{1}{T}\sum (e_n)^2 - \left(\frac{1}{T}\sum e_x e_n\right)^2\right\} \tag{4B.9}$$

This objective function is used in the alternative estimate. The results are shown in Table 4C.2. The parameters are more or less the same. Note that the original objective function (F) is increased in the full maximum likelihood (ML) estimate and that the residuals of the demand for labour (F_n) are mainly responsible for this increase. The objective function of the full ML estimate (F_{ml}) is clearly below the corresponding value with the parameters from the original estimation. Note furthermore that the objective function is altered to a large extent while the parameters only slightly change.

dependent variable					
I	e_x	e_n		c	$\bar{R}^2$
		0.189 (0.87)		0.0013 (0.41)	-0.008
II	e_x	e_n	e_{n-1}	c	$\bar{R}^2$
		0.030 (0.12)	0.295 (1.2)	0.0008 (0.23)	-0.0015
III	e_n	e_x	e_{x-1}	c	$\bar{R}^2$
		0.457 (2.30)	-0.521 (2.59)	-0.0005 (0.21)	0.17
IV	e_x		*time*	c	$\bar{R}^2$
			-0.0005 (1.49)	0.009 (1.51)	0.04
V	e_n		*time*	c	$\bar{R}^2$
			-0.0002 (0.49)	0.002 (0.44)	-0.03
VI	e_x	e_{x-1}	*time*	c	$\bar{R}^2$
		0.65 (3.9)	-0.00004 (0.12)	0.001 (0.20)	0.37
VII	e_n	e_{n-1}	*time*	c	$\bar{R}^2$
		0.46 (2.6)	-0.00002 (0.05)	-0.0005 (0.08)	0.15

Table 4C.1. Some statistics on the residuals of the original estimation results

Some statistics on the residuals of the alternative estimate are given in Table 4C.3. Comparison of these results with the results in Table 4C.1 shows that the correlation between both residuals does indeed decrease, which means that the alternative objective function is a more efficient estimator than the original. However, the estimation results with respect to the parameters are not influenced by this alternative objective function. This could be the case in the model statistics but, as mentioned previously and as shown in appendix 4E, the model is highly discontinues of nature as a result of which an reliable estimator of the gradient cannot be obtained.

	original obj func	full ML obj func		original obj func	full ML obj func
μ_n	3.39%	3.34%	ξ	0.90	0.90
μ_i	1.04%	1.06%	χ	0.60	0.60
γ_n	0.007%	0.000%	β	0.015	0.016
γ_i	0.000%	0.000%	α_0	0.003	0.003
ε_n	0.036%	0.023%	α_1	0.56	0.56
ε_i	0.080%	0.083%	α_2	1.76	1.76
A_0	9.65	9.63	F	0.0115	0.0164
B_0	5.97	5.97	F_u	0.0070	0.0073
σ	0.55	0.55	F_n	0.0045	0.0091
$f_{\mu n}$	0.50	0.50	F_{ml}	-269.43	-324.39

Table 4C.2. Parameter estimates of the original and alternative objective function

dependent variable					
I	e_x	e_n		c	R^2
		-0.059 (0.32)		-0.005 (1.44)	0.004
II	e_x	e_n	e_{n-1}	c	R^2
		0.050 (0.22)	-0.184 (0.82)	-0.004 (1.06)	0.03
III	e_n	e_x	e_{x-1}	c	R^2
		-0.424 (1.82)	0.621 (2.62)	0.010 (3.20)	0.22

Table 4C.3. Some statistics on the residuals of the alternative estimation results

Appendix 4D. Comments on the Complex Method and the Random Search Method[155]

The complex estimation routine is an adjusted version of the method described in Bunday and Garside (1987: 98-107), which is based of the simplex method developed by Nelder and Mead (1965). The adjustments involve mainly the permission of constraints and the computation of the centre of gravity of the complex. The method will be briefly described below.

In the first phase, a complex with k corners is defined in which the corners are randomly chosen within a certain permitted range. A corner contains a parameter vector and an accompanying value of the objective function. This range is chosen on a priori grounds — for instance, for the rate of embodied technological change, we imposed a lower bound of zero and an upper bound of 8%. The number of corners is equal to 5 times the number of parameters, and the objective function is evaluated at each corner.

In the second phase, the iteration phase, the corner with the worst value of the objective function is replaced by a new corner. This new corner is determined by reflecting the worst corner through the weighted centre of gravity of the remaining complex in which the values of the objective function at each corner are used as weights. The reflection will be repeated with different stepsizes until a new point is found in which the value of the objective function is lower (better) than the value of the worst one. The old corner is replaced by the new corner and the process starts all over again. If one fails to find a better corner, the bad corner will be deleted from the complex.

This procedure is repeated until at least one convergence criterion is satisfied. We employed two different criteria. First, the standard deviation of the values of the objective function of all corners must be below a certain value, and secondly, the Euclidean distance between the corners, in terms of differences between parameters values, must be below a certain value. All parameters are scaled such that their values ranges from about 1 to about 10. The criterium for the standard deviation of the objective functions is 0.00001 whereas the minimal distance between the corners is equal to 0.0001.

The random search method is used next to the complex method and is mainly employed to check for local minima. This procedure calculates a cloud of 300 randomly chosen points. The point with the worst objective function is replaced by a new randomly chosen point which is located within the cloud. This procedure is repeated until the Euclidean distance of all points within the cloud is below 0.0001.

Both the complex and the random search method are used many times to check whether a parameter vector is indeed minimizing the objective function. The grid search and the quasi-Newton method (E04JBF from the NAG-library) are used to search for improvements in the neighbourhood of the parameter vector which results from both other methods. Although it is unlikely that other parameter vectors exist which yield a lower objective function, this estimation procedure does not guarantee global minimization.

Appendix 4E. Discontinuities of the Objective Function

In the main text, we mentioned some estimation difficulties which are related to severe discontinuities in the objective function. In this appendix, we will present some graphs in order to emphasize these discontinuities. For all parameters, we examined the value of the objective function around the optimal value of these parameters with a simple grid step procedure. The behaviour of the objective function can be split into three groups of parameters. First, all parameters which influence scrapping due to negative quasi-rents in a direct way, such as μ_n, μ_i, γ_n, γ_i, ε_n, σ, $f_{\mu n}$, ε_i, A_0 and B_0. Secondly, parameters related to scrapping due to underutilisation (χ) and to labour hoarding (ξ), and thirdly, the parameters which influence the diffusion of technologies (α_0, α_1, α_2 and β).

155. The modifications of the estimation routines are mainly initiated by A. van Zon.

As expected, the parameters in the first case lead to severe discontinuities, which is shown is Figures 4E.1 to 4E.5. The optimal value of μ_n is 3.3873%. This point is visible in Figure 4E.1 as the point at which the objective function falls from about 0.021 (μ_n=3.3873%) to 0.011477 (μ_n=3.3874%). The movements of the objective function at the left and at the right of the hugh jump seems to be smooth at first sight. But if we take a closer look at the figure of the objective function, for instance at the right of the fracture, which is done in Figure 4E.2, severe discontinuities are observed. The same holds true for changes in A_0 (Figures 4E.3 and 4E.4) and for changes in σ (Figure 4E.5).

Changes in the second class of parameters, which do not influence scrapping due to negative quasi-rent, or at least not directly, lead to smooth changes of the objective function. Such changes are displayed in Figure 4E.6 for χ, the amount of scrapping due to underutilisation. Changes in the amount of labour hoarding (ξ) leads to similar results.

Finally, changes of parameters which describe the diffusion process lead to an intermediate case. For large changes in such parameters, we find discontinuities (e.g. Figure 4E.7) but for small changes, the objective function is rather smooth (Figure 4E.8). However, note that the gradient is not zero at the most right point in Figure 4E.8.

Finally, Figure 4E.9 shows the shape of the objective function in a three-dimensional space. The figure at the top, which is obtained by using ‘large’ stepsizes, shows some flat areas at the most left and at the most right. These areas are surrounded by some ridges which cannot be walked-over by a quasi-Newton method, nor by a grid search with small stepsizes. This holds also for the objective function around its minimal value.

From these figures, it is clear that a quasi-Newton method can be applied to estimate the parameters of the second class, which are only 2 out of 15 parameters. Other methods should be used to find all other parameters. A simple grid search combined with a (random) complex method proved to work well. One should notice, however, that these estimation procedures should be repeated several times to ensure global minimization. Finally, these figures show why the gradient is not equal to zero for the optimal parameter vector and that we cannot compute standard errors.

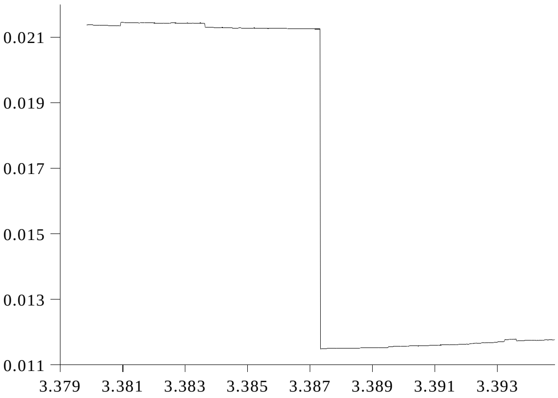

Figure 4E.1. μ_n (* 0.01)

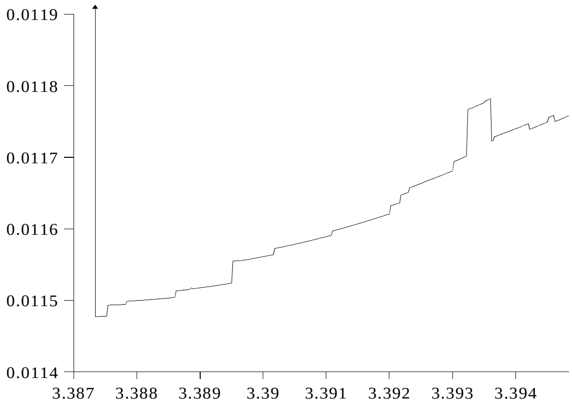

Figure 4E.2. μ_n (* 0.01)

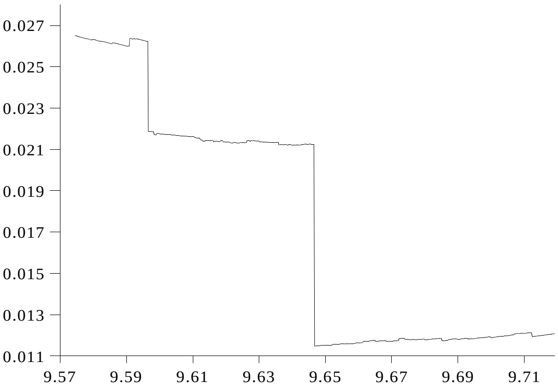

Figure 4E.3. A_0

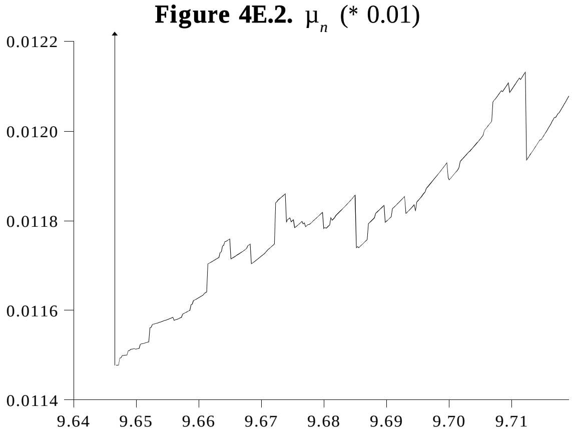

Figure 4E.4. A_0

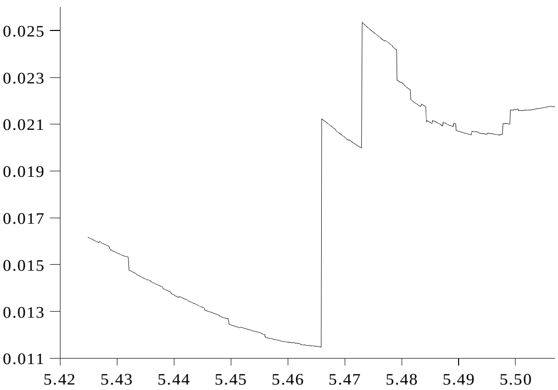

Figure 4E.5. σ (* 0.1)

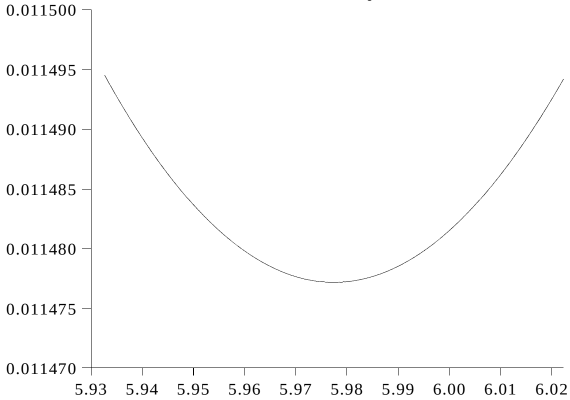

Figure 4E.6. χ (* 0.1)

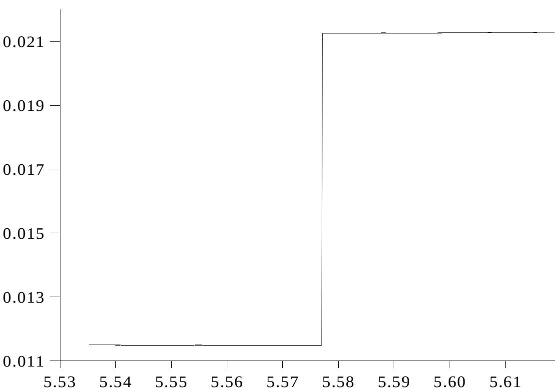

Figure 4E.7. α_1 (* 0.1)

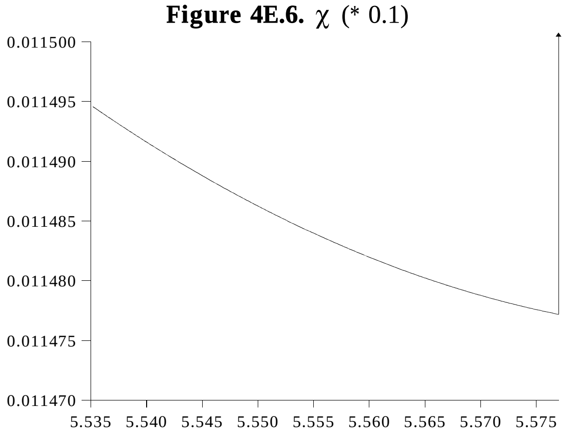

Figure 4E.8. α_1 (* 0.1)

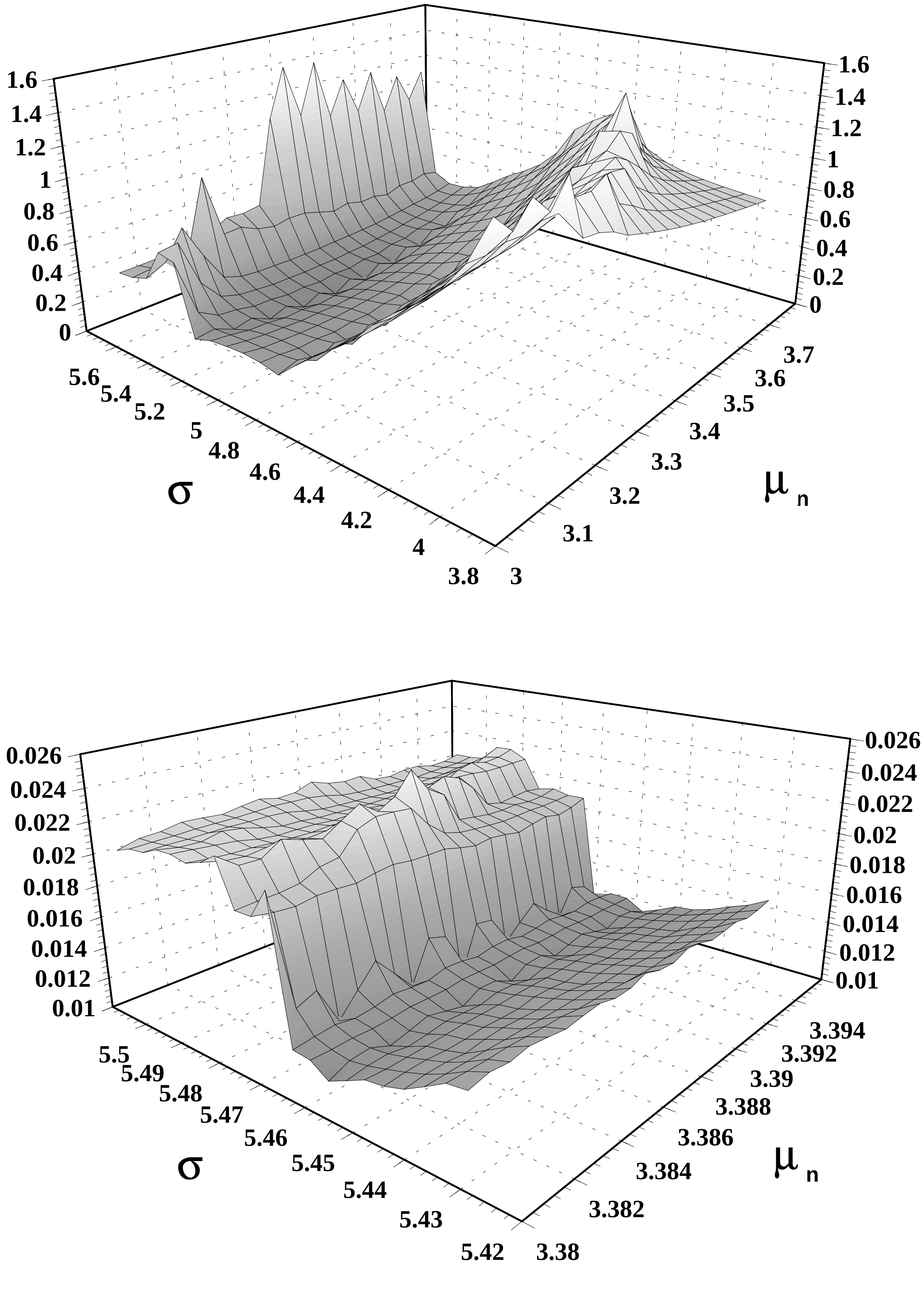

Figure 4E.9. Shape of the objective function for combined changes in μ_n and σ (Relative large stepsizes at the top and small stepsizes at the bottom)

Appendix 4F. Results of the Diffusion Model in the Bounded Estimate

	with diffusion	with diffusion ($\xi \leq 0.35$)	without diffusion		with diffusion	with diffusion ($\xi \leq 0.35$)	without diffusion
μ_n	3.39%	3.28%	4.06%	ξ	0.90	0.35	0.35
μ_i	1.04%	1.51%	0.12%	χ	0.60	0.59	0.62
γ_n	0.007%	0.19%	--	β	0.015	0.014	--
γ_i	0.000%	0.58%	--	α_0	0.0003	0.0006	--
ε_n	0.036%	0.04%	0.08%	α_1	0.56	0.71	--
ε_i	0.080%	0.54%	1.83%	α_2	1.76	2.21	--
A_0	9.65	11.23	9.93	F	0.0115	0.0159	0.1123
B_0	5.97	7.49	12.11	F_u	0.0070	0.0079	0.0129
σ	0.55	0.60	0.60	F_n	0.0045	0.0080	0.0994
$f_{\mu n}$	0.50	0.41	0.26				

Table 4F.1. The parameter estimates for the unbounded as well as for the bounded ($\xi \leq 0.35$) model

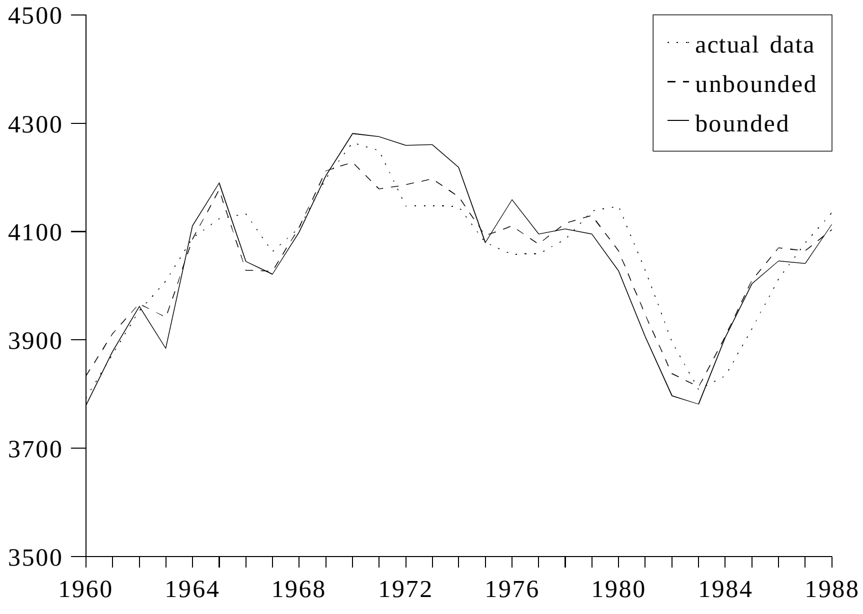

Figure 4F.1. The demand for labour, the unbounded and the bounded estimation results compared

PART III

ENTRE-PRENEURIAL BEHAVIOUR

5 The Choice of Technologies under Uncertainty

Part II describes a macro-economic model in which the diffusion process originates from the Mansfield model. Since the Mansfield model is basically built on the epidemic diffusion model, the behaviour of firms with respect to the choice of technologies is not well described in that part. Moreover, the distribution of technologies is related to characteristics of technologies (profitability and knowledge), rather then firm characteristics so that the macro-model does not answer the question why some firms invest in older technologies and why other firms buy newer types of equipment. Furthermore, the capital stock, which contains several heterogeneous vintages, cannot be described for each individual firm which implies that the relation between scrapping of old vintages and investment in new equipment can only be applied at the aggregate level. Therefore, the Malcomson scrapping condition, which describes active profit-maximizing behaviour, cannot be applied and we are restricted to the loss-avoiding quasi-rent condition in the model of part II.

In this part, we will pay attention to the behaviour of firms in the sense that a model is put forward in which the investment decision of firms with respect to the technologies depends on both firm characteristics and on technology characteristics. Such an approach enables us to relate investment and scrapping behaviour more explicitly in such a way that the life cycles of technologies become interdependent.[156] This approach is not without some costs, however. We will use a simplified version of the putty-clay model described in part II in the sense that we will develop a quasi-clay-clay vintage model in which firms can choose equipment from a range of technologies and in which each technology is described by a clay-clay

156. Note that scrapping due to negative quasi-rents determines the capacity gap which means that the amount of investment is related to scrapping decisions to some extent. However, in case of the Malcomson scrapping condition, the total costs per unit of output of new equipment determines the amount of scrapping. In other words, there exists a direct relation between the choice of the technology and the amount of investment through the scrapping condition.

production function. Moreover, we will assume that the capital-output ratio is constant and identical for all technologies. At the end of chapter 5 we will compare both models and there show that there are more similarities than one would expect at first sight.

Although we will examine some properties of the model by performing a number of experiments — in which an aggregate level is obtained by simulation of a finite number of firms — the model as described in the next chapters cannot be used for estimation purposes. Whereas there exist a number of analogies between the macro-economic model in part II and the micro-economic model in part III, this part is *not* a full micro-economic foundation of the macro-model described in the previous part. It can be viewed as providing some micro-economic theories which may underlie the distribution function with regard to technologies which is postulated in the macro-model.

The first chapter of part III, chapter 5, describes a model in which we will concentrate on the investment decisions. In other words, this chapter describes firm behaviour regarding the newest vintage. In fact, we will discuss the choice of technologies only, without determining the amount of investment. Chapter 6 describes the complete vintage model in which we will develop two versions: a static and an intertemporal model. In both versions, we will determine the amount of investment as well as the amount of scrapping. Both chapters will elaborate some characteristics of the diffusion process, such as the shape and the speed of diffusion. Chapter 7 presents some simulation experiments in which we will highlight the properties of the model and will be concluded with some possible extensions of the model as regard to the supply of new technologies. The formal implementation of these extensions of left for further research.

5.1 Introduction

Before we turn to the actual model in this chapter, we will discuss the role of investment in models on adoption and diffusion of new technologies. In doing so, we will touch upon some aspects of the theory of investment in relation to the literature on adoption and diffusion. After that, we will discuss the implementation of uncertainty and learning in models on adoption and diffusion of new technologies. This will lead to the basic features of our model.

5.1.1 Theory of Investment in Adoption and Diffusion Models

During the last decades, investment has gained increasing importance in studies on the adoption and diffusion of process innovations. This phenomenon is quite understandable given the non-volatile nature of the adoption of new technologies. Adoption and diffusion of process innovations are inherently connected with investment decisions regarding fixed factors of production.

Reviewing the literature on the adoption and diffusion of process innovations that make a link with the investment theory, almost all authors introduce adjustment costs into their model. Additionally, we find several authors who assume myopic behaviour[157]. Others apply intertemporal or static optimization behaviour with an infinite planning horizon, next to adjustment costs[158]. In general, however, the possibility of a planning horizon between zero and infinity is ignored.[159] The purpose of this chapter is to rectify this omission. We will develop a general framework in which firms have different views regarding the future and in which investment is irreversible, meaning that investment expenditures are treated as sunk costs.

Three aspects of the theory of investment are particularly relevant to our analysis: the secondhand market, the length of the planning horizon, and adjustment costs. These aspects are closely related to one another in the sense that if we assume a (perfect) secondhand market for investment goods, firms can adjust both the variable and the 'fixed' factors of production instantaneously. In this case, adjustment costs have to be assumed in order to make a distinction between fixed and variable factors of production. Moreover, this distinction also disappears if firms are myopic, i.e., if they do not consider future consequences of their current investment decisions.

First, consider the existence of a secondhand market for capital goods in which each firm can act as a buyer or as a seller. If capital is assumed to be a homogeneous good in time, then new capital is indistinguishable from old capital, and a secondhand market would not be unrealistic. But in a situation where capital is heterogeneous in time, such an assumption becomes unreasonable. Given the fact that we are considering investment decisions in relation to the diffusion of new technologies, capital simply cannot be seen as a homogeneous good. Moreover, as Nickell (1977) pointed out, a considerable proportion of all capital goods are highly specific to the firms purchasing them. He concludes with "*Now it is quite clear that there is a large class of capital goods which are, in reality, almost impossible to sell other than to scrap.*"[160] A similar observation is made by Pindyck (1991). Following these findings, we will assume that investment is an irreversible process, i.e., that there is no secondhand market for capital goods.

The second topic is the behaviour of firms with respect to the planning horizon. We can make a distinction between an infinite and a finite planning horizon in

157. See for instance Stoneman and Ochoro (1980), Feder (1980), Stoneman (1981), Kim et al. (1992).

158. See for instance Tsur et al. (1990).

159. An exception can be found in for example Davies (1979) in which a (finite) pay-back period comes down to a finite planning horizon.

160. Nickel (1978: 39). Exceptions are made for vehicles, some types of building (offices) and some simple kinds of machinery (heavy-duty sewing machines) for which a secondhand market does indeed exist.

which the finite horizon includes myopic behaviour. Given the non-volatile nature of most investment goods, and assuming that investing is an irreversible process, the assumption of myopic behaviour is very unrealistic. Another extreme case is the assumption of an infinite planning horizon in which the firm is concerned with all future developments while making its current (investment) decisions. The intermediate case of a planning horizon somewhere in between zero (in the case of myopic behaviour) and infinite seems to be the most realistic one.

Closely related to the length of the planning period is the question whether to assume (multi-period) static or dynamic optimization. In a model including static behaviour and a non-zero planning period, firms are assumed to consider future consequences of their current decisions without taking into account the consequences of current decisions on future *decisions*. In a dynamic, or intertemporal model, firms take all consequences of their current decisions into account. This chapter is limited to static optimization for convenience, but in chapter 6, both versions are used in the entire vintage diffusion model.

Third, we have to make some assumptions about the existence of adjustment costs. The theory of investment can be introduced into the models of adoption and diffusion of new technologies by assuming adjustment costs, or by assuming sunk investment costs, or both. As we assume irreversible investment decisions, we have to introduce the sunk cost approach. Although we will not deny the existence of adjustment costs, we will ignore them to keep our analysis as simple as possible.

To summarize, this chapter elaborates a model in which firms are assumed to have a multi-period planning horizon which is not necessarily infinite, in which investment expenditures are treated as sunk costs and without adjustment costs. Furthermore, we assume static optimizing behaviour.

Next, we will review the literature on the adoption and diffusion of process innovations. We will also discuss some typical adoption and diffusion features besides the aspects described above.

5.1.2 Uncertainty and Learning: A Quick Refresher

In the literature on adoption of new innovations, we find several approaches which try to explain why not all firms adopt a specific innovation at the same point in time (inter-firm diffusion) or why a single firm adopts different technologies at the same point in time (intra-firm diffusion). In general, this phenomenon is explained by means of learning, uncertainty and/or supply-side effects. In this section, we will concentrate on the first two aspects.

As we have shown in Chapter 2, learning appears in three different forms, (i) gathering information on the existence of a technology, (ii) learning about the actual performance of a technology, and (iii) learning how to use a new production process.[161] Uncertainty comes in two versions: (i) technology-specific and (ii) non-technology-specific uncertainty. Learning type (i) is not directly related to uncertainty and is mainly used in epidemic diffusion models. Learning type (ii) is related to technology-specific uncertainty. If there is no technology-specific uncertainty, learning about the actual performance of that technology is not very worthwhile because there is nothing to be learned. Finally, learning type (iii) is not related to uncertainty and can be used next to the other types of learning.[162]

In the macro-economic model of part II, we showed that the productivity slowdown can be related to the slowdown of the diffusion speed. We related the speed of diffusion to differences in profitability between several technologies. An increase in uncertainty could be another explanation for the slowdown (cf., for example, Scott, 1989, and Davies, 1991). It is hard to believe that a general increase of uncertainty is technology-specific because this would imply that uncertainty of *all* new technologies increased in the seventies and the eighties. In other words, uncertainty of all technologies would have increased independently from one another, which is very unlikely. But an increase of general, non-technology-specific, uncertainty could explain the slowdown. A sudden price shock, for instance, could increase uncertainty and cause firms to hesitate to invest in new (expensive) technologies. We will develop the micro-based model along this line, which implies that we will ignore technology-specific uncertainty. By doing so, we also exclude learning in the sense of gathering information about the actual performance of a technology. However, we will introduce learning in the sense of improving productivity due to previous experience, i.e., 'learning-by-doing'.

Furthermore, the number of technologies a firm can choose from is mostly limited to two, whereas a larger number is possible in reality. Nabseth and Ray (1974), for instance, show that multi-technology markets are even more likely.[163] We feel that our model should be capable of incorporating more than a few technologies.

161. Learning to learn is a forth type of learning but this version comes only with at least one of the other types of learning and is not a necessary nor a sufficient condition to explain diffusion (cf. Tsur et al., 1990).

162. Note that learning about macro-economic (stochastic) variables such as factor prices, could be related to non-technology-specific uncertainty (cf. Pindyck, 1991). However, we will disregard this type.

163. Examples are the steel-making industry (open-heart, LD-converter and electric furnace technologies) and the textile industry with a main distinction between shuttle and shuttleless loom weaving but with several different technologies of the shuttleless loom type (projectile, rigid gripper, flexible gripper, air jet and water jet), all of them developed in the 1970s (cf. Nabseth and Ray, 1974). Other (classical) examples of such multi-technology markets are the electricity industry (power-plants) as well as the computer industry.

5.1.3 *Outline of the Model*

Summarizing the above, chapters 5 and 6 will develop a vintage-diffusion model in which the choice of technologies depends on non-technology-specific uncertainty, in which firms are non-myopic and in which investment expenditures are sunk costs. Furthermore, we assume that there exists a range of technologies from which firms may choose to invest. According to the macro-model, we assume that technologies differ from one another with regard to both the productivity and the price of capital in which the technologies are embodied, i.e., that a more advanced technology is more expensive. Contrary to the macro-model, however, the development of new technologies is not restricted to one per year. We assume that at any moment in time there is an infinite range of different technologies supplied in the market for capital goods and that both prices and technological characteristics are given. This has the advantage that we can concentrate on the demand of new technologies. The price of equipment, and the determination of the most advanced technology, should be incorporated in a model which determines both demand and supply. With respect to the most advanced technology, a link can be made with the Romer's endogenous growth model. In Romer (1990), it is assumed that the development of the most advanced technology depends on learning effects whereas the technologies not yet invented are modelled as being infinitely high priced. Although chapter 7 will provide some directions in which the supply side could be incorporated, the implementation into a formal model is left for further research.

The planning period employed by firms will play an important role in our model and will be related to risk and risk aversion. As pointed out previously, we will introduce uncertainty with respect to output prices and assume that all firms face the same variability with respect to these prices.[164] Firms are assumed to maximize expected utility which depends positively on expected profits and negatively on expected risk. Both expected profits and risk will be evaluated by firms over a certain planning period, and a longer planning period implies that the expected profits will increase (at least as long the marginal quasi-rents are positive) but also that output prices will be more uncertain as a result of which the risk involved in the investment project increases. In contrast to the macro-economic model presented in part II, the planning period is *not* equal to the expected lifetime of a capital good, but the expected lifetime is an upper boundary of the planning period. Given the level of risk aversion, a firm will maximize expected utility with respect to the planning period and the technology index. Because of the first-order condition as regards to the planning period, the marginal utility evaluated at the optimal planning period will be zero, as a result of which the expected value of the investment project at the end of the planning period — in terms of utility — will be zero.

164. We also experimented with uncertainty with respect to wages but this strategy failed due to severe analytical problems.

Moreover, it seems quite natural to us that a particular firms employs only one planning period at a moment in time, i.e., we exclude the possibility of diversification regarding the planning period. Moreover, because there is no technology specific uncertainty, diversification in the sense of buying a portfolio of different technologies will not reduce risk as compared to expected profits.[165]

If firms differ with respect to risk aversion, less risk-averse firms will apply a longer planning horizon than more risk-averse firms, which means that the *annual* costs of capital are positively related to the level of risk aversion. As a result, more risk would be related to higher expected profits, even if the firm were buying the same technology. However, because of the reduction of the annual costs of capital, relative to the integral labour costs, less risk-averse firms will produce less labour-intensive and buy more advanced, but also more productive technologies. An (exogenous) distribution of firms with respect to risk aversion will therefore lead to a distribution of technologies, which enables us to obtain an inter-firm diffusion model which is more explicitly based on firm behaviour. This is the main goal of this chapter.[166]

The model fits in the real business cycle (RBC) theories to some extent.[167] In RBC models, business cycles are explained by (unexpected) price shocks or by technology shocks. All technologies are assumed to exist in the present model and thus we disregard the second possible explanation of the RBC models, at least as far as it concerns the source of business cycles. However, we allow for shocks in output prices, and this leads to changes in technological progress. Moreover, Chapter 7 presents a situation where prices of capital goods are changed. Again, this will lead to (sudden) changes in the optimal technologies, and therefore in changes of technological progress. Shocks in the growth rate of wages would also lead to changes in the optimal technology, but as previously mentioned, the development of a model with stochastic wages failed due to analytical problems.

The model comes in two versions: A version in which the choice of technologies is related to the level of risk aversion, which can be viewed as the ‘actual’ version of the model and represents the views expressed above. We will show that the choice of the optimal technology cannot be solved analytically in this version. We therefore introduce a second version, which relates the choice of technologies directly to

165. Technology-specific uncertainty can be found in, for instance, Stoneman (1981) and Tsur et al. (1991) and their results can be interpreted in the connotation of portfolio analysis.

166. Davies’ (1979) inter-firm diffusion model is based on differences in the expected and acceptable pay-back period. The expected pay-back period is related to the size of firms and Davies assumes that the acceptable pay-back period is also related to firm size. Larger firms are willing to accept a longer pay-back period and will therefore invest in a more advanced technology. Since the relation between firm size and acceptable as well as expected pay-back period is not elaborated in detail, the choice of the technology, or the date at which a firm switches to a new technology, is based on a theoretically less-founded framework.

167. Cf. Plosser (1989) for an overview or Blanchard and Fischer (1989), for a textbook treatment of RBC models.

the length of the planning period. This is more easy to handle and appears to be a (fairly good) approximation of the first version. To improve readability, we will start with the second version, i.e., the choice of a technology given the length of the planning period, in section 5.2. In that model, we assume that a longer planning period can be interpreted as a lower level of risk aversion. The first version, which will be discussed later in section 5.3, solves the length of the planning period as well as the choice of the technology for a given level of risk aversion. There, we will show that there is a strong relation between risk aversion and the length of the planning period, and demonstrate that the second version is indeed a good approximation.

In both cases, we will consider a model without and a model with learning-by-doing effects. Both models can explain inter-firm diffusion, and the learning-by-doing model will give some motivations for intra-firm diffusion.[168] Recall that we only consider the choice of a new technology in this chapter and that the choice regarding the level of investment will be discussed in chapter 6. This implies that the resulting diffusion patterns indicate which technologies are chosen, rather than how much is invested in each technology.[169] Section 5.4 shows the resulting diffusion process for both the non-learning and the learning case, thus making apparent the difference between inter- and intra firm diffusion.

Finally, section 5.5 compares the choice of technologies with the choice of the optimal labour intensity in a standard putty-clay model. Moreover, we will compare the distribution of firms with respect to the choice of technologies with the distribution of technologies which is postulated in part II. Both comparisons will provide some insight into the similarities of and differences between the models of part II and III.

5.2 The Choice of a Technology Given the Length of the Planning Period

In this model, we assume that firms sell their products in a competitive output market. Thus, output is assumed to be homogeneous and output prices are given. The labour market is also assumed to be homogeneous with a given wage rate, but capital is assumed to be heterogeneous. Firms can invest by choosing from a continuous and infinite range of different capital goods. These capital goods differ from each other with respect to both the incorporated technology and their price. The technologies are described by a positive index number where a higher index represents a more advanced, i.e., a more productive, technology. Firms maximize the present value of future rents per unit of output, in which the discount rate is

168. Note that a (standard) vintage model describes intra-firm diffusion to some extent. However, since each firm will choose the same best-practice technology each year, this is a poor description of intra-firm diffusion.

169. An alternative view is that each firm buys only one unit of equipment, which means that the choice of technologies comes down to the amount of investment in each technology.

constant in time. Furthermore, we assume that the production structure can be described by a constant returns to scale Leontief production function, and we treat investment costs as sunk costs.

The next section describes the characteristics of the technologies in terms of productivity and prices for both the learning and the non-learning case. Subsequently, the choice of the optimal technology is discussed in which we will start with a graphical presentation, followed by a formal approach. Finally, we will determine the least and the most advanced technology in which firms will invest. A brief summary concludes this section.

5.2.1 Description of the Technologies

In both the learning and the non-learning versions of the model, it is assumed that there is a range of different technologies available. Technologies differ from each other with respect to the incorporated labour productivity and with respect to their price. The capital productivity is assumed to be constant and identical for all technologies. This corresponds to a large extent with our results of the macro-economic model in part II.[170]

The Non-Learning Case

The labour productivity is assumed to be fixed in the non-learning case and is related to the technology index (i) by:

$$\lambda^i = \lambda_0 i^\mu \qquad \forall\ i \in [0..\infty> \quad \text{with } \lambda_0 > 0;\ \mu > 0 \tag{5.1}$$

in which we left out time indices for convenience. μ denotes the relative change of the labour productivity with respect to a percentage change of the technology index, productivity elasticity for short. This parameter is comparable to embodied technological change in the macro-model. In this formulation, the labour productivity can be a concave ($\mu \le 1$) or a convex ($\mu \ge 1$) function of the technology index. We assume that this relation is the only connection to technological change, or, in other words, we assume that technological change is purely labour-augmenting and embodied in new capital goods. However, in the case of learning by doing, we allow for disembodied technological change.

If labour productivity were the only difference between technologies, all firms would install the most advanced technology, as this is the most profitable one. But it is reasonable to assume that the price of investment goods increases as the incorporated technology is more advanced, i.e., as the technology index increases. However, we cannot determine on a priori grounds whether the change of these prices will be more, equally or less than proportional to the technology index. Hence, we assume that the price of an investment good is an exponential function of the

170. Moreover, this is one of the Kaldorian stylized facts.

technology index. Furthermore, we assume that the price of investment goods can be divided into a technology-specific and a non-technology-specific part. The non-specific part is assumed to be the result of changes in variables (e.g. wages) which affects all supplying firms in the same way. We therefore assume that the price of investment goods is given by:

$$q_t^i = q_t \, i^{\gamma} \quad \text{with } q_t, \gamma > 0 \tag{5.2}$$

in which γ denotes the relative change in the price of equipment with respect to a percentage change of the technology index, the price elasticity for short.

Although the choice of the technology index i will depend on the ratio of μ over γ, we do not impose a restriction on their relative size. Whereas we will endogenize the price of equipment to some extent in chapter 7, γ can be interpreted as being the relative additional costs required to improve the relative labour productivity, μ, embodied in capital goods.

The Learning Case

In this case, we assume that a firm will learn from experience with previous production[171], and that within a firm knowledge can be transferred instantaneously and without any costs. Furthermore, to keep the analysis as simple as possible, we assume that a firm does not consider future investments while making its current decisions. Thus, the expected increase of knowledge depends on (future) output produced with the *current* capital stock, which includes current investments.[172] Moreover, we assume that learning is completely specific to the technology in question. This implies that the increase in labour productivity due to learning by doing depends on the amount of output produced with a specific technology and within that specific firm. Another implication of the above is that if a firm invests in a specific technology more than once, all equipment in which that particular technology is incorporated will yield the same labour productivity as the initial one, i.e., independently of the year of installation. The new work force which will be associated with the new technology jumps on the learning curve of initial, incumbent labourers already working with that technology. Moreover, the above assumptions imply that the learning process starts all over again for each new technology. In this section, we simplify the analysis to a large extent by assuming that at the moment of investment, a firm does not have any experience with a specific technology. In other words, we consider the investment decisions at a single point in time. Section 5.4 presents some simulation results of the model in which investment decisions in the course of time are considered. In that case, a

171. This is different from Arrow (1962), who assumes that learning is linked to investment, although the examples given in his paper indicate learning by producing.

172. This avoids the intertemporal case, in which current decisions would depend on future investment decisions as the labour productivity of the current capital stock is affected by future output. The development of the intertemporal case was unsuccessful, however, due to analytical problems.

firm can choose to invest in a technology in which it has previously invested and thus benefit from the experience, or to invest in a new technology and learn from scratch.

As in the non-learning case, the initial labour productivity depends positively on the technology index, but now, labour productivity increases as firms continue to produce output with that technology, i.e., as time goes on. Following the seminal work of Arrow (1962), we assume that labour productivity increases exponentially in the first stage of the learning process, but we believe that there will be some upper limit on the increase in labour productivity due to learning by doing (cf. Stiglitz, 1977). Another example of an upper limit can be found in Majd and Pindyck (1989) but they assume a lower limit of an exponential cost function, which can be transformed into an upper limit of an exponential productivity function. We think that an asymptotic approach of an upper limit is more natural, however. Hence, the labour productivity will increase in time and the second derivative will be positive in the first stage of the learning process and negative in the second stage. The ultimate labour productivity will be reached asymptotically. We will describe the learning process by a logistic function, which embodies the properties described above. Furthermore, we assume that both the initial labour productivity as well as the ultimate labour productivity are positively related with the incorporated technology.

For a technology i, labour productivity is given by:

$$\lambda^i_{t,t_0} = \frac{\lambda_0 i^{\mu}}{\beta + (1-\beta)\alpha^{Z^i_{t,t_0}}} \quad \forall i \in [0..\infty> \tag{5.3}$$

$$\text{with} \quad \lambda_0 > 0;\ 0 < \beta \leq 1;\ 0 < \alpha < 1;\ t \geq t_0;\ \mu > 0$$

in which Z^i_{t,t_0} describes the amount of output already produced with technology i at time t. If t_0 is the point in time at which the firm invests in that particular technology for the first time, Z^i_{t,t_0} is given by:

$$Z^i_{t,t_0} = \int_{t_0}^{t} X^i_s \, ds \tag{5.4}$$

in which X^i_t stands for the output produced at time t with technology i. To simplify the analysis, we assume that each firm operates at full capacity at every point in time, that there is no depreciation and that all firms are identical except for their level of risk aversion. Without loss of generality, we can scale marginal output to unity so that Z^i_{t,t_0} becomes equal to $t - t_0$.[173] Thus, labour productivity can be written as:

173. Note that the assumption of full capacity operating is crucial in this model. With a varying degree of capacity utilisation, firms would face a variable pace of learning.

$$\lambda^i_{t,t_0} = \frac{\lambda_0 i^\mu}{\beta + (1-\beta)\alpha^{(t-t_0)}} \tag{5.5}$$

From this it follows that the initial labour productivity, with $t{=}t_0$, is equal to:

$$\lambda^i_{t_0,t_0} = \lambda_0 i^\mu \tag{5.6}$$

and that the ultimate labour productivity, with $t-t_0=\infty$, is equal to:

$$\lambda^i_{\infty,t_0} = \frac{\lambda_0 i^\mu}{\beta} \tag{5.7}$$

Thus, labour productivity increases in the course of time due to learning by using if $0<\beta<1$. If we assume that $\beta=1$, equation (5.5) is equal to equation (5.1), i.e., equation (5.5) describes both the learning and the non-learning case. The point of inflection of the learning curve is given by $\ln(\beta/(1-\beta))/\ln(\alpha)$ while the halflife of the labour output ratio is equal to $\ln(\beta/(1+\beta))/\ln(\alpha)$ (in the case $0<\beta<1$). If we take the inverse of the halflife as a measurement of the speed of learning, it follows that the speed of learning depends positively on β and negatively on α.

We assume that the price of equipment is the same as in the non-learning case, i.e., that this price is related to the costs of producing new technologies and not to the returns of the users. The ratio of μ over γ is not affected by learning from the viewpoint of the producers of the technologies. In general, the users will buy a more advanced technology in the case of learning by doing, at least if they are non-myopic, which we assumed to be the case.

5.2.2 *Firm Behaviour: The Choice of the Optimal Technology*

Firms are assumed to choose the technology that maximizes the net present value of total rents per unit of output. Recall that the length of the planning period is a result of risk aversion in the ‘actual’ model — which will be discussed in the next section — and that we approximate this model by assuming that firms differ with respect to the length of the planning period. Thus, the planning period is not related to the expected lifetime of equipment, as is the case in the macro-economic model in part II, but to the level of risk aversion.

The expected value of discounted total rents per unit of output is given by:

$$PV^i_{\tau,t_0,\theta} = \int_\tau^{\tau+\theta} QR^i_{t,t_0} e^{-r(t-\tau)} dt - q^i_\tau \psi \tag{5.8}$$

in which QR^i_{t,t_0} stands for the quasi-rent per unit of output, i.e.,

$$QR^i_{t,t_0} = p_t - \frac{w_t}{\lambda^i_{t,t_0}} = p_t - \frac{w_t(\beta + (1-\beta)\alpha^{t-t_0})}{\lambda_0 i^\mu} \tag{5.9}$$

p_t stands for the output price, w_t for the wage rate, q^i_τ for the price of capital embodying technology i, λ^i_{t,t_0} for the labour productivity of technology i, ψ for the capital output ratio and r for the discount rate. ψ is assumed to be both constant in time and identical for all technologies. The planning period is θ. We assume that total output is given for each firm and that this amount of output is constant over time.

The capital costs are assumed to be sunk costs. If a firm finances these costs internally, the financial burden should be incorporated in the present value of expected rents as a once and for all payment, which is shown in equation (5.8). Appendix 5A shows that a similar result can be obtained if the investment is debt financed. Furthermore, this Appendix shows that the annual average discounted costs of capital are equal to $\frac{1}{\theta}q_{\tau}^{i}$ such that indeed, the annual costs of capital decrease as the planning period increases, ceteris paribus.

Finally, firms are assumed to have identical and constant expectations concerning the growth of future prices and wages, i.e., $p_{t,\tau} = p_{\tau}e^{\pi(t-\tau)}$ and $w_{t,\tau} = w_{\tau}e^{\rho(t-\tau)}$, in which $x_{t,\tau}$ denotes the expected value of variable x at time t, and where expectations are formulated at time τ. So π describes the expected growth rate of output prices and ρ is the expected growth rate of nominal wages.

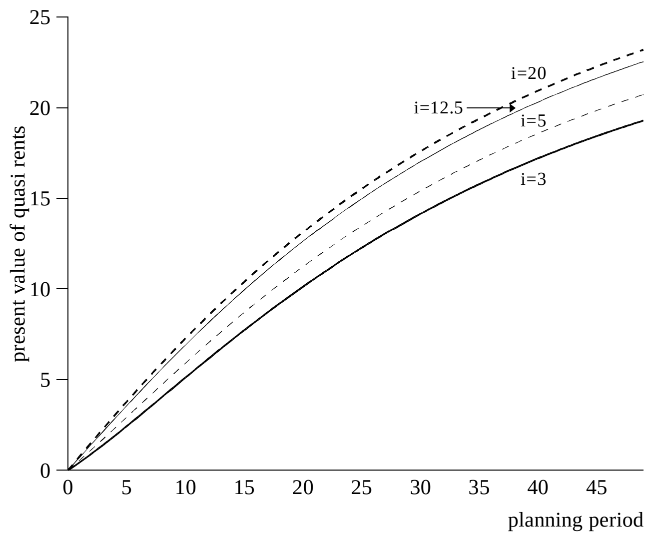

Figure 5.1. The present value of quasi-rents for different technologies[174]

174. The values of the parameters used are: π=0, ρ=0, μ=0.5, γ=0.0, ψ=1, λ_0=1, α=0.9, β=0.2, p_τ=1, w_τ=1, q_τ=0 and r=0.03. Note that τ=t_0=0.

The Choice of Technologies: A Graphical Approach

It is obvious that when prices of capital goods are the same for all technologies, i.e. $\gamma=0$, the present value of future rents per unit of output will increase as the technology index increases. This is shown in Figure 5.1. Since the capital costs are identical for all technologies, we plotted the present value of the quasi-rents per unit of output, pvqr for short, against the length of the planning period θ. In this figure, we assumed that the growth rate of real wages is zero and the real discount rate is positive (i.e., $\pi=\rho \wedge \pi<r$). Appendix 5B shows that, in this case, the pvqr increases monotonically in θ for advanced technologies, that is, provided that the labour productivity is sufficiently high to ensure the wage costs to be below the price of output. For less advanced technologies, the pvqr will decrease monotonically, thus resulting in a negative pvqr for all values of the planning period. We require the pvqr to be positive, because no firm will invest in a technology which yields a negative pvqr. This implies that there exists a least advanced technology in which firms will invest.[175] The present value of the *marginal* quasi-rents with regard to θ will asymptotically decline towards zero, because the growth rate of nominal wages is less than the discount rate. From this it follows that the present value of quasi-rents will eventually reach an upper limit.[176] It is shown in appendix 5B that the same conclusion holds for the non-learning case. Furthermore, the pvqr will increase as the technology index increases, because a more advanced technology implies a higher labour productivity.

Thus, all firms would choose the newest technology because that technology incorporates the highest labour productivity for all values of the planning period. This result changes if prices of capital goods are not independent of the incorporated technology, i.e., if $\gamma>0$, which is shown in Figure 5.2. In this figure we plotted the present value of future rents against the length of the planning period for four different technologies.

As capital costs are assumed to be sunk costs, the curves of Figure 5.1 move downwards when the costs of capital are positive. Furthermore, the costs of capital increase for more advanced technologies so that the pvqr moves downwards to a larger extent if the index of the embodied technology is higher. Starting at the origin and increasing the length of the planning period, we see that technology i=3 is the most profitable technology for a short planning period. Note however that the planning period is even so short that the costs of capital are larger than the

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175. Cf. case (b) in Figure 5B.1.

176. See appendix 5B for the general properties of the present value of the quasi-rents. The case described above corresponds with Figure 5B.1(b). If the real interest rate is zero or negative, the pvqr will increase unbounded for increasing values of the planning period. This case is highly unrealistic, however. Note furthermore that the planning period is bounded by the expected lifetime of capital goods such that we could impose an upper limit on the planning period by imposing an upper limit on the lifetime of equipment. We will not impose such upper limit, but instead, we assume that the real interest rate is positive, which implies that the pvqr will reach an asymptotic upper/lower limit. Cf Figures 5B.1(a), (b) and (c).

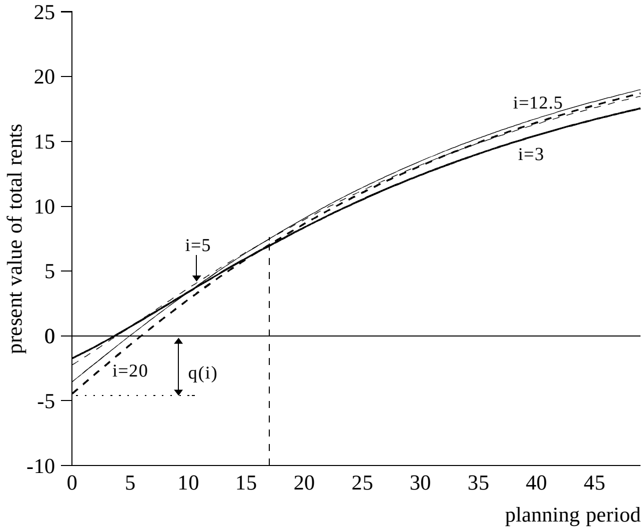

Figure 5.2. The present value of future rents for different technologies[177]

present value of future quasi-rents. In this case, the present value of the expected rents is negative, which means that a firm which is risk-averse to the extent that the planning period is below θ^0, will not invest at all. This results in an optimal technology, given the length of the planning period, which yields zero expected rents, and this is the first, or least advanced, feasible technology in which firms will invest. Moving to the right, we see that technology i=5 yields the highest present value of future rents for a planning period between about 4 and 17 years. After that, technology i=12.5 becomes the most profitable one. Note moreover that this figure suggests that technology i=12.5 will always dominate the most advanced technology (i=20), for all values of θ>17. This implies that there is a technology which yields the highest present value of future rents, regardless of the value of θ above a certain value. We will go into this phenomenon in more detail below.[178]

If we allow for an infinite and continuous range of technologies, it is clear that the choice of the technology depends on the length of the planning period. If the planning period increases, firms will be able to deduct the capital costs over a longer period so that the annual costs of capital decrease, given a specific technology. As a result, firms with a longer planning period will choose a more advanced technology, which embodies a higher labour productivity but is also more expensive. No firm will invest in a technology if the planning period is short to the extent that the present value of expected rents is negative. This implies that

177. The values of the parameters are the same as used in Figure 5.1. q(i) describes the price of capital goods, ie. $q(i) = q_\tau^i = q_\tau i^\gamma$, where γ=0.5 and q_t=1.

178. Note that the planning period is given for a specific firm which means that we are talking about different firms if we assume that the planning period is extended.

the least advanced technology is determined by the non-negative rent condition. The *marginal* increase in the net present value of the expected *quasi-rents* with respect to the length of the planning period will approach zero if the real discount rate is positive, and if the growth rate of nominal wages is below the nominal discount rate. Thus, there will be a most advanced technology in which firms with a relatively long planning period will invest. So, if we assume that the level of risk aversion is inversely related to the length of the planning period, then it follows that less risk-averse firms will choose a more advanced technology. Moreover, there will be minimal length of the planning period which is required to invest in a technology at all. The relation between risk aversion and the choice of the technology is elaborated in section 5.3. Now, we will present a more formal approach to the relation between the choice of the technology and the length of the planning period.

The Choice of Technologies: A Formal Approach
In a more formal way, the firm's profit maximization problem is defined by equations (5.5), (5.2), (5.8), (5.9) and the expectations of future prices:

$$\begin{aligned}\max_{i|\theta} PV^{i}_{\tau,t_0,\theta} &= \max_{i|\theta} \int_{\tau}^{\tau+\theta} \left(p_t - \frac{w_t}{\lambda^{i}_{t,t_0}}\right) e^{-r(t-\tau)} dt - q^{i}_{\tau}\psi \\ &= \max_{i|\theta} \; p_\tau g(\theta,\tau) - \frac{w_\tau}{\lambda_0 i^{\mu}} f(\theta,\tau,t_0) - q_\tau i^{\gamma}\psi \end{aligned} \tag{5.10}$$

$$\text{s.t.} \quad PV^{i^*}_{\tau,t_0,\theta} \geq 0 \quad \text{and} \quad i>0$$

$$\text{where } f(\theta,\tau,t_0) = \int_{\tau}^{\tau+\theta} (\beta+(1-\beta)\alpha^{(t-t_0)}) e^{(\rho-r)(t-\tau)} dt \geq 0$$

$$\text{and } g(\theta,\tau) = \int_{\tau}^{\tau+\theta} e^{(\pi-r)(t-\tau)} dt \geq 0$$

Solving for i yields:[179]

$$i^{*}_{\tau,\theta} = \left(\frac{w_\tau \mu \; f(\theta,\tau,t_0)}{q_\tau \gamma \, \psi \lambda_0} \right)^{\frac{1}{\mu+\gamma}} \quad \text{for } f(\theta,\tau,t_0) > 0 \tag{5.11}$$

The choice of the optimum technology is independent of current and future output prices. This is due to the fact, first, that output is homogeneous — the price of output is independent of the technology with which the output is produced, and secondly, that we used a linear homogeneous production function — the costs per

179. It is easy to verify that in the optimum the second derivative is negative.

unit of output are independent of scale of output. Solving the dual problem, i.e., cost minimization, would give the same result.

Note that the optimal technology depends positively on current and discounted future wage costs (w_τ and $f(\theta,\tau,t_0)$) as well as on μ, the productivity elasticity. If wages rise while capital costs remain the same, firms will invest in a less labour-intensive technology by choosing a more advanced technology, i.e., with a higher technology index i. If μ increases, the same argument applies as the change of the labour productivity due to a change of the technology index increases. The optimal technology depends negatively on the prices of capital goods, both with regard to the non-specific part and to the price elasticity. If capital costs increase, firms will choose a less advanced technology to decrease the capital intensity of production. The same applies if γ rises.

Now, we will investigate whether firms with a longer planning period will choose a more advanced technology. If we assume that no firm has any experience with a technology at time τ, time t_0 is equal to the time of investment, τ. In this case, f(..) depends solely on the length of the planning period. We will denote this function by f(θ). Differentiating the optimal technology index with respect to the length of the planning period, we obtain:

$$\frac{\partial(i^*_{\tau,\theta})}{\partial\theta} = \frac{i^*_{\tau,\theta}}{(\mu+\gamma)}\,\frac{f_\theta}{f(\theta)} \geq 0$$

as

$$f(\theta) = \frac{\beta(e^{(\rho-r)\theta}-1)}{\rho-r} + \frac{(1-\beta)(e^{(\rho+\ln(\alpha)-r)\theta}-1)}{\rho+\ln(\alpha)-r} > 0 \tag{5.12}$$

and

$$f_\theta = \beta e^{(\rho-r)\theta}+(1-\beta)e^{(\rho+\ln(\alpha)-r)\theta} \geq 0$$

Thus, the technology index increases as the length of the planning period increases, a result which was to be expected.[180]

If the discount rate exceeds the growth rate of nominal wages, the technology index will reach some upper limit as the planning period increases.[181] The most advanced technology which firms will buy is then given by:[182]

180. Note that the function $f(\theta)$ is the addition of two integrals (cf. equation (5.10) in which $t_0=\tau$). The first is equal to β times the present value of future wage rates, relative to the current wage rate, and the second term is $(1-\beta)$ times the present value of the future wage rate, relative to the current wage rate (w_τ), minus the discounted future labour productivity, relative to the current labour productivity ($\lambda^i_{\tau,\tau}$), which can occur due to learning-by-doing effects. Both integral terms are positive for all values of ρ and r if $\theta>0$ and if $0<\alpha<1$, so that the term $f(\theta)$ is always positive.

181. This is exactly the situation we discussed in relation with Figure 5.2. The increase in the fixed costs between technologies i=12.5 and i=20 is larger than the decrease of the discounted variable costs.

182. Note that $\rho+\ln(\alpha)-r<0$ if $\rho-r<0$ because $0<\alpha<1$.

$$i^{**}_{\tau,\infty} = \left(\frac{w_\tau \mu \; f(\infty)}{q_\tau \gamma \psi \lambda_0}\right)^{\frac{1}{\mu+\gamma}}$$

$$\text{with} \quad f(\infty) = -\left(\frac{\beta}{\rho - r} + \frac{(1-\beta)}{\rho + \ln(\alpha) - r}\right) > 0 \quad \text{if } \rho - r < 0 \tag{5.13}$$

$$\text{and} \quad f(\infty) = \infty \qquad \text{if } \rho - r > 0 \;\; \text{or } \rho + \ln(\alpha) - r > 0$$

Thus, there exists an upper limit of the optimal technology indices if we assume that a more advanced technology is more expensive than less advanced technologies and if we assume that the growth rate of nominal wages is less than the discount rate. This is true, even if more advanced technologies are supplied, i.e., with a technology index $i > i^{**}_{\tau,\infty}$, and if the planning horizon of firms tends to infinity. The gains from an increase in the planning period will move towards zero, as the discount rate is larger than the growth rate of wages. As a result, a more advanced technology will be more profitable if the decrease of the variable costs at the margin is larger than the increase of the fixed costs. But as the changes in $f(\theta)$ will tend to zero, the decrease of the marginal variable costs due to an increase of the technology index, $w_\tau \; f(\theta)\mu \; / (\lambda_0 i^{\mu+1})$, will go to zero. For technologies above i^{**}, the increase of the fixed costs will be larger than the gains of discounted variable costs, and a firm will not invest in such a technology.[183] This holds for both the learning and the non-learning case.

If the growth rate of wages exceeds the discount rate, the technology index will increase unboundedly if the planning period increases. But if we assume that the real interest rate is positive, the growth rate of wages should be larger than the growth rate of output prices, i.e., the growth rate of real wages should be positive in this case. But if the planning period is extended, wages will increase more rapidly than the discount rate, which means that the present value of marginal wage costs will increase for increasing values of θ. Because the growth rate of output prices is below the discount rate, the present value of marginal returns decreases for increasing values of θ. The expected profits will decrease if the planning period is extended. The only way in which firms can increase the expected profits in this case, is to buy a more advanced technology so as to reduce the wage costs due to increases of labour productivity. However, since a more advanced technology also implies higher investment costs, we cannot determine a priori whether firms with a longer planning period will achieve higher profits if the growth rate of nominal

183. Applying the parameters we used in Figures 5.1 and 5.2 to equation (5.13) shows that the index of the most advanced technology is approximately 12.58.

wages exceeds the growth rate of output prices. The next section will address this issue by elaborating the relation between expected profits and the optimal technology index.

5.2.3 The Optimal Technology and Expected Profits

The previous section shows that the optimal technology index is an non-decreasing function of the length of the planning period. Furthermore, we required expected profits to be non-negative. In this section we will answer two different questions. First, are the expected profits a non-decreasing function of the (optimal) technology index, and secondly, can we say something about the minimal length of the planning period which yields just zero expected profits? As we have done before, we will first give a graphical presentation of the relation between the length of the planning period, the optimal technology and the expected profits, followed by a formal approach.

A Graphical Approach

Previously, we showed that the relation between the optimal technology index and the length of the planning period depends on the growth rate of nominal wages (ρ) and on the discount rate (r). The relation between the expected profits and the planning period depends on the chosen technology, on the growth rate of nominal wages and on the growth rate of output prices (π). This leads to four different cases. (i) $\rho<r$ and $\rho\leq\pi$, (ii) $\rho\geq r$ and $\rho\leq\pi$, (iii) $\rho<r$ and $\rho>\pi$, and finally (iv) $\rho\geq r$ and $\rho>\pi$. The optimal technology reaches asymptotically an upper limit in cases (i) and (iii) and will grow unboundedly in cases (ii) and (iv). We will show that the expected profits will reach a maximum value in case (iv). Case (ii) will lead to an infinite technology index if the planning period becomes very large and the expected profits will also grow unboundedly for increasing values of θ. However, note that this case implies that the real interest rate is negative, which is rather exceptional if we examine actual data, so that we exclude the case in which $\pi>r$. Below, we will show that cases (iii) and (iv) are quite similar. Disregarding cases (ii) and (iii), we will present two different cases in this section: one case in which the growth rate of nominal wages is less than the growth rate of output prices, and therefore also less than the discount rate (i), and the second case in which the growth rate of wages exceeds both the growth rate of output prices and the discount rate (iv).

If the growth rate of nominal wages is less than the interest rate, the optimal technology is an increasing function of the length of the planning period and will asymptotically reach an upper limit. This is shown in Figure 5.3, curve II. Curve III describes the relation between the length of the planning period and the present value of expected rents per unit of output, PV for short, given the optimal technology index i^*. As expected, the PV is negative for small values of the planning

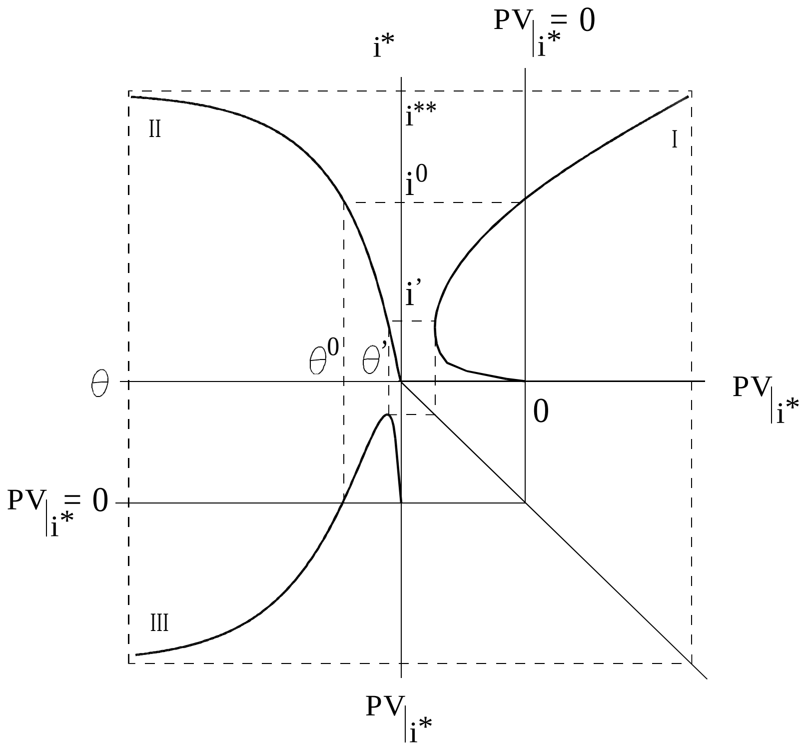

Figure 5.3. The present value of discounted expected rents and the technology index ($\rho \leq \pi < r$)

period and asymptotically reaches an upper limit if the planning period becomes infinite. As is the case for the choice of the technology, the asymptotic approach is due to the fact that the interest rate exceeds the growth rate of expected output prices which means that an increase of the planning period has a diminishing impact on the marginal PV. Finally, curve I describes the relation between the optimal technology index and the present value of expected rents, given the length of the planning period. The PV is negative for small values of i^* and note that this curve simply stops if the technology index is equal to i^{**}. As no firm will invest in a technology with a negative PV, the least advanced technology firms are willing to buy is equal to i^0. This will be the case if the firm has a planning period equal to θ^0. If other firms are less risk-averse and therefore have a longer planning period,, they will invest in a more advanced technology, which yields higher profits. Both the technology index and the profits asymptotically reach an upper limit. If firms are distributed with respect to the length of the planning period, we obtain a distribution of technologies which is located between i^0 and i^{**}.

If the growth rate of nominal wages exceeds the discount rate, and if the growth rate of real wages is positive, the marginal variable costs will increase as the planning period increases. The optimal technology index will grow unboundedly as the planning period goes to infinity in that case (cf. equation (5.13)), which is illustrated in Figure 5.4. The technology index increases unboundedly ($i^{**} \rightarrow \infty$) if the

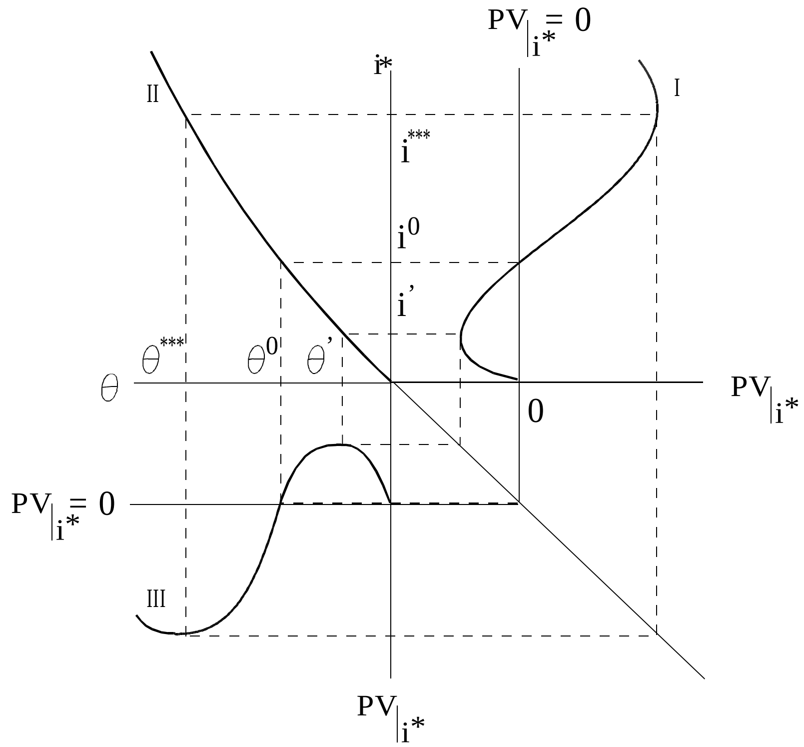

Figure 5.4. The present value of discounted expected rents and the technology index ($\rho>\pi$ and $\rho\geq r$)

planning period becomes infinite. But because the growth rate of wages exceeds the growth rate of output prices, the present value of expected rents will reach a maximum.[184] Consequently, firms with a planning period longer than θ^{***} will buy a more advanced technology but face smaller profits than firms with a planning period of θ^{***}, which are assumed to be less risk-averse. This is rather counter-intuitive.

However, if we assume that the planning period is a measure of the *maximum* level of risk a firm is prepared to take, and the firm may freely choose a shorter planning period if this increases profits, then the optimal technology is defined by i^{***} in Figure 5.4. No firm will choose a more advanced technology if this will lower the expected profits and will raise the risk involved. Therefore we have to reconsider the optimization problem and make the length of planning period a control variable which is bounded by a maximum. This is elaborated in the next section.

Finally, note that in this case, the technology index is bounded between i^0 and i^{***}. Furthermore, whereas the length of the planning period is only bounded from below in the previous case ($\theta\geq\theta^0$), it is now also bounded from above ($\theta^0\leq\theta\leq\theta^{***}$). A plot of the technology index against the expected profits shows that the curve is backward-bending with maximum profits at point i^{***}.

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184. Which we will prove in the next section.

The Optimal Technology and Expected Profits: A Formal Approach
First, we will examine the expected profits as a result of maximizing the expected profits with respect to the technology index, conditional on a fixed length of the planning period. After that, we will reconsider the optimization problem and make the planning period a bounded control variable, i.e., firms may freely choose a planning period as long as it does not exceed a maximum ($\bar{\theta}$).

Substitution of the optimal technology in the present value of expected rents gives:

$$
\begin{aligned}
PV_{\tau,\theta}\Big|_{i^*} &= p_\tau\, g(\theta) - \left(\frac{w_\tau\, f(\theta)}{\lambda_0}\right)^{\frac{\gamma}{\mu+\gamma}} \left(\frac{\mu}{\psi q_\tau \gamma}\right)^{\frac{-\mu}{\mu+\gamma}} \left(1+\frac{\mu}{\gamma}\right) \\
&= p_\tau g(\theta) - c_t\, f(\theta)^{\frac{\gamma}{\mu+\gamma}} \left(1+\frac{\mu}{\gamma}\right) \qquad (5.14) \\
\text{with } c_t &= \left(\frac{w_\tau}{\lambda_0}\right)^{\frac{\gamma}{\mu+\gamma}} \left(\frac{\mu}{\psi q_\tau \gamma}\right)^{\frac{-\mu}{\mu+\gamma}} > 0
\end{aligned}
$$

The first part of this equation describes the total discounted marginal returns over the planning period. The second part denotes the total costs, in which the first part, $c_t f(\theta)^{\gamma/\mu+\gamma}$, is the total discounted marginal wage sum over the planning period and the last part, $c_t f(\theta)^{\gamma/\mu+\gamma} \mu/\gamma$, are the marginal costs of capital. This implies that the ratio of the total discounted wage sum over the total costs of capital is equal to γ/μ. This holds for all firms, irrespective of the length of the planning period.

A firm will invest in a technology as long as the present value of expected rents per unit of output (expected profits for short) is non-negative. Hence, equation (5.14) has to be non-negative. Both functions g and f are positive for all $\theta > 0$, which gives no decisive answer regarding the sign of the present value of rents. In appendix 5C we show that the derivative of the expected profits with respect to the length of the planning period and conditional on the choice of the technology, is negative for small values of the planning period. There, we also show that the derivative is positive if $\theta \to \infty$ and if the growth rate of wages is less than or equal to the growth rate of output prices. This implies that the expected profits are negative and decreasing for small values of the planning period, but are an increasing function of the planning period for larger values of θ. Curve III in Figure 5.3 displays the profits as a function of the planning period.[185]

185. It is possible that the upper limit of the expected profits is negative, for instance due to high nominal wage rates or high values of the non-technology-specific part of capital costs (q_τ). This would imply that no firm will invest at all. As we did before, we will exclude such situations.

If we reconsider the optimization problem in such a way that the length of the planning period is a bounded control variable, no firm will choose a planning period and a corresponding technology if it has the opportunity to choose another technology, by choosing a shorter planning period, thus achieving an increase in profits. The new optimization problem is described by:

$$\max_{i,\theta} PV^{i}_{\tau,t_0,\theta} = \max_{i,\theta} \; p_\tau g(\theta,\tau) - \frac{w_\tau}{\lambda_0 i^{\mu}} f(\theta,\tau,t_0) - q_\tau i^{\gamma}\psi$$

$$\text{s.t.} \quad PV^{i^*}_{\tau,t_0,\theta} \geq 0 \qquad (5.15)$$

$$0 \leq \theta \leq \bar{\theta}$$

$$i > 0$$

in which $\bar{\theta}$ is the maximum length of the planning period. Firms are assumed to be distributed with respect to $\bar{\theta}$. The first-order condition with respect to i remains the same, which implies that equation (5.11) (the optimal technology, conditional on the length of the planning period) still holds. The new first-order condition is:[186]

$$\frac{\partial PV}{\partial \theta} = p_\tau g_\theta - \frac{w_\tau}{\lambda_0 i^{*\mu}} f_\theta = 0 \qquad (5.16)$$

in which we have to substitute equation (5.11) for i^*. This condition says that no firm will apply its maximum length of the planning period if it can increase profits by choosing a shorter planning period and, correspondingly, a less advanced technology. In appendix 5C, we show that the expected profits will decrease for large values of the planning period if the growth rate of wages exceeds the growth rate of output prices. This implies that there exists a maximum value of expected profits, as displayed by curve III in Figure 5.4.

Summary

This section develops a model in which a firm maximizes the expected present value of future rents given a certain length of the planning horizon. It is shown that, in such a case, the chosen technology will be more advanced if the length of the planning period increases. Moreover, we showed that no firm will invest in a technology due to negative expected profits, if the planning period is very short.

186. Note that we must also apply the appropriate second-order condition because there exists a minimum value of the expected profits as a function of the planning period (cf. curves III in Figures 5.3 and 5.4).

	$\rho < r \Rightarrow i^{**} =$ finite	$\rho > r \Rightarrow i^{**} = \infty$
$\pi > \rho \Rightarrow$ $\theta = \bar{\theta}$	*(i)* $i^0 \leq i^* \leq i^{**}$ $\theta = \bar{\theta}$	$i^0 \leq i^* \leq \infty$ *(ii)* $\theta = \bar{\theta}$ but note that $\pi > r$
$\pi < \rho \Rightarrow$ $\theta = \min(\bar{\theta}, \theta^{***})$	*(iii)* $i^0 \leq i^* \leq \min(i^{**}, i^{***})$ $\theta = \min(\bar{\theta}, \theta^{***})$	*(iv)* $i^0 \leq i^* \leq i^{***}$ $\theta = \min(\bar{\theta}, \theta^{***})$

Table 5.1. Ranges of i^* and θ for several combinations of parameters

We showed that the optimizing behaviour of firms leads to two different conditions. First of all, firms will choose a specific technology which depends on the wage rental ratio. Secondly, firms have to choose a planning period. Although the maximum length of the planning period is given to each firm, firms may choose a shorter planning horizon if this increases profits. This leads to a condition in which both costs *and* returns are relevant. Both conditions as well as the resulting technology index and planning period, are summarized in Table 5.1.If the growth rate of output prices exceeds the growth rate of nominal wages, an extension of the planning period will always have a positive impact on the present value of rents, given a specific technology. This implies that firms will always apply their maximum planning period $\bar{\theta}$. If the opposite holds true, there will be a turning point of the length of the planning period (θ^{***}), which is technology-dependent. For a planning period shorter than this turning point, the discounted rents at the margin are positive and firms will apply $\bar{\theta}$. For planning periods longer than θ^{***}, the discounted rents at the margin are negative. Hence, firms will not choose a planning horizon which is longer than θ^{***}.

With respect to the chosen technologies, there are two different considerations, which are simultaneously examined by firms, but which will be treated separately here. First, firms will choose the technology that maximizes their expected profits, conditional on a *given* planning period. This leads to i^*. Secondly, firms consider whether a shorter planning period, and, correspondingly, a less advanced technology, can increase profits.

With respect to the first issue, the optimal technology index depends on the length of the planning period through ρ and r.[187] If the growth rate of nominal wages is below the discount rate, it is shown that the optimal technology asymptotically reaches some upper limit as the planning period becomes longer. The decrease of wage costs due to a more advanced technology will not be large enough to offset the increase of the capital costs if the interest rate is high com-

187. In fact, also on the learning parameter (α). But note that learning is restricted to an upper limit, so that the difference between ρ and r is relevant in the present discussion.

pared to the growth rate of wages. If the opposite holds true ($\rho > r$), there is no upper limit, so that firms with an infinite planning horizon will invest in a technology with an infinite index.

The second issue is illustrated in Table 5.1. In the left-upper entry point, firms apply their maximum planning period and will invest in their initial optimal technology. When moving one cell to the right, the same holds true, but notice that the real interest rate is negative in this case. In the bottom row, the optimal planning period is not necessarily equal to the maximum planning period. In other words, the optimal technology is always limited to i^{***}. A longer planning period implies less profits, which is rather counter-intuitive. We therefore reconsidered the optimization problem giving firms the opportunity to freely choose a shorter planning period if this will increase expected profits.

Referring to Figures 5.3 and 5.4, the optimal technology is positively related to the length of the planning period in all cases. The most advanced technology is limited except for the case in which the real interest rate is negative. Furthermore, the optimal technology is bounded between i^0 and i^{**} if the growth rate of wages is less than the discount rate, and it is bounded between i^0 and i^{***} if the growth rate of wages exceeds the discount rate. This implies that if firms are distributed with respect to the length of the planning period, this will lead to a distribution of technologies. This is a basic feature of our model.

The probit model of Davies (1979) is comparable to our model. However, in our model firms are assumed to be distributed with respect to their size, while Davies assumes that the firm size can be related to the expected as well as the acceptable pay-back period. The relation between firm size and expected pay-back period is not that clear and the acceptable pay-back period is based on satisfying behaviour. In our model, the firms are assumed to maximize expected profits and they are distributed with respect to the length of the planning period. This leads to a distribution of technologies.

Our main goal here is to develop a vintage-diffusion model in which the choice of technologies depends on both firm characteristics and characteristics of the capital goods, i.e., of the incorporated technologies. We discussed the choice of technologies without investigating the amount of investment and without exploring the relation between investment and scrapping behaviour. Moreover, we claimed that the choice of technologies depends on risk aversion and uncertainty. But up to now, we just assumed that the length of the planning period is a measure of the level of risk aversion. Furthermore, the model is deterministic and it does not incorporate uncertainty as such.

The next section develops a similar model in which we take uncertainty and risk aversion into account. In fact, this is the ‘actual’ model we want to develop in this chapter. As pointed out in the introduction to this chapter, we are not able to solve the choice of the technology index and the length of the planning period analytically in the model with risk aversion and uncertainty. However, we will show that the length of the planning period is positively related to the level of risk aversion and that the technology index is positively related to the length of the planning period. In other words, a distribution of firms with respect to the level of risk aversion is equivalent to assuming a distribution of firms with respect to the length of the planning period.

Because of these analytical problems, we will use the model in which firms are distributed with respect to the length of the planning period in our full vintage-diffusion model. This is elaborated in chapter 6. The purpose of the next section is to show that a positive relation between the technology index (i^*) and the length of the planning period is indeed a good approximation of the relation between the level of risk aversion and i^*.

5.3 Risk Aversion and the Choice of Technologies

This section extends the model described in the previous section. First, we will introduce a stochastic process in the expected quasi-rents to incorporate uncertainty, and second, we will maximize a utility function with constant absolute risk aversion in order to determine the optimal technology as well as the corresponding length of the planning period as a function of the level of risk aversion.

We investigated two variants of the model: a variant in which output prices are assumed to be stochastic and a variant in which the wages are stochastic. Because the latter involved major analytical problems, we will elaborate only the first variant. The second variant will be referred to parenthetically.

Assume that future prices are stochastic and that these prices can be described by a normal distribution with mean p_t and variance σ_t^2:

$$\tilde{p}_t \sim N(p_t, \sigma_t^2) \tag{5.17}$$

The variance reflects uncertainty about future prices, and it is reasonable to allow the variance to increase as the time horizon, or planning period, increases. Similar to, for instance, Tsur et al. (1990), we assume that the variance can be described as $\sigma^2_{\tau+\theta} = \sigma^2_\tau e^{\omega\theta}$ with ω being the variance inflation parameter. Furthermore, we assume that the expected mean value of future prices can be written as $p_{\tau,t} = p_t e^{\pi(t-\tau)}$, in which π describes the expected growth rate of prices. Thus, the present value of expected rents is equal to:

$$PV^i_{\tau,t_0,\theta} = \int_\tau^{\tau+\theta} (\tilde{p}_t - \frac{w_t}{\lambda^i_{t,t_0}}) e^{-r(t-\tau)} dt - q^i_\tau \psi \tag{5.18}$$

All variables have already been defined in the previous section.

The expected present value of future rents remains the same as the expression for this term used in the previous section. Assuming that $\tilde{p}_t$ and $\tilde{p}_s$ are stochastically independent for any $t \neq s$, we find for the variance of the present value:[188]

$$VAR(PV)_{\tau,\theta} = \sigma^2 \int_{\tau}^{\tau+\theta} e^{(\omega-2r)(t-\tau)} dt = \sigma^2 h(\theta) \quad \text{with } h(\theta) = \frac{e^{(\omega-2r)\theta}-1}{\omega-2r} \tag{5.19}$$

We adopt a utility function with constant absolute risk aversion, similar to, for instance, Tsur et al. (1990). Firms are assumed to maximize:[189]

$$E(U_\tau) = E(1-e^{-R \cdot PV^i_{\tau,\theta}}) \tag{5.20}$$

where $R>0$ is the absolute risk aversion coefficient. Thus, we assume that firms first calculate the present value of discounted rents and then assign a utility level to this value. Using the properties of the moment-generating function of a normal distribution, we get:[190]

$$E(U_\tau) = 1-e^{-R\,[E(PV^i_{\tau,\theta}) - \frac{R}{2} VAR(PV)_{\tau,\theta}]} \tag{5.21}$$

Firms will maximize $E(U_\tau)$ with respect to the technology index i and the length of the planning period θ, given the level of risk aversion R. This is equivalent to maximizing:[191]

$$\begin{aligned} \max_{i,\theta|R} J_\tau &= \max_{i,\theta|R} \; E(PV^i_{\tau,\theta}) - \frac{R}{2} VAR(PV)_{\tau,\theta} \\ &= \max_{i,\theta|R} \; p_\tau g(\theta) - \frac{w_\tau f(\theta)}{\lambda_0 i^\mu} - q_\tau i^\gamma \psi - \frac{R}{2}\sigma^2 h(\theta) \end{aligned} \tag{5.22}$$

Note that the variance is independent of the technology, so that maximizing equation (5.22) with respect to the technology index is equivalent to the maximization problem as defined in the previous section. Thus, the optimal technology index is

188. See appendix 5D for the derivation.

189. Absolute risk aversion is defined as $R_A = -U''(PV)/U'(PV)$ in which the single and double prime denotes the first and the second derivative respectively. An alternative would be to use a utility function with relative risk aversion ($R_r = PV \cdot R_a$), for instance $U(PV) = \frac{1}{(1+R_r)} PV^{1+R_r}$ with $R_r<0$ and $R_r \neq -1$. In consumer theory, the latter function is believed to be more plausible since rich consumers (a high PV in our terms) are likely to be more tolerant of risk than the poor. However, it is not clear that the same holds true for the present value of an investment project in the case of firm behaviour. Moreover, the constant risk aversion utility function is used very frequently because of its attractive mathematical form. (cf. Deaton and Muellbauer (1980: 401-404) or Blanchard and Fischer (1989: 44) for a discussion on this topic).

190. See Mood, Graybill and Boes (1974).

191. This is the objective function of the mean-variance approach. Stoneman and Ochoro (1980) as well as Stoneman (1981) started from the mean-variance approach and used a utility function which is equivalent to equation (5.22).

the same as that found in the previous section, i.e., equation (5.11), conditional on θ. The present model, however, enables us to determine the length of the planning period as a function of the level of risk aversion. Differentiating equation (5.22) with respect to the planning period, we obtain:

$$\frac{\partial J_\tau}{\partial \theta} = p_\tau g_\theta - \frac{w_\tau f_\theta}{\lambda_0 i^\mu} - \frac{R}{2}\sigma^2 h_\theta = 0 \tag{5.23}$$

$$\text{with} \quad h_\theta = e^{(\omega - 2r)\theta}$$

where f_θ is already defined in equation (5.12) (page 173). We would like to find a solution for the planning period, given the level of risk aversion, but it is impossible to solve the above equation for the length of the planning period. However, equation (5.23) can be solved for the level of risk aversion, given the length of the planning period, or for the technology index, conditional on the level of risk aversion. We will discuss both methods, which obviously lead to the same result, but which emphasize the properties of the model in a somewhat different manner.

5.3.1 Solution, Mark I

The first solution we present is the determination of the level of risk aversion, given the length of the planning period. Substitution of equation (5.11) (the optimal technology for a given planning period (i^*)), in equation (5.23) and solving for R gives:

$$R_\tau^* = \left(p_\tau g_\theta - \frac{w_\tau f_\theta}{\lambda_0 i^\mu}\right)\frac{1}{\frac{1}{2}\sigma^2 h_\theta} = \left(p_\tau g_\theta - \left(\frac{w_\tau}{\lambda_0}\right)^{\frac{\gamma}{\mu+\gamma}} \left(\frac{\mu f(\theta)}{q_\tau \psi \gamma}\right)^{\frac{-\mu}{\mu+\gamma}} f_\theta\right)\frac{1}{\frac{1}{2}\sigma^2 h_\theta} \tag{5.24}$$

Since the level of risk aversion must be positive, the term between brackets in equation (5.24) must also be positive. But this term between brackets denotes the marginal change of the present value of discounted quasi-rents due to a change of the planning period. This implies that, if the growth of wages exceeds the growth rate of output prices, a firm will increase its planning period and choose a more advanced technology as long as this increases the net present value of future rents. This is exactly the same condition as we have found in the previous section, cf. equation (5.16). Or, in terms of Figure 5.4, page 177, this implies that a firm will never exceed its planning period beyond θ^{***} or choose a technology index larger than i^{***}.

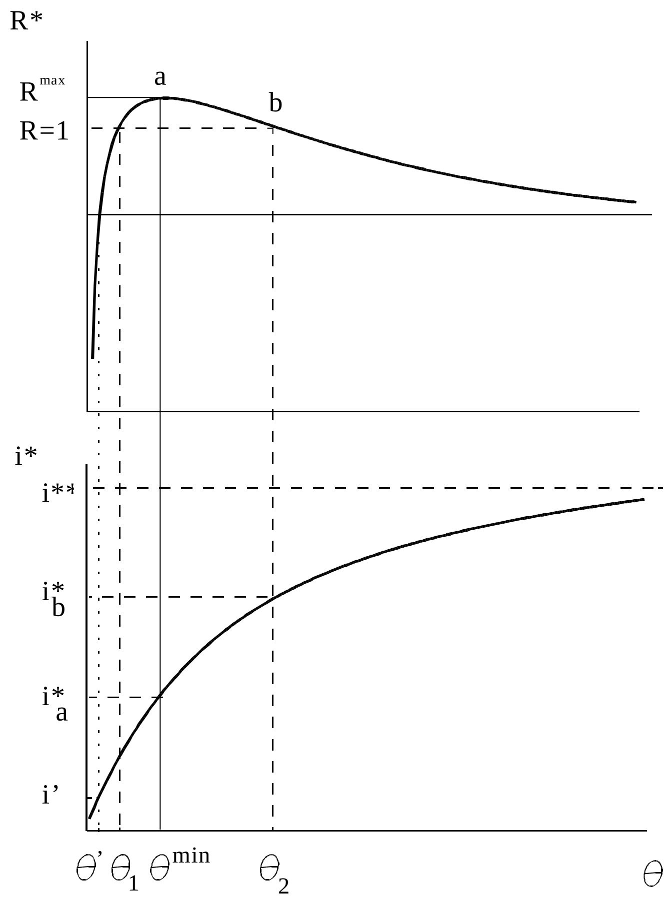

Figure 5.5. Determination of the technology index, given the level of risk aversion, solution I [192]

A graphical presentation of both the optimal technology and the level of risk aversion, both as a function of the planning period, is given in Figure 5.5. The figure at the top shows the level of risk aversion R^* (equation (5.24)) and the figure below shows the technology index i^* (equation (5.11), cf. curve II in Figure 5.3). The top figure shows that the level of risk aversion is negative for small values of the planning period, it increases as the planning period increases, becomes positive and reaches a maximum. After that, the level of risk aversion decreases and goes asymptotically to zero. Appendix 5E shows that the maximum value of R^*, i.e. at point a in Figure 5.5, coincides with the point at which the determinant of the Hessian is zero, and that the second-order condition of the optimization problem holds for larger values of the planning period. From this it follows that for levels of risk aversion between zero and R^{max}, there is a unique planning period and, as shown in the previous section, a unique technology index.

For instance, a firm with a level of risk aversion equal to 1 will choose a planning horizon of θ_2 and technology i_b^*. The intersection of R which results in a planning horizon of θ_1 is outside the feasible region, i.e., the second-order condi-

192. The parameters are the same as those used in the previous figures. The values for the additional parameters are ω=0.08 and σ^2=0.5.

tion is not satisfied in that point. Firms with a level of risk aversion above R^{max} will not invest in any technology at all. They are simply too risk-averse.

Note that the point at which R is zero (at $\theta^{/}$ with technology index $i^{/}$) corresponds with the point at which the expected profits reaches a minimum value in Figures 5.3 and 5.4. If $\rho > r$ and $\pi < r$, the function of R against the planning period will have a second intersection with the horizontal axis in Figure 5.5 which is located to the right of point a (not shown in the figure). This point corresponds with θ^{***} and i^{***} in Figure 5.4. Note furthermore that R^{max} (at θ^{min} and technology index i_a^*) does not necessarily correspond with the point at which the expected profits become non-negative (points θ^0 and i^0 in Figures 5.3 and 5.4).

5.3.2 Solution, Mark II

The second solution of the optimization problem is given by solving equation (5.23) for the technology index. This results in two different equations for the optimal technology index, this new one plus equation (5.11), a result of maximizing J_τ with respect to the technology index. Solving equation (5.23) for the technology index gives:

$$i^+_{\tau,\theta} = \left(\frac{w_\tau f_\theta}{\lambda_0 [p_\tau g_\theta - \frac{R}{2} \sigma^2 h_\theta]} \right)^{\frac{1}{\mu}} \tag{5.25}$$

Combining equations (5.11) and (5.25) gives an implicit relation between the level of risk aversion and the length of the planning period. From the level of risk aversion we can determine both the length of the planning period and the optimal technology. As we did before, we will give a graphical solution below.

Figure 5.6 shows a graphical presentation of the optimal choice according to the second solution. Line III, in the third quadrant, is the optimal technology index as defined by equation (5.11) and has been shown previously in Figure 5.3, curve II. Lines a, b and c are the optimal technology indices as defined by equation (5.25) for decreasing values of risk aversion, respectively. The level of risk aversion which corresponds with line a has been chosen in such a way such that line a is tangent to line III.

Intersection of lines a, b and c with line III gives the optimal technology index and the corresponding length of the planning period, given the level of risk aversion.[193] In this figure, the intersection of lines a and b with curve III corresponds with points a and b in Figure 5.5. The point at which line a is tangent to line III corresponds with the maximum level of risk aversion R^{max} in Figure 5.5. The line labelled b intersects line III at two points, one at which the planning period is shorter than the point of tangency of lines a and III, and a second in which the

193. There is also an imaginary part of the optimal technology index i^+, which intersects line number III more to the left.

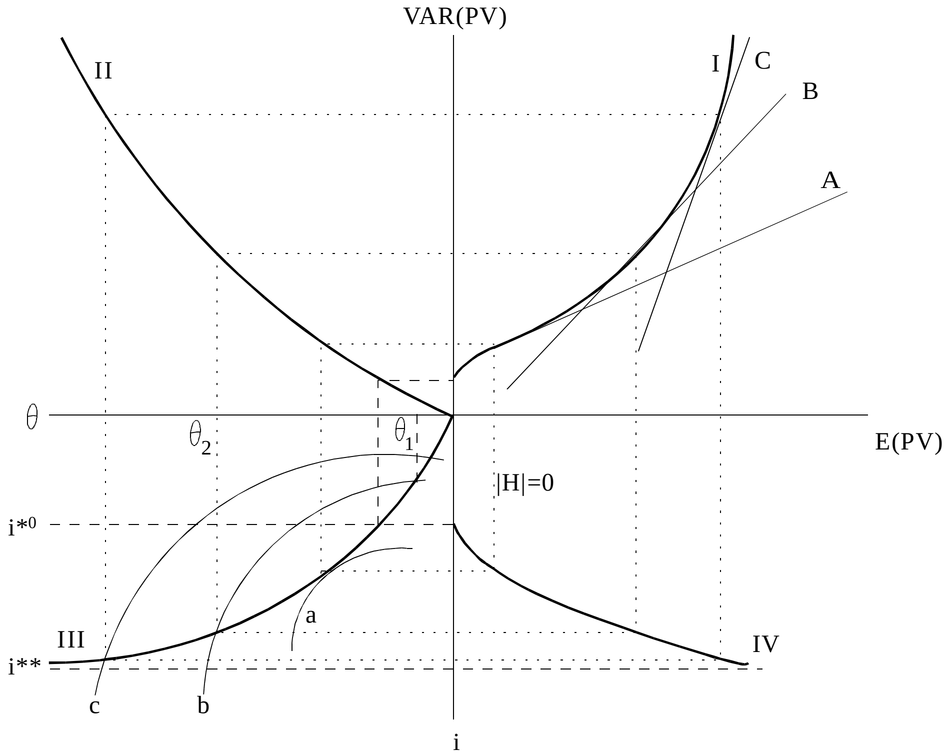

Figure 5.6. Determination of the technology index, given the level of risk aversion

planning period is longer (at θ_2). Again, these two points correspond with the intersection of a level of risk aversion equal to one with R^* in Figure 5.5. As pointed out before, appendix 5E shows that the first point of intersection is not feasible because the determinant of the Hessian is negative in that case.

The optimal choice can also be explained in the upper-right quadrant of Figure 5.6. Line III is transformed to line I by lines II and IV. Line II represents the relation between the length of the planning period and the variance of the present value as is defined in equation (5.19), whereas line IV represents the expected profits given the optimal technology index and the corresponding length of the planning period.[194] Line I describes the optimal combinations of the variance and the expected value of the expected profits. Firms which choose a less advanced technology given a certain length of the planning period will achieve lower expected profits for a certain variance. Thus, line I describes the efficient combinations of technology indices and planning periods in terms of the expected profits and the variance.[195]

194. This curve has been shown previously in Figure 5.3, curve I. Note that we display the positive part only.

195. Note that in Figure 5.6, risk is plotted at the vertical axis and expected profits at the horizontal one. These axes are inverted compared to standard textbook treatment of risk and expected profitability. Note furthermore that concepts of convexity and concavity are also inverted.

From equation (5.21)it is easy to see that a constant utility level is displayed by a linear combination of variance and expected value of the profits: $VAR(PV) = \frac{2}{R}E(PV)$ $+constant$. The slope of this curve is equal to 2/R, i.e., the more risk-averse a firm is, the smaller will be the slope of the variance-expected value line (line A denotes a firm which is more risk-averse than firms described by lines B and C).

The optimal choice of the technology is given by the tangent of lines A, B and C with line I. The levels of risk aversion, used to draw curves A, B and C, are the same as those used to draw lines a, b and c, respectively. The point of tangency between lines A and I occurs exactly at the point of inflection of line I. So in this example, A is the marginal risk-averse firm which invests in the least advanced technology. The feasible solutions of the maximization process are outside the square denoted by $|H|>0$, i.e., the region where the variance-expected value curve is convex.

Note that even for a zero-expected value of profits, firms have to face some risk. In the previous model, we found a minimum length of the planning period to generate some non-negative expected present value. These results are comparable.

From this figure it follows that there exist technologies that are optimal given the length of the planning period and that yield positive expected rents, but which are not optimal in the case of risk aversion and uncertainty.[196] As the utility function is concave in this region, firms can (and will) increase utility by choosing a longer planning period and a more advanced technology. The gains, in terms of utility, from an increase of the expected profits are larger than the loss of utility due to an increase of the variance.[197] So the first main difference between this model and the model described in the previous section is that the least advanced technology as well as the minimum length of the planning period is determined by the convexity restriction. In the previous model, the least advanced technology is determined by the non-negative rent condition. Note that the former is more restrictive, which implies that the least advanced technology has a higher index in the present model.

If the growth rate of wages exceeds the growth rate of output prices, curve IV will be backward bending as shown in Figure 5.4. This implies that the utility function is backward bending. This figure shows that no firm will invest in a technology which yields more risk, higher variance, but less expected profits.[198] Thus, both models are the same with respect to this particular point.

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196. As discussed in the previous section, it is also possible that the determinant of the Hessian is positive while the expected value of the rents is negative. In that case, the minimum value of the level of risk aversion is determined by the non-negative condition of the expected rents.

197. In appendix 5E, we prove that $R^*_{\tau,\theta}>0$ and that $\partial R/\partial\theta < 0$ as long as the determinant of the Hessian is positive. We also show that $\partial R/\partial\theta = 0$ if the determinant of the Hessian is zero. Furthermore, we prove that this point is equal to R^{max} in Figure 5.5.

198. Note that the slope of the backward-bending curve is negative, which would imply negative risk.

5.3.3 Conclusions, Similarities and Differences between Both Models

In this section, we extended the model of the previous section in the sense that we assumed a distribution of the relative number of firms with respect to risk aversion in a world of uncertainty. We showed that a certain level of risk aversion corresponds with a certain length of the planning period. This is the main correspondence between the two models, i.e., less risk-averse firms will apply a longer planning period. Furthermore, we showed that the minimal level of risk aversion is determined by the convexity restriction of the utility function. Thus, whereas the firm with the shortest planning period is determined by the non-negative rent condition in the first model, the most risk-averse firm is determined by the non-concavity restriction. With respect to the firms with the longest planning period and the lowest level of risk aversion, we showed that both models lead to the same optimal technology if we assume that firms may always choose a shorter planning period and ,correspondingly, a less advanced technology, if this increases expected profits. Although the model in which the length of the planning period is assumed to be a measure of risk aversion deviates from the present model at some points, the main property, i.e., a longer planning period implies less risk aversion and leads to a more advanced technology, holds for both models.

In the previous section, we showed that the choice of technologies is independent of the growth rate of output prices, given the length of the planning period. However, in the present analysis, both the length of the planning period and the technology index will increase due to an increase in the growth rate of output prices, given the level of risk aversion. This is demonstrated by equation (5.24). The level of risk aversion, which is a function of the length of the planning period, increases if p_τ or g_θ (due to a higher π) increases. This implies that, given a level of risk aversion, the length of the planning period increases. However, the firm will choose a more advanced technology. This shows the main difference between the models. A distribution with respect to risk aversion will lead to a certain distribution with respect to the length of the planning period, conditional on the expected profits. The length of the planning period is now determined by the level of risk aversion and depends therefore on both the mean and the variance of an investment project, while it was assumed to be fixed in the previous model.

The fact that there is a unique relation between the level of risk aversion and the length of the planning period at each point in time shows the main correspondence between the models. There is still a positive relation between the length of the planning period and the optimal technology index.[199]

199. In the case of stochastic wages, the variance of the expected profits depends on the technology index (cf. equation (5D.5) on page 209). This implies that firms can decrease the variance of total wage costs by choosing a more advanced technology (a higher labour productivity). Unfortunately, the model could not be solved analytically. Whereas we were able to obtain the same relationships between risk aversion, the length of the planning period and the technology index for specific parameter values, we were not successful in proving this in general.

Chapter 6 will incorporate this model into a vintage framework, where the amount of investment will be determined, next to the choice of technology. Furthermore, that chapter will address firm behaviour with regard to scrapping. Because the choice of the optimal technology cannot be determined analytically in the present model of risk aversion and uncertainty, and because there is a clear relation between risk aversion and the length of the planning period, we will use the model in which firms are distributed with respect to the planning period in the remaining chapters of this thesis.

But before we will turn to the next chapter, we will answer two remaining questions. In the introduction of this chapter, we claimed that the model without learning by doing is capable of describing inter-firm diffusion and that the learning-by-doing variant can also describe intra-firm diffusion. The first question is: is this true? One element of this question is what the diffusion process looks like, or in other words, what do we need to generate an S-shaped diffusion pattern? In the previous part, we showed that the productivity slowdown could be explained by a slowdown in the growth rate of both real and nominal wages. Thus, the second element of the first question is: can we obtain a similar result with the present model? Answers to these questions will be given in the next section.

In the introduction, we also claimed that there are more similarities between the present model and the putty-clay model presented in part II than one would expect at first sight. The second question to be answered in this chapter — more specifically in section 5.5 — is whether this is true.

5.4 Inter-Firm and Intra-Firm Diffusion Patterns

Up to now, the choice of technologies has been determined for an individual firm. It has been shown that a more risk-averse firm will choose a shorter planning period and will invest in a less advanced technology. The choice of technologies has been considered at one point in time, however. This section will give a short impression of the diffusion process, i.e., of the choice of technologies in the course of time. Note that the model described so far does *not* determine the amount of investment nor the capital stock or total amount of output. Thus, the resulting diffusion process demonstrates nothing but the choice of technologies in time.[200] First, we will show the diffusion process in the case without learning by doing, where it is easy to verify that there is no intra-firm diffusion in this case. After that, the diffusion process of the learning-by-doing case is investigated, in which intra-firm diffusion will appear. In both cases, it is assumed that firms differ from each other with regard to the length of the planning period. In fact, a distribution of the

200. An alternative view is that all firms buy only one unit of the investment good at each point in time.

level of risk aversion is the underlying assumption, but we have showed in the previous section that the choice of technologies is much more complicated in this case.

5.4.1 The Non-Learning Case

Recall the choice of the optimal technology for a firm with planning period $\bar{\theta}$:

$$i^*_{t,\bar{\theta}} = \left(\frac{w_t \mu f(\theta)}{q_t \lambda_0 \gamma \kappa}\right)^{\frac{1}{\mu+\gamma}} = \left(\frac{w_t}{q_t}\right)^{\frac{1}{\mu+\gamma}} \left(\frac{\mu f(\theta)}{\lambda_0 \gamma \kappa}\right)^{\frac{1}{\mu+\gamma}} \quad \text{where} \quad 0 < \theta \leq \bar{\theta} \tag{5.26}$$

in which the last term is constant in time for each individual firm in the non-learning case.[201] Clearly, if there is no change in the ratio of wages over the non-technology-specific part of prices of capital goods, each firm will choose the same technology at every point in time. In chapter 8, however, we will show that this situation is very unlikely, given profit-maximizing behaviour of the supplying industries. There, we will demonstrate that the supplier of a specific technology will decline its output price relative to the nominal wage rate (q^i_t / w_t) in the course of time, at least as long the quasi-rents are non-negative. Here, we assume that the growth rate of nominal wages exceeds the growth rate of the non-technology-specific part of prices of capital goods.[202]

Note that the present model is comparable to the probit type models of David (1969) and Davies (1979). If we consider a specific technology, the ratio of w_t over q_t acts as the critical value (cf. Figure 2.6 at page 48) whereas firms are assumed to be distributed with respect to the level of risk aversion in our model (or with respect to the length of the planning period). Less risk-averse firms will buy a specific technology sooner than more risk-averse firms. If the growth rate of nominal wages exceeds the growth rate of q_t, the critical value in Figure 2.6 will move to the left. Moreover, if the growth rates of w_t and q_t are constant over time, the critical value will move to the left at a constant rate. Then, the shape of the diffusion process is completely determined by the shape of the distribution of firms with respect to the planning period. If the distribution is uniform, the diffusion curve will be linear but if the distribution is bell-shaped, for instance normal, log-normal or Weibull, the diffusion curve will be S-shaped. Previously, we have shown that both the level of risk aversion and the length of the planning period are

201. Note that this implies a constant planning period for each firm, which is not generally true in case the level of risk aversion is constant. Furthermore, a constant θ implies that the profits conditional on i^* are a non-decreasing function of the planning period, so that each firm applies its maximum planning period ($\theta = \bar{\theta}$).

202. Note that this does not imply that total (discounted) wage costs over total capital costs increase in time. This term is equal to γ/μ, as was shown in equation (5.14), and therefore constant over time for given values of μ and γ.

bounded from below. Such lower bounds can be described by both the lognormal and the Weibull distribution. Both distributions 'look alike', at least if the shape parameter of the Weibull function exceeds one. Both are bell-shaped, skewed to the right and both asymptotically reach the horizontal axis. The Weibull function has the advantage that both the probability density function and the cumulative distribution function can be written as an explicit — analytical traceable — function.

Thus, assume that the relative number of firms is distributed with respect to the length of the planning period according to a Weibull distribution defined as:

$$WEI(S^c,S^h,S^l) \;=\; \frac{S^h}{S^c}\left(\frac{\theta - S^l}{S^c}\right)^{S^h-1} e^{-\left(\frac{\theta - S^l}{S^c}\right)^{S^h}} \tag{5.27}$$

in which S^c is the scale parameter, S^h is the shape and S^l the shift parameter. The pdf is bell-shaped for values of the shape parameter $S^h>1$. In the example given below, a WEI(50,2,2) distribution is used. This distribution is shown as a thin solid line in Figure 5.7.

As mentioned above, a distribution with respect to the level of risk aversion should be preferred, but this requires a numerical solution of the corresponding planning period, i.e., solving equation (5.24) for given values of R^*. It is possible, however, to give a visual impression of the distribution with respect to the level of risk aversion, by calculating this distribution conditional on the distribution of the planning period (cf. equation (5.24)). The result is shown in Figure 5.7 as a thick solid line. Note that the (second) horizontal axis is inverted, so that high values of the planning period correspond with low values of risk aversion and vice versa.

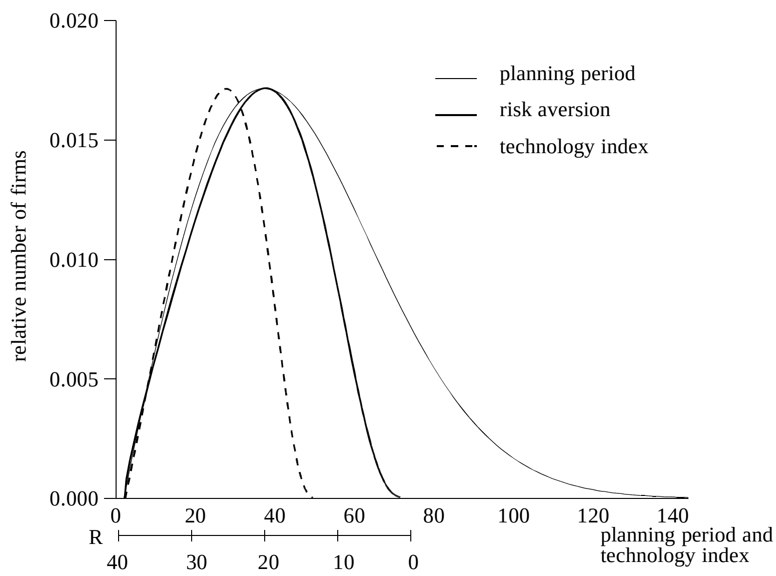

Figure 5.7. The Weibull distribution and the corresponding distribution of risk aversion and of the optimal technologies

Recall the shape of the level of risk aversion as plotted against the length of the planning period, the graph at the top in Figure 5.5. The density of R, given the planning period, decreases as the planning period increases because the level of risk aversion asymptotically tends to zero as the planning period increases. This implies that the original distribution, which is skewed to the right, will be transferred asymmetrically thus resulting in a less skewed distribution. Or, to put it the other way around, if we assume a more or less symmetric distribution of the relative number of firms with respect to the level of risk aversion, the distribution of the number of firms with respect to the length of the planning period will be skewed to the right. Finally, solving the optimal technologies for each value of the planning period, according to equation (5.26), yields a distribution of the relative number of firms with respect to the optimal technologies, which is shown as a dashed line.[203]

To obtain the diffusion pattern for a specific technology, the distribution of optimal technologies has to shift to the right over time. This will be the case if the growth rate of nominal wages exceeds the growth rate of q_t. As the critical value shifts to the left (or as the distribution shifts to the right), the diffusion pattern of an individual technology will be S-shaped due to the bell-shaped pattern of the distribution. For example, examine the diffusion pattern of technology indexed by i=50. This technology is the most advanced technology at time t_0, as shown in Figure 5.7. The diffusion pattern of this technology is shown as a solid line in Figure 5.8 (case I), which is the result of a growth rate of nominal wages of 4% and a constant q_t. The speed of diffusion depends on both the width of the distribution and on the speed at which the distribution moves to the right, in other words, on the speed at which firms choose new technologies. Differentiating equation (5.26) towards t yields $di/dt = (\rho - \nu)\, i_t$, in which ν denotes the growth rate of q_t. This implies that the relative change of technologies is the same for all firms and is constant in time for given values of ρ and ν. The (relative) speed of diffusion depends on the difference between these two growth rates. In absolute terms, in which the speed of diffusion is inversely related to the time span between the first and last adoption, the speed of diffusion increases as the technology index increases.

Both the position and the shape of the diffusion process changes if, for example, the growth rate of wages changes. The dashed diffusion curve is obtained by setting the growth rate of wages equal to 2%, which implies that the most advanced

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203. The values of the parameters are: μ=0.5, γ=0.5, w_0=1, q_0=1, λ_0=1, ψ=1, r=0.06, ρ=0.04 which results in a most advanced technology of i^{**}=50. To calculate the corresponding level of risk aversion we used the values of additional parameters: p_0=10, π=0.04, ω=0.12 and σ^2=0.5. The latter parameters have been chosen in such a way that R is equal to R^{max} if the planning period is at its lower bound (θ=S^l=2).

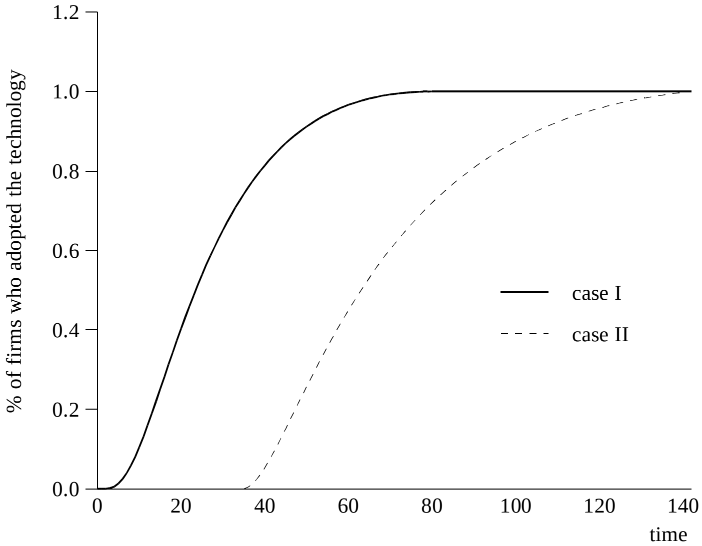

Figure 5.8. An example of the diffusion pattern in the non-learning case

technology at time t_0 is equal to 25. In the first stage, no firm will invest in technology i=50. However, after about 35 periods the least risk-averse firms will start adopting it. But as the difference between the growth rates of w_t and q_t is now smaller than it was in the first case, the technology distribution moves to the right at a slower rate. This implies that the rate of diffusion is slower, leading to an increase in the time span between first and last adoption.

This is exactly what we have seen in the macro-economic model. If the growth rate of nominal wages decreases, which was the case in the Netherlands after the mid-seventies, more firms adopted less advanced technologies and the speed of diffusion slowed down, resulting in a slowdown of the growth rate of the labour productivity. If the growth rate of nominal wages decreases, the present model predicts that firms will buy less advanced technologies and that the speed of diffusion slows down. As a result, the growth rate of labour productivity slows down, which shows that both models are comparable with respect to the relation between the growth rate of nominal wages and the speed of diffusion.

5.4.2 The Learning Case

The previous section has shown that each firm will choose a more advanced technology at successive points in time if the growth rate of wages exceeds the growth rate of q_t. This implies that there is no intra-firm diffusion, which we attributed to the non-learning hypothesis. This section examines the choice of technologies in the case of learning by doing. The choice of the technology depends on the expected profits, which will increase for each technology due to learning effects. Note that we do not consider intertemporal effects, which implies that we assume that firms ignore future investment decisions.

At each point in time, each firm will maximize expected profits. Because no firm has any experience with a technology at the first point in time, the best choice is to invest in the optimal technology (i_t^*) as defined in the previous sections. One period later, the firm will invest in the same technology again if the expected profits exceed the expected profits of the best alternative. The best alternative, however, is to choose another technology with which the firm does not have any experience leading to, again, the optimal technology as we found before (i_{t+1}^*).[204] Investment in the same technology at $t+1$ as at t yields a higher labour productivity, due to the learning effects, but the capital costs remain the same, at least relative to the costs of capital of other technologies. As the labour productivity increases more than proportionally in the first stage of the learning process, it is likely that if the firm invests in the same technology again, the expected profits will exceed the expected profits of the best alternative. This implies that a firm will invest in the same technology for some time. However, because the change of the labour productivity due to learning by doing is assumed to decrease, there will be a point a time at which the best alternative will yield higher expected profits. The firm will then switch to a new technology, and the process starts all over again.

It is not possible to illustrate this phenomenon analytically, but a graphical presentation will clarify the principal mechanism. In Figure 5.9, we plotted the expected profits and the optimal technology index for three different firms, i.e., each with a different length of the planning period. The most risk-averse firm, i.e. the firm with the shortest planning horizon, will choose the least advanced technology. It will continue to invest in the same technology for some time as the expected profits exceed the expected profits of the best alternative which can be obtained by connecting the lowest points of the expected profits in the top figure. The curvature of the expected profits between two points in time at which a new technology is chosen, illustrates the learning effect. The labour productivity increases rapidly in the first stage of the learning process, but decreases afterwards and reaches an upper bound so that, after a while, the expected profits are equal to the profits of a new technology. The parameters have been chosen in such a way that the growth rate of wages exceeds the growth rate of output prices and that the firm with the shortest planning horizon will ultimately face negative expected profits, as a result of which it will stop investing and drop out. Because the other firms are less risk-averse and choose more advanced technologies, the increase in the labour productivity outweighs the increase in real wages. Note that the more risk-averse a firm is, the longer it will wait before it invests in another technology. Thus, more risk-averse firms will not only invest in less advanced technologies, but they will also

204. Note that investing in a technology in which the firms invested some time ago will be less profitable than investing in the technology which has been adopted most recently. This holds as long as the growth rate of wages exceeds the growth rate of the non-technology-specific part of prices of capital goods.

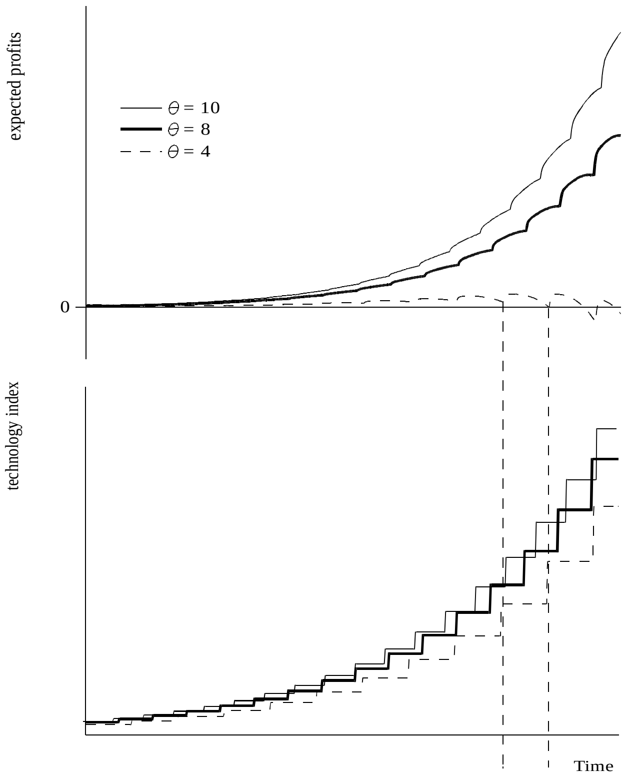

Figure 5.9. Expected profits and the technology index in the case of learning-by-doing

wait longer before they switch to a newer technology. Moreover, it is even possible that a more risk-averse firm will invest in a more advanced technology for some time than the less risk-averse firm as shown in the figure at the bottom.

To conclude, this section shows that the diffusion curve is S-shaped if the distribution of firms with respect to risk aversion is bell-shaped and if the growth rate of nominal wages (ρ) exceeds the growth rate of the non-technology-specific part of capital goods (ν). Moreover, we showed that the speed of diffusion slows down as the difference between ρ and ν becomes smaller. This result is similar to that found in the macro-economic model. Finally, we showed that firms will choose the same technology more than once if learning by doing matters. This does not lead to an S-shaped intra-firm diffusion process, however.

5.5 The Choice of Technologies under Uncertainty: A Quasi-Clay-Clay Model

This section will show that the present model can be viewed as a (modified) version of the putty-clay model. Although each technology is described by a clay-clay production function in the present model, firms may choose different technologies which embody different labour productivities and, given the fixed value of the capital output ratio, different labour intensities. Because of these ex-ante substitution possibilities between clay-clay technologies, we will refer to the present model as a quasi-clay-clay vintage model.

It is obvious that a plot of the labour coefficient against the capital coefficient for different technologies — which leads to a standard production function isoquant such as displayed in Figure 3.2 (page 85) — appears to be a vertical line, i.e., a varying labour coefficient against a fixed capital coefficient. In a standard (ex-ante putty) production function model, firms may choose a labour intensity by moving along the isoquant, in which a profit-maximizing firm chooses the labour intensity for which the marginal rate of substitution is equal to the wage rental ratio. But because in such a (standard) setting, the wage rental ratio determines the slope of the isocosts curve, the optimal labour intensity is determined by the point of tangency between the isocosts curve and the production function.

However, this is not the case in our model. If firms decrease labour intensity (increase labour productivity), they buy a more advanced technology, which is more expensive by assumption. Capital costs are not the same for all technologies, which implies that moving along the (vertical) production function is not neutral with respect to factor costs. Thus, by moving along the isoquant, i.e., choosing other technologies in the present model, one should take changes of capital prices into account. If we correct the amount of investment by an index which denotes differences between the costs of equipment, we would be able to present the choice of technologies in the present model as a counterpart of the choice of the labour intensity in standard putty-clay models.

Define $I^{i'}$ as $i^{\gamma}I$ such that $I^{i'}$ includes price differences between several technologies.[205,206] Define the capital output ratio on this new definition of capital such that:

$$\frac{I'}{X} = \psi i^{\gamma} \quad => \quad i = \left(\frac{I'}{X\psi}\right)^{\frac{1}{\gamma}} \tag{5.28}$$

in which we dropped all technology indices for convenience. If we disregard learning by doing for the moment, the labour productivity is given by:

$$\frac{X}{N} = \lambda_0 i^{\mu} = \lambda_0\left(\frac{I'}{\psi X}\right)^{\frac{\mu}{\gamma}} \tag{5.29}$$

Solving for the amount of output gives:

205. Note that price of equipment is given by $q_t i^{\gamma}$, in which q_t denotes the non-technology-specific part and i^{γ} the technology-specific part of price of equipment. Note furthermore that the amount of investment in a technology with index i is defined as $I^{i}_{\tau,\tau}$. We will drop both time subscripts and the technology index for convenience.

206. The definition of price adjusted amount of investment is related to a Paasche index in which the price of technology $i = 1$ is set to one.

$$X = \lambda_0^{(1-\beta)} \psi^{-\beta} N^{(1-\beta)} (I')^{\beta}$$
$$\text{where } \beta = \frac{\mu}{\mu+\gamma} \qquad (5.30)$$

So we are able to derive a Cobb-Douglas production function equivalent of our model in which output depends on labour and price-adjusted capital. Whereas we used a CES production function model in the macro-economic model, we are using a Cobb-Douglas function in the present model.[207] An important difference between the two models is the way in which technological change enters the model. In the macro-economic model, we used the familiar assumption that the production isoquant shifts towards the origin due to technological change. Furthermore, we assumed ex-ante substitution possibilities, thus enabling firm to choose the optimal labour intensity by moving along a specific isoquant. Although there is no exogenous shift of the production function as such in the present model, firms may change labour intensity by buying different technologies. This process can be described by moving along the isoquant which is given by equation (5.30). Whereas moving along the isoquant is costless in the macro-economic model, this is not the case in the present model. Firms have to pay for more productive capital.

Figure 5.10 illustrates the equivalence between choosing the optimal labour intensity in the macro-model and choosing the optimal technology in the present model. The unit production isoquant is implicitly given by equation (5.30). The slope of the isocosts curve is given by the wage rental ratio, in which the wage costs are equal to the current wage rate times the discounted present value of future changes of the wage rate and of the labour productivity.[208] It is easy to verify that the optimal technology index is equal to i^* if we require the marginal rate of substitution to be equal to the wage rental ratio.[209] The most risk-averse firms will choose the point at which the labour coefficient is equal to $(N/X)^0$ whereas the less risk-averse firms — for which the planning period is infinite in this case — choose the technology for which the labour coefficient is equal to $(N/X)^{**}$. If the distribution of the relative number of firms with respect to the length of the planning period is bell-shaped, cf. Figure 5.7, the distribution of the relative number of firms with respect to the labour coefficient appears to be bell-shaped and skewed to the less labour-productive technologies. An example of such a distribution is also given in the previous part, cf. the top graph of Figure 3.6 on page 102.

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207. Note that the Cobb-Douglas function satisfies the Inada conditions so that all values of the labour productivity between 0 and ∞ can be obtained in the present model.

208. Note that the latter is zero in the non-learning case.

209. Solving the marginal rate of substitution condition gives:

$$\frac{\partial X/\partial N}{\partial X/\partial I'} = \frac{w_t f(\theta)}{q_t} \quad \Rightarrow \quad \frac{(1-\beta)\frac{X}{N}}{\beta \frac{X}{I'}} = \frac{w_t\, f(\theta)}{q_t} \quad \Rightarrow \quad \frac{\lambda_0 i^{\mu}}{(i^{\gamma}\psi)^{-1}} = \frac{\mu w_t f(\theta)}{\gamma q_t} \quad \Rightarrow \quad i = \left(\frac{\mu\, w_t\, f(\theta)}{\gamma q_t \psi \lambda_o}\right)^{\frac{1}{\mu+\gamma}}$$

which is equal to the optimal technology index.

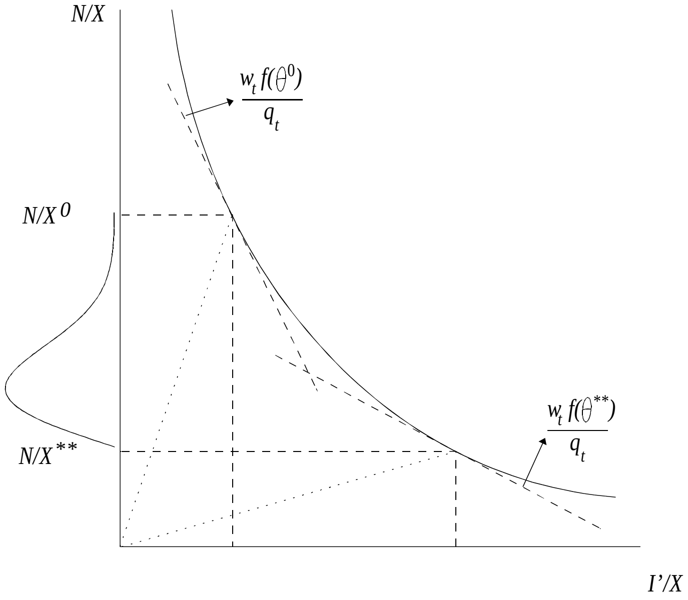

Figure 5.10. The production function equivalent of the quasi-clay-clay diffusion model

Moreover, if we calculate the expression for the optimal labour intensity for the present model, we obtain:

$$\frac{N}{I'} = \left(\frac{w_t\ f(\theta)}{q_t}\right)^{-1} \frac{\gamma}{\mu} \tag{5.31}$$

in which we still use price-adjusted capital. The optimal labour intensity of the macro-economic model is given by (cf. equation (3.19) at page 77):

$$\frac{N}{I} = \left(\frac{w_t\ S_2(\theta)_t}{q_t}\right)^{-\sigma} \left(\frac{A_t}{B_t}\right)^{-\sigma\rho} \tag{5.32}$$

in which:

$$S_2(\theta)_t = \sum_{s=t}^{t+\theta_t-1} \left\{ \left[\frac{(1+\hat{w}_t^e)\ (1+\hat{hi}_t^e)\ (1+\varepsilon_i)}{(1+r_t^e)\ (1+\hat{hn}_t^e)\ (1+\varepsilon_n)} \right]^{s-t} \Omega_{s-t} \right\}$$

Note, first of all, that the elasticity of substitution is equal to one in the present model, which implies that $\sigma = 1$ and $\rho \downarrow 0$ in the CES production function. From that, we obtain a similar expression for the labour intensity in both models. Secondly, note that the function $f(\theta)$ is similar to $S_2(\theta)$. Both denote the discounted present value of future wage costs, relative to the current wage rate. In the present model, we disregard changes in working hours ($\hat{hi} = \hat{hn} = 0$) and depreciation of capital goods ($\Omega = 1$). Moreover, we do not allow for disembodied capital-augmenting technological change ($\varepsilon_i = 0$). In the non-learning case, we also neglect disembodied labour-augmenting technological change ($\varepsilon_n = 0$), so that $f(\theta)$ is equal to

$S_2(\theta)$. In the learning case, the increase of labour productivity can be viewed as disembodied technological change, which is similar to $\varepsilon_n > 0$ in the macro-model. This leads to the conclusion that the optimal labour intensity is comparable in both models.

Returning to the non-adjusted definition of capital goods, the production isoquant is a vertical line and we obtain the same bell-shaped distribution of the labour coefficient, as displayed along the vertical axis in Figure 5.10. Moreover, the labour intensity is now given by:

$$\frac{N}{I} = \left(\frac{w_t\, f(\theta)}{q_t}\right)^{-\beta} \left(\frac{\mu}{\gamma}\right)^{-\beta} \left(\frac{1}{\lambda_0 \psi}\right)^{1-\beta} \tag{5.33}$$

where the term $\beta = \mu\ /(\mu+\gamma)$ can be interpreted as the elasticity of substitution between labour and non-adjusted capital.

The main difference between the present model and the macro-economic model is that we assume that the capital productivity is constant here. However, our estimation results suggest that this term is relatively stable, which means that this difference is not that important from a practical point of view. Another difference between both models is that the putty-clay vintage diffusion model allows for exogenous technological change and for substitution of production factors. In the quasi-clay-clay model we combined both movements, enabling firms to change the labour intensity by buying other technologies. Moreover, we imposed exogenous technological change in the macro-model by assuming that a new technology becomes available each year. In the present model, we assume that there is an infinite range of technologies available and we showed that the most advanced technology is determined by the relative (expected) costs of the factors of production. The least advanced technology is determined by the negative rent condition in both models. Finally, there is a difference between the expected lifetime in the macro-model and the length of the planning period in the present model. The next chapter, which incorporates the present model in a full vintage framework, shows that there are considerable similarities between these two measures.

5.6 Conclusions

In this chapter, we argued that firms will have a multi-period planning horizon which is not necessarily infinite or myopic. Furthermore, we showed that we have to treat investment expenditures as sunk costs. The sunk costs approach does not exclude costs of adjustment, but we did not introduce costs of adjustment for analytical convenience. The number of different technologies is assumed to be infinite, and more advanced technologies embody a higher labour productivity but are also more expensive. Within this framework, we introduced a learning case as well as a non-learning case. In the first case, firms are able to increase productivity as a result of their experience with producing output with the same technology. The labour productivity is constant in the non-learning case. In both models we assumed that capital productivity is constant and independent of the incorporated technology.

Section 5.2 shows that, given the assumption that less risk-averse firms will have a longer planning horizon, these firms will choose a more advanced technology than firms with a shorter planning horizon. Furthermore, we showed that the least advanced technology which is still chosen (i.e., the ‘marginal’ technology) is determined by the non-negative rent condition and that the most advanced technology is finite when the growth rate of nominal wages is smaller than the discount rate. If the growth rate of wages exceeds the discount rate, and if the growth rate of real wages is positive, the most advanced technology is finite if we assume that firms can always choose a shorter planning period if this is expected to increase profits. Since the length of the planning period is limited in this case, the most advanced technology index will be finite.

In section 5.3, we introduced non-technology-specific uncertainty by assuming that future prices are uncertain. Firms are assumed to be utility maximizers, and we which used a utility function with constant absolute risk aversion. We showed that the length of the planning horizon can be determined as a function of the level of risk aversion in the case of price uncertainty and that firms with different levels of risk aversion will choose different technologies, even in the case of non-technology-specific uncertainty. The relation between the length of the planning period and the choice of technologies is exactly the same as that found in section 5.2. Moreover, we showed that the length of the planning period is negatively related to the level of risk aversion, which implies that the length of the planning period is a fairly good approximation of risk aversion. Furthermore, we demonstrated that the utility function is backward-bending if the growth rate of nominal wages is larger than the growth rate of output prices. Utility-maximizing firms will not invest in a technology if it can lower risk and increase expected profits by buying a less advanced technology. This is exactly the same condition as that imposed on the model in section 5.2. Finally, we demonstrated that each firm has to take some risk, even in the case of the least advanced, but still profitable, technology.

The main difference between the models in sections 5.2 and 5.3 is that the distribution with respect to the planning period depends on the distribution with respect to the level of risk aversion *and* on the expected profits. If we examine this relation at one point in time, there is a unique relation between the planning period and the level of risk aversion. However, if we examine the behaviour of one firm over time, the relation between its level of risk aversion and the planning period depends on the expected profits. For example, if profits increase, each firm with a specific level of risk aversion will apply a longer planning period and, consequently, buy more advanced technologies, ceteris paribus. Besides this main difference, we showed that the lower boundary with respect to the least advanced technology is not the same in both models. In general, the least risk-averse firm in the model with risk aversion and uncertainty will buy a more advanced technology than the firm with the shortest planning period in the model in section 5.2.

Section 5.4 investigates the diffusion pattern for both the non-learning and the learning case. The results are based on the model which is described in section 5.2. In the non-learning case, we can obtain S-shaped inter-firm diffusion patterns if the relative number of firms is distributed in a bell-shaped way with respect to the length of the planning period, and if the growth rate of nominal wages exceeds the growth rate of the non-technology-specific part of prices of capital goods. The speed of diffusion depends on both the specified distribution function and on the difference between the growth rate of wages and the growth rate of q_t. In the learning case, it is likely that firms will invest in a technology for more than once, which is the basic property of intra-firm diffusion models. The shape of the intra-firm diffusion curve is linear if the firm buys the same amount of investment goods at each point in time. The next chapter includes the present model in a vintage framework, enabling us to investigate the intra-firm diffusion pattern by some simulation experiments. These experiments will be carried out in chapter 7.

Finally, we showed that the present model can be interpreted as a quasi clay-clay vintage model. Moreover, we examined the similarities and differences between the quasi-clay-clay model and the putty-clay vintage diffusion model which is described in part II. The choice of a technology in the present model is similar to substitution between factors of production in the putty-clay model and we showed that the optimal labour intensity is the same in both models.

This chapter has shown that different firms will choose different technologies, which is a basic property of inter-firm diffusion. The amount of investment is not determined by the model described so far. Furthermore, there is no relation between investment and scrapping decisions. The next chapter presents a full quasi-clay-clay vintage model in which the present choice of technologies is integrated into a general vintage framework. We will use the model from section 5.2, because it enables us to determine the technology index analytically and because it is comparable with the more advanced, but analytically less attractive, model of risk aversion and uncertainty.

Appendix 5A. Equivalence of Sunk Costs and Debt Financed Costs of Capital

This appendix shows that the sunk costs approach is equivalent to the situation in which a firm finances its investment costs by debts.[210] We assume that (i) debt is incurred for the length of the planning period; (ii) each year a fixed proportion of the outstanding debt is repaid, in which the proportion is equal to the inverse of the length of the planning period; (iii) interest payments are equal to the outstanding debt times the interest rate, in which the interest rate is assumed to be equal to the initial interest rate; (iv) the financial consequences are independent of the usage of the capital good, and (v) the value of equipment is zero at the end of the planning period.

This implies that, if the debt is incurred at time τ, the costs of capital in year t are equal to:

$$C_{\tau,t} = q_\tau^i \left\{ r_\tau \left(1 - \frac{t-\tau}{\theta}\right) + \frac{1}{\theta} \right\} \tag{5A.1}$$

in which the first term between brackets denotes the interest payments of the outstanding debt, which decreases linearly in time. The second term between brackets denotes debt repayments. The present value of total cost of capital per unit of output during the whole planning period is equal to:

$$PVTC_{\tau,\theta} = q_\tau^i \int_0^\theta \left\{ r_\tau \left(1 - \frac{s}{\theta}\right) + \frac{1}{\theta} \right\} e^{-r_\tau s}\, ds \tag{5A.2}$$

in which we assume that the discount rate is equal to the interest rate. Solving the integral term gives:

$$\begin{aligned} & \int_0^\theta r e^{-rs} ds \quad - \int_0^\theta \frac{r}{\theta} s e^{-rs} ds \quad + \int_0^\theta \frac{1}{\theta} e^{-rs} ds \\ = & \left(1 - e^{-r\theta}\right) \quad - \left(\frac{1}{\theta r} - e^{-r\theta} - \frac{1}{\theta r} e^{-r\theta}\right) \quad + \left(\frac{1}{\theta r}\left[1 - e^{-\theta r}\right]\right) \\ = & \quad 1 \end{aligned} \tag{5A.3}$$

which implies that both internal and external financing yield the same present value of total rents. This also implies that the annual average discounted costs of capital are equal to $\frac{1}{\theta} q_\tau^i$ so that indeed, the annual costs of capital decrease as the planning period increases, ceteris paribus.

Appendix 5B. Properties of the Present Value of Quasi-Rents

In this appendix, we will derive some properties of the present value of quasi-rents. First, we will present the non-learning case, followed by some remarks for the case in which we allow for learning as defined in the main text. The present value of quasi-rents, PVQR for short, for the general case is defined as:[211]

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210. Cf. van Zon (1989) for a similar approach.

211. We still assume that no firm has experience with a technology, i.e., $\tau = t_0$.

$$PVQR^{i}_{\tau,\tau} = p_\tau \int_\tau^{\tau+\theta} e^{(\pi-r)(t-\tau)}dt - \frac{w_\tau \beta}{\lambda_0 i^\mu}\int_\tau^{\tau+\theta} e^{(\rho-r)(t-\tau)}dt - \frac{w_\tau(1-\beta)}{\lambda_0 i^\mu}\int_\tau^{\tau+\theta} e^{(\rho+\ln(\alpha)-r)(t-\tau)}dt$$

$$= p_\tau \cdot \frac{e^{(\pi-r)\theta}-1}{(\pi-r)} - \frac{w_\tau \beta}{\lambda_0 i^\mu}\cdot\frac{e^{(\rho-r)\theta}-1}{(\rho-r)} - \frac{w_\tau(1-\beta)}{\lambda_0 i^\mu}\cdot\frac{e^{(\rho+\ln(\alpha)-r)\theta}-1}{(\rho+\ln(\alpha)-r)} \tag{5B.1}$$

Thus, the PVQR with a planning period of zero years is equal to zero (no production, so no returns nor variable costs).[212]
The non-learning case can be obtained by setting β equal to 1. In this case, the last term at the right-hand side vanishes and the derivative of the PVQR with respect to the planning period is equal to the output price at the margin minus the effective wage rate:[213]

$$\frac{\partial PVQR}{\partial\theta} = p_\tau e^{(\pi-r)\theta} - \frac{w_\tau}{\lambda_0 i^\mu}e^{(\rho-r)\theta} = e^{(\pi-r)\theta}\left(p_\tau - \frac{w_\tau}{\lambda_0 i^\mu}e^{\tilde{\rho}\theta}\right) \quad \text{with} \quad \tilde{\rho} = \rho - \pi \tag{5B.2}$$

With a planning period of zero years, the first derivative is equal to the price of output minus the total wage sum, both per unit of output, denoted as the gross margin for short. This term will be negative for an older technology, and positive for a more advanced one. For a positive planning period, the sign of equation (5B.2) depends furthermore on the expected growth rate of output prices (π), the expected growth rate of nominal wages (ρ) and on the expected discount rate (r).

First, we assume that both the rate of inflation as well as the growth rate of nominal wages are positive but smaller than the discount rate. In this case, $\partial PVQR/\partial\theta$ will go to zero as θ goes to infinity, so the PVQR will reach some upper or lower bound asymptotically. Within this case, we can distinguish three sub-cases: the growth rate of real wages is negative ($\tilde{\rho}<0$), zero ($\tilde{\rho}=0$) or positive ($\tilde{\rho}>0$). If the growth rate of real wages is negative, the sign of both the PVQR and the first derivative depends on the sign of the gross margin. If this last term is positive, equation (5B.2) is positive for θ equal to zero, the PVQR as well as $\partial PVQR/\partial\theta$ will be positive for all values of θ. If this term is negative, for instance for a less advanced technology, $\partial PVQR/\partial\theta$ and thus PVQR, will be negative for small values of θ. As the growth rate of real wages is negative, the $\partial PVQR/\partial\theta$ will change sign for some value of θ. The PVQR can be positive or negative in this last case. This situation is displayed in Figure 5B.1.(a).

212. From this it follows immediately that the present value of the rent will be negative for a short planning period if prices of capital goods are positive.

213. We will drop the time subscript as we will discuss the PVQR at one point in time.

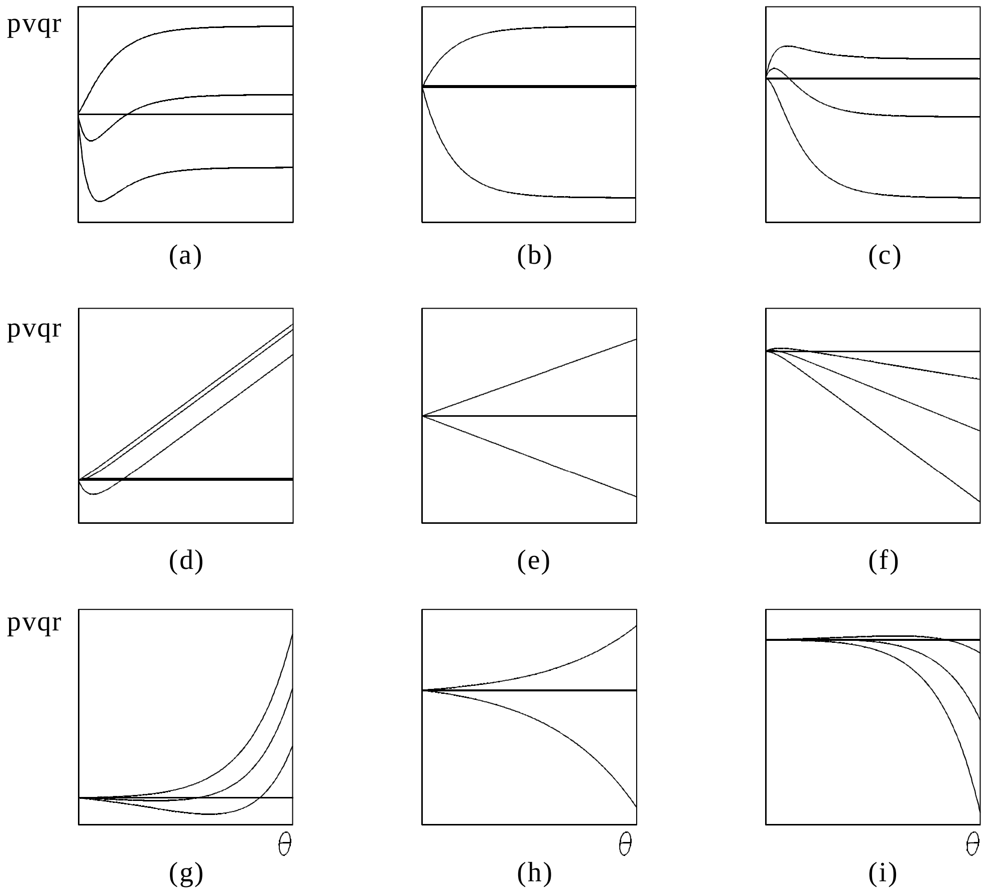

Figure 5B.1. The shape of the present value of quasi-rents with different values for the parameters.[214]

The sign of $\partial PVQR/\partial\theta$ does not change if the growth of real wages is zero. Thus, PVQR stays positive of negative, depending on the sign of the gross margin (Figure 5B.1.(b)). If the growth rate of real wages is positive, we find the opposite of the first sub-case as is shown in Figure 5B.1.(c).

Next, we will briefly survey the other possible cases. If the real wage rate is negative, but the growth rate of output prices is equal to the discount rate, we find that the $\partial PVQR/\partial\theta$ will tend to a constant term if θ goes to infinity (Figure 5B.1.(d)). If both π and ρ are equal to r, $\partial PVQR/\partial\theta$ will be constant for all values of θ (Figure 5B.1.(e)) and if the real wage rate is positive but the growth of nominal wages is equal to the discount rate, we find the opposite of Figure 5B.1.(d) as is shown in Figure 5B.1.(f).

The last class of sub-cases we will discuss in this non-learning case is characterized by growth rates which are larger than the discount rate. If this is the case, $\partial PVQR/\partial\theta$ will go to plus or minus infinity as θ becomes large. If the growth rate of real wages is negative, but $\pi>r$, the PVQR will always go to infinity (Figure 5B.1.(g)). If $\pi=\rho$, the PVQR will go to plus infinity if the initial effective wages are positive, but will go to minus infinity if the

214. The relative values of the parameters are:

(a) $\pi>\rho \wedge \pi<r$ (b) $\pi=\rho \wedge \pi<r$ (c) $\pi<\rho \wedge \rho<r$

(d) $\pi>\rho \wedge \pi=r$ (e) $\pi=\rho \wedge \pi=r$ (f) $\pi<\rho \wedge \rho=r$

(g) $\pi>\rho \wedge \pi>r$ (h) $\pi=\rho \wedge \pi>r$ (i) $\pi<\rho \wedge \rho>r$

For all graphs holds that the upper line denotes an advanced technology, the line in the middle represents a medium technology and the lower line denotes a less advanced technology.

initial effective wage rate is negative (Figure 5B.1.(h)). If the growth rate of real wages is positive, the PVQR will always go to minus infinity as θ becomes large (Figure 5B.1.(i)).
In the learning case, we find for the first derivative of PVQR:

$$\frac{\partial PVQR}{\partial\theta} = e^{(\pi-r)\theta}\left(p_\tau - \frac{w_\tau e^{\hat{\rho}\theta}}{\lambda_0 i^\mu}(\beta+(1-\beta)\alpha^\theta)\right) \tag{5B.3}$$

The last term $(\beta+(1-\beta)\alpha^\theta)$ is equal to zero, if the planning period is zero (no learning occurred yet) and will tend to β as θ goes to infinity (everything what could be learned has been learned). So the value of $\partial PVQR/\partial\theta$ is the same in both the learning and the non-learning case if θ is equal to zero. As the planning period becomes longer, the last term becomes smaller, and the derivative becomes larger, but may still be positive or negative or change sign as discussed in the non-learning case. If we assume that the rate of inflation as well as the growth rate of nominal wages are smaller than the discount rate (cases (a), (b) and (c) in the non-learning case), the PVQR will reach some asymptote which is defined by:

$$\lim_{\theta\to\infty} PVQR = \frac{-p_\tau}{(\pi-r)} + \frac{w_\tau}{\lambda_0 i^\mu}\left[\frac{\beta}{(\rho-r)} + \frac{(1-\beta)}{(\rho+\ln(\alpha)-r)}\right] \tag{5B.4}$$

The asymptote depends negatively on π, p_τ, λ_0, μ, i and α and positively on r, w_τ and β, which are all intuitively clear, except maybe for α. This latter parameter describes the speed of learning. The faster learning takes place, the sooner the labour productivity will reach its upper value, and so will the quasi-rents. As the PVQR is the integral of all quasi-rents, it will be larger as the speed of learning increases.

The shape of the functions in the learning case is not fundamentally different from the non-learning case. With regard to the relative size of the parameters, we will assume throughout this chapter that both the growth rate of output prices and the growth rate of nominal wages is below the discount rate. In this case, the present values of quasi-rents, and thus the present value of rents, will asymptotically reach some boundary as the planning horizon becomes infinitely long. These cases are shown in Figures (a), (b) and (c).

Appendix 5C. Expected Profits, the Choice of Technologies and the Planning Period

Above, we stated that the less advanced technology is determined by the non-negative rent condition. Here, we will elaborate this boundary. The sign of the expected profits therefore depends on the sign of the first derivative for small values of the planning period. This derivative is equal to:

$$\frac{\partial PV}{\partial\theta} = p_\tau g_\theta - \frac{\gamma}{\mu+\gamma} c_\tau\, f(\theta)^{\frac{-\mu}{\mu+\gamma}} f_\theta \left(1+\frac{\mu}{\gamma}\right) \tag{5C.1}$$

in which c_τ is defined in equation (5.14)first term denotes the marginal change, due to a change in the length of the planning period, of the discounted marginal returns while the marginal change of the discounted marginal costs are described by the second term. Both terms are positive for all values of θ. The function g_θ is equal to one if the planning period is near to zero and it will go to zero for a long planning period if the rate of inflation is smaller than the discount rate. The same holds true for the function f_θ if the growth rate of nominal wages is smaller than the discount rate.[215] If θ is near to zero, the function f(θ) is also near to zero, which leads to a negative derivative for small values of the planning

215. Note that this is true for both the learning and the non-learning case.

period.[216] Thus, the present value of expected rents is negative for small values of the planning period. The analysis of equation (5.14) becomes more complicated as the planning period increases. First, we will analyze the sign and size of the derivative, and after that, we will return to the present value of expected rents.

The sign as well as the size of the derivative depends on the rate of inflation, the growth rate of nominal wages and on the discount rate. As before, we will assume that the rate of inflation and the growth rate of nominal wages are smaller than the discount rate. As the planning period increases from zero onwards, the function f_θ starts at one and will decrease until it becomes asymptotically zero. The function $f(\theta)$, the variable part of the total wage sum, is the integral of f_θ. Therefore, it will be smaller than f_θ if the planning period is somewhere between zero and one, but it will be larger than f_θ for a planning period larger than one. As the function g_θ has the same properties as f_θ, the marginal changes of the discounted marginal rents will be negative for small values of the planning period, but it will become positive afterwards. As the planning period goes to infinity, the functions g_θ as well as f_θ will go to zero. This follows from the assumption that the discount rate exceeds the rate of inflation and the growth rate of nominal wages. An increase of the planning period will add less and less to both the returns and the costs, as the planning period increases. Note that if the rate of inflation exceeds the discount rate, the marginal returns will go to infinity as the planning period increases. The same holds true for the marginal costs if the growth rate of nominal wages exceeds the discount rate. As $f(\theta)$ will asymptotically reach some positive value, the marginal discounted rents will eventually go to zero. So, in the case where both the rate of inflation and the growth rate of nominal wages is smaller than the discount rate, the marginal changes of the expected rent will be negative for small values of the planning period; it will become positive afterwards but will go to zero as the planning period goes to infinity. This implies that the present value of rents will be negative for small values of the planning period but reaches some minimum. After that, it will increase until it asymptotically reaches some upper boundary. Whether this upper boundary is positive or negative cannot be determined a priori.[217]

To clarify this point, Figure 5C.1 shows the present value of expected rents for some combinations of parameters. The two Figures (A.1) and (B.1), at the top, display the present value of rents for the optimal technology in function of the length of the planning period. The expected growth rate of *real* wages is negative in Figures (A.1) to (A.3), whereas it is assumed to be positive in Figures (B.1) to (B.3). The corresponding technology indices are shown in Figures (A.2) and (B.2). Finally, a combination of both graphs yields the (optimal) technology against the expected profits, which is displayed at the bottom (A.3 and B.3). The line labelled (a) is our base projection.[218] The technology index, line (a) in A.2, starts from zero and asymptotically reaches an upper boundary as the growth rate of nominal wages is equal to the discount rate. The boundary is the most advanced technology firms

216. This is not true in two distinct cases. First if the price of output relative to the effective wage rate is infinite and second if μ over γ is infinite. This latter case describes the situation in which the labour productivity of different technologies is about the same, while there are huge differences in the prices of capital goods. Both cases seem to be unlikely to happen.

217. That the expected profits should have a minimum follows also from a brief analysis of equation (5.16). Setting this equation to zero and collecting all terms which depend on θ at the left-hand side, it can be shown that if the rate of inflation exceeds, or is equal to, the growth rate of nominal wages and if the growth rate of nominal wages is less than the discount rate, the term at the left-hand side will start from zero and will increase monotonically towards infinity. The term at the right-hand side is some finite number. Thus, equation (5.16) is zero for a unique value of the planning period. Therefore the expected profits have a unique minimum.

218. The values of the parameters for the base projection are: π=0, ρ=0, μ=0.5, γ=0.5, κ=1, λ_0=1, α=0.9, β=0.5, p_τ=1, w_τ=2, q_τ=2 and r=0.05.

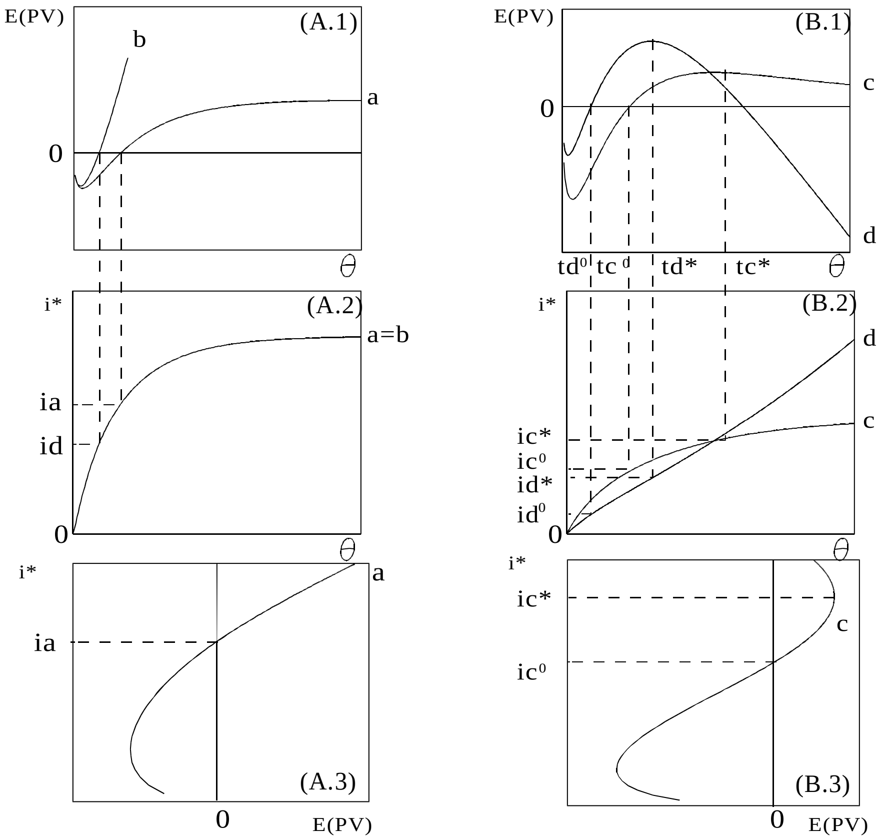

Figure 5C.1. The present value of expected rents and the (optimal) technology index for several combinations of parameters

will invest in. The present value of discounted rents starts below zero, reaches a minimum planning period. A plot of the expected profits against the technology index gives a similar result.[219]

Now, consider a change in the growth rates of both prices and wages. If the growth rate of output prices increases but remains below the discount rate, the expected profits will increase but will still asymptotically reach some upper value as the planning period increases. Because ρ and r have not changed, the optimal technology remains the same. However, if the rate of inflation is above the discount rate, the expected profits will increase exponentially as the planning period increases. This is shown by curve (b). The technology index remains at the curve (a). Some firms with a short planning period which did not invest in a technology before the shift in output prices, case a, will invest now, due to an overall increase of profits.[220]

Finally, consider a change in the growth rate of nominal wages. This will cause a change of the optimal technologies chosen. The technologies will reach an upper boundary as long as the growth rate of nominal wages is below the discount rate, eg. curve (c). If the growth rate of nominal wages is equal to or below the rate of inflation, the expected profits will increase as the planning period increases (curve a). But if the growth rate of nominal wages is above the rate of inflation (curves c and d), the expected profits will decline first

219. This is not surprising as the technology index increases monotonically in Figure (A.2).

220. Note that this is the case because we assume a fixed planning period for each firm. In the next section, we will show that for a given level of risk aversion, the planning period will increase as the expected profits increase, ceteris paribus.

until they reach a (local) minimum, will grow thereafter, but will reach a maximum and will then decrease again. The determination of the optimal technology depends now on the interpretation of the planning period as a proxy for the level of risk aversion. If we assume that the planning period is given for each firm, the optimal technologies are given by curves c and d in Figure 5C.1.

Appendix 5D. Deriving the Variance of the Present Value of Future Rents

If the output prices are stochastic ($\tilde{p}_t \sim N(p_t, \sigma_t^2)$), the variance of the present value of rents is given by:

$$VAR(PV) = E(\tilde{PV}^2) - E^2(\tilde{PV})$$

$$= E\left[(\int \tilde{p}e^{-rt}dt)^2 + (\int \frac{w}{\lambda^i}e^{-rt}dt)^2 + (q^i\kappa)^2 - 2\int \tilde{p}e^{-rt}dt \int \frac{w}{\lambda^i}e^{-rt}dt - 2q^i\kappa \int \tilde{p}e^{-rt}dt + 2q^i\kappa \int \frac{w}{\lambda^i}e^{-rt}dt\right] - \qquad (5D.1)$$
$$\left[(\int pe^{-rt}dt)^2 + (\int \frac{w}{\lambda^i}e^{-rt}dt)^2 + (q^i\kappa)^2 - 2\int pe^{-rt}dt \int \frac{w}{\lambda^i}e^{-rt}dt - 2q^i\kappa \int pe^{-rt}dt - 2q^i\kappa \int \frac{w}{\lambda^i}e^{-rt}dt\right]$$

In which we dropped time subscripts for convenience. The wage rate as well as the costs of capital are known by the firm and not stochastic. Because the expected value of an integral is equal to the integral of the expected value, the above function simplifies to:

$$VAR(PV) = E\left[(\int \tilde{p}e^{-rt}dt)^2\right] - (\int pe^{-rt}dt)^2 \qquad (5D.2)$$

We assumed that the expected values of prices are stochastically independent of each other, i.e., $E(\tilde{p}_t \cdot \tilde{p}_s) = E(\tilde{p}_t) \cdot E(\tilde{p}_s) = p_t \cdot p_s$ for any t ≠ s, which gives:

$$\begin{aligned} VAR(PV) &= \int E(\tilde{p}^2)e^{-2rt}dt - \int E^2(\tilde{p})e^{-2rt}dt \\ &= \int \left[E(\tilde{p}^2) - E^2(\tilde{p})\right]e^{-2rt}dt \end{aligned} \qquad (5D.3)$$

Thus, the variance of the present value of rents is equal to:

$$VAR(PV) = \int e^{-2rt}\sigma_t^2 dt \qquad (5D.4)$$

Which corresponds with equation (5.19) in the main text.

If the wages are stochastic ($\tilde{w}_t \sim N(w_t, \sigma_t^2)$), it is easy to verify that the variance of expected profits is equal to:

$$VAR(PV) = \int \frac{e^{-2rt}}{(\lambda^i)^2}\sigma_t^2 dt \qquad (5D.5)$$

Whereas the variance is independent of the technology index in the case in which prices are stochastic, it depends on labour productivity, and therefore on the technology index if wages are stochastic. Although this is an interesting case, because firms are able to control the variance by choosing a specific technology, this specification leads to severe analytical problems.

Appendix 5E. Second-Order Conditions

In this appendix, we will first derive the conditions for the optimization problem defined in section 5.3. Thereafter, we will show that the maximum value of the level of risk aversion occurs at the same point at which the determinant of the Hessian is zero. Finally, we will show that the point of tangency of i^* and i^+ (lines III and a in Figure 5.6) coincides with R^{max} and $|H|=0$.
The determinant of the Hessian is defined as:

$$\frac{\partial^2 J}{\partial i^2}\frac{\partial^2 J}{\partial \theta^2} - \left(\frac{\partial^2 J}{\partial i \partial \theta}\right)^2 > 0 \tag{5E.1}$$

which has to be positive. The first term is equal to:

$$\frac{\partial^2 J}{\partial i^2} = -\frac{\mu(\mu+1)w_\tau f(\theta) i^{-\mu-2}}{\lambda_0} - \gamma(\gamma-1)q_\tau i^{\gamma-2}\psi \tag{5E.2}$$

Substitution of the optimal value of i gives:

$$\frac{\partial^2 J}{\partial i^2} = \left(\frac{w_\tau \mu f(\theta)}{q_\tau \gamma \psi \lambda_0}\right)^{\frac{\gamma-2}{\mu+\gamma}} (q_\tau \gamma \psi)(-\mu-\gamma) < 0 \tag{5E.3}$$

which is negative for all values of the planning period. Note that this is also the second-order condition of the optimization problem as defined in section 5.2, i.e., the choice of the technology given the length of the planning period. The second term of the determinant of the Hessian is equal to:

$$\frac{\partial^2 J}{\partial \theta^2} = p_\tau g_{\theta\theta} - \frac{w_\tau f_{\theta\theta}}{\lambda_0 i^\mu} - \frac{R}{2}\sigma^2 h_{\theta\theta}$$

$$\text{with} \quad h(\theta) = \int_0^\theta e^{(\omega-2r)t}dt \quad \text{so} \quad h_{\theta\theta} = e^{(\omega-2r)\theta}(\omega-2r) \tag{5E.4}$$

which is not necessarily negative for each value of risk aversion. In some specific cases, we can derive the necessary conditions for this second derivative to be negative. For example, for the non-learning case, substitution of the optimal technology index and the level of risk aversion yields:

$$\frac{\partial^2 J}{\partial \theta^2} = p_\tau g_\theta(\pi-\omega+r) - c_\tau f_\theta f(\theta)^{\frac{-\mu}{\mu+\gamma}}(\rho-\omega+r)$$

$$\text{with} \quad c_\tau = \left(\frac{w_\tau}{\lambda_0}\right)^{\frac{\gamma}{\mu+\gamma}} \left(\frac{\mu}{q_\tau \gamma \psi}\right)^{\frac{-\mu}{\mu+\gamma}} > 0 \tag{5E.5}$$

If we assume that $\pi=\rho$, this equation becomes:

$$\frac{\partial^2 J}{\partial \theta^2} = (\pi-\omega+r)\left(p_\tau g_\theta - c_\tau f_\theta f(\theta)^{\frac{-\mu}{\mu+\gamma}}\right) \tag{5E.6}$$

The term between brackets is equal to the nominator of the expression for the optimal level of risk aversion, equation (5.24), which has to be positive. So, for the second derivative to be negative in this case, it is necessary that the variance inflation parameter exceeds the rate of inflation plus the discount rate. Note that this does not exclude the situation in which the variance inflation parameter is less than twice the discount rate. This implies that the variance of the expected profits may asymptotically reach an upper boundary if the rate of inflation is below the discount rate. However, we cannot determine the exact conditions for the second derivative with respect to the planning period to be negative. But we know that these conditions have to hold if the second-order condition of the total optimization procedure holds. We will continue with this latter condition now.

First, we will determine the point at which the determinant of the Hessian is zero and we will show that this point coincides with the point at which the level of risk aversion is at its maximum level. Then, we will show that the second-order condition holds if the first derivative of the level of risk aversion with respect to the planning period is negative. That is, for values of the planning period longer than the point indicated by θ^{min} in Figure 5.5. The determinant of the Hessian is zero if:

$$\left(-\frac{\mu(\mu+1)w_\tau\ f(\theta)i^{-\mu-2}}{\lambda_0} - \gamma(\gamma-1)q_\tau i^{\gamma-2}\psi\right)\left(p_\tau g_{\theta,\theta} - \frac{w_\tau\ f_{\theta,\theta}}{\lambda_0 i^{\mu}} - R\tfrac{1}{2}\sigma^2\ h_{\theta,\theta}\right) - \left(\frac{w_\tau \mu\ f_\theta}{\lambda_0 i^{\mu}}\right)^2 = 0 \tag{5E.7}$$

Substituting equation (5.11) for i, and solving for R gives:

$$R_{|H|=0} = \frac{\dfrac{(c\mu)^2}{c\mu f(\theta)(\mu+\gamma)} - cf_{\theta,\theta} + p_\tau g_{\theta,\theta}}{\tfrac{1}{2}\sigma^2 h_{\theta,\theta}} \tag{5E.8}$$

or:

$$R_{|H|=0} = \frac{p_\tau g_{\theta,\theta} - c\left(f_{\theta,\theta} - \dfrac{\mu}{\mu+\gamma}\dfrac{(f_\theta)^2}{f(\theta)}\right)}{\tfrac{1}{2}\sigma^2 h_{\theta,\theta}} \tag{5E.9}$$

Thus, the determinant of the Hessian is equal to zero if the above equation holds. The point at which the level of risk aversion is at its maximum level is given by:

$$\frac{\partial R}{\partial\theta} = \frac{p_\tau g_{\theta,\theta} - c\left(f_{\theta,\theta} - \left(\dfrac{\mu}{\mu+\gamma}\dfrac{(f_\theta)^2}{f(\theta)}\right)\right)}{\tfrac{1}{2}\sigma^2 h_\theta} - \frac{h_{\theta,\theta}}{h_\theta}R = 0 \tag{5E.10}$$

Solving this equation for R yields the same solution as that found in equation (5E.9). Therefore, the determinant of the Hessian is zero if the level of risk aversion is at its maximum level.

It is easy to verify that the determinant of the Hessian is positive if:

$$R^* \gtrless R_{|H|=0} \quad \text{if} \quad (\omega-2r) \gtrless 0 \tag{5E.11}$$

holds. We will now prove that this is always true if the derivative of the level of risk aversion with respect to the planning period is negative. This derivative is equal to:

$$\frac{\partial R^*}{\partial\theta} = \frac{pg_{\theta\theta} - cf(\theta)^{\frac{-\mu}{\mu+\gamma}}\left(f_{\theta\theta} - \frac{\mu}{\mu+\gamma}\frac{(f_\theta)^2}{f(\theta)}\right)}{\frac{1}{2}\sigma^2 h_\theta} - \frac{(\omega-2r)(pg_\theta - cf(\theta)^{\frac{\mu}{\mu+\gamma}}f_\theta)}{\frac{1}{2}\sigma^2 h_\theta} \tag{5E.12}$$

This term is negative if the first term at the RHS is smaller than the second term at the RHS. The first term at the RHS is equal to the solution of $R_{|H|}$ (equation (5E.9)) except for the change of $h_{\theta\theta}$ into h_θ in the denominator. The second term at the RHS is equal to the optimal level of risk aversion R^*, equation (5.24), except for the addition of the multiplicative term (ω-2r). But note that $h_{\theta\theta} = h_\theta(\omega - 2r)$. Therefore:

$$R^* > R_{|H|=0} \quad \text{if } \omega - 2r > 0$$

and

$$R^* < R_{|H|=0} \quad \text{if } \omega - 2r < 0$$

which we had to prove.

Finally, we will show that $\frac{\partial i^*}{\partial\theta} = \frac{\partial i^+}{\partial\theta}$ if $R = R_{|H|=0}$, i.e., that curve a is tangent to curve III in Figure 5.6 if $|H| = 0$.

$$\frac{\partial i^*}{\partial\theta} = \frac{i^*}{\mu+\gamma}\frac{f_\theta}{f(\theta)} \tag{5E.14}$$

and

$$\frac{\partial i^+}{\partial\theta} = \frac{i^+}{\mu}\left(\frac{f_{\theta,\theta}}{f_\theta} - \frac{p_\tau g_{\theta,\theta} - \frac{1}{2}R\sigma^2 h_{\theta,\theta}}{p_\tau g_\theta - \frac{1}{2}R\sigma^2 h_\theta}\right) \tag{5E.15}$$

Equating both and using the fact that $i^* = i^+$ gives:

$$\left(p_\tau g_\theta - \frac{1}{2}R\sigma^2 h_\theta\right)\left(\frac{f_{\theta,\theta}}{f_\theta} - \frac{\mu}{\mu+\gamma}\frac{f_\theta}{f(\theta)}\right) = p_\tau g_{\theta,\theta} - \frac{1}{2}R\sigma^2 h_{\theta,\theta} \tag{5E.16}$$

substitution of equation (5.24) for R at the left-hand side gives equation (5E.9). Therefore, the point of tangency of i^* and i^+ coincides with the point at which the solution becomes feasible, i.e., the point at which the second-order condition holds, in other words, the point of tangency between lines a and III in Figure 5.6 corresponds with $|H| = 0$.

6 A Quasi-Clay-Clay Vintage Model

In the previous chapter, we developed a model in which more risk-averse firms invest in less advanced technologies. The model is based on the assumption that capital costs are sunk costs and that firms with a longer planning period are able to deduct the capital costs over a longer period and thus achieve a decline of the average unit costs. This implies that they will invest in a more capital-intensive, or labour-extensive, technology which is more advanced by assumption. The other side of the coin is that a longer planning period implies more risk. We showed that the main conclusions are consistent with the stochastic model in which output prices are uncertain. The model described so far determines nothing but the choice of technologies. The amount of investment and the relation between investment and scrapping is ignored.

This chapter extends the basic model in which the length of the planning period is taken as a measure of risk aversion, i.e., we will extend the model presented in section 5.2. That model is incorporated in a vintage framework in order to determine the amount of investment, the role of scrapping of equipment and the amount of output produced with each technology. Furthermore, the relation between scrapping and investments will emphasize the interdependence between technologies. Moreover, up to now it has been assumed that output is homogeneous and that output prices are given, i.e., the output market is assumed to be competitive. This is rather a peculiar assumption if firms differ from one another in the sense that firms with a different level of risk aversion will invest in different technologies, leading to a differences in the cost structure between firms. Additionally, there may also be differences between firms with respect to customer relations, service, geographical distribution etc., as a result of which products are not homogeneous. This chapter relaxes the (perfect) competitiveness assumption and assumes monopolistic competition as a more realistic description of the market structure, thus thinking of firms as being price setters and quantity takers.

In section 2.2.3 (page 33), we showed that the Malcomson scrapping rule — which describes active profit maximizing behaviour — coincides with negative quasi-rent scrapping behaviour in a competitive output market. But because we now assume that the output market is characterized by monopolistic competition, we have to apply the Malcomson scrapping rule explicitly as we will show below. This implies that scrapping behaviour is determined by the marginal total costs of the newest vintage, as a result of which the amount of scrapping is influenced by the choice of the technology. Although there exists a relation between scrapping and investments in a vintage model in which old equipment is scrapped due to negative quasi-rents, the Malcomson scrapping condition will emphasize the interdependence between old and new technologies to a larger extent.[221] Before we turn to the description of the model, we will review the role of the expected lifetime, the planning period and risk aversion.

6.1 Expected Lifetime, the Planning Horizon and Risk Aversion

In the macro-economic model, we required the planning horizon of firms to be equal to the expected lifetime of equipment. Furthermore, since we assumed a competitive output market, we can apply the quasi-rent scrapping condition. Consequently, the expected lifetime is determined by the date at which the quasi-rents of the equipment in consideration become negative. The expected date of scrapping depends on the ex-post labour productivity and on future real wage rates. The ex-post labour productivity is determined by the ex-ante level of labour productivity — which is determined by the embodied technology and by the optimal labour-intensity — and by the ex-post growth rate of the labour productivity (disembodied technological change). If the expected lifetime becomes large in the macro-model, we imposed an upper limit on the length of the planning period.

In the previous chapter, we introduced risk and uncertainty into our model. This implies that firms which employ a longer planning horizon, consider production and therefore expected quasi-rents over a longer period. Although they will face higher expected profits, at least as long as future quasi-rents remain positive, they will take more risk, ceteris paribus. Future quasi-rents will continue to be positive if the growth rate of output prices is equal to or higher than the growth rate of nominal wages, and we showed that there exists an upper limit of the optimal technology index, but no upper limit of the planning period in this case.

However, if the growth rate of wages exceeds the growth rate of output prices, there will be a point in the future at which the quasi-rents of the current equipment

221. The amount of scrapping determines the capacity gap and thus the amount of investments in the case of negative quasi-rent scrapping. In the case of Malcomson scrapping, the choice of the technology — which is embodied in the newest vintage — determines the amount of scrapping. This determines the capacity gap and the amount of investment.

becomes zero or negative. Similar to the macro-model, the ex-post labour productivity is determined by ex-ante choice of the technology and by ex-post changes due to learning by doing. Because the labour productivity ex-post is fixed — in the non-learning case —, or may increase for some time but asymptotically reaches an upper limit — in the learning case — there will always be a point in the future at which the quasi-rents become zero if $\rho > \pi$. This implies that the marginal expected profits become zero, and we showed that no firm will apply a longer planning period if this will decrease expected profits. Notice that this is exactly the same condition as that is used in the macro-model to determine the expected lifetime.

The main difference between the two models is that the macro-model does not include uncertainty and risk aversion, which implies that a longer planning horizon does not have a negative impact on utility, ceteris paribus. The previous chapter has shown that if we include the concepts of uncertainty and risk aversion, firms will limit their planning horizon. Moreover, we showed that firms will never increase the planning horizon if the expected quasi-rents at that point in the future become zero. Because the marginal expected profits are zero at that point, the utility function is backward bending. Again, this is the same condition as that employed in the macro-model.

In Figure 6.1, we compare both the macro-economic model and the quasi-clay-clay model with respect to the length of the planning horizon and the expected lifetime. The expected lifetime in the case of Malcomson scrapping is discussed below. In case *(i)*, the expected lifetime (EL^q) is larger than the maximum length of the planning period ($\bar{\theta}$). In the macro-model, we imposed an upper limit upon the length of the planning period on a priori grounds. Because there is no risk or uncertainty, the planning period of all firms is restricted to the same maximum value.[222] In the present model, firms differ from each other with respect to risk aversion and it is shown that the length of the planning period corresponds to a certain level of risk aversion. The maximum length of the planning period is given by $\bar{\theta}$, which differs between firms due to different attitudes towards risk. If the expected lifetime of equipment exceeds $\bar{\theta}$, the planning period is bounded to this upper limit in both models. In general, this will be the case if the growth rate of output prices exceeds the growth rate of nominal wages.

If the growth rate of nominal wages exceeds the growth rate of output prices, there will be a point at which the quasi-rents become negative. This holds true for the present model as well as in the macro-model if the rate of disembodied technological change is below the difference between the growth rate of wages and the growth rate of output prices. The expected date of scrapping is no longer bounded, leading firms to apply a planning period which is below $\bar{\theta}$ (cases *(ii)* and *(iii)* in Figure 6.1). This holds true for both models.

222. In part II, we imposed an upper limit of 15 years.

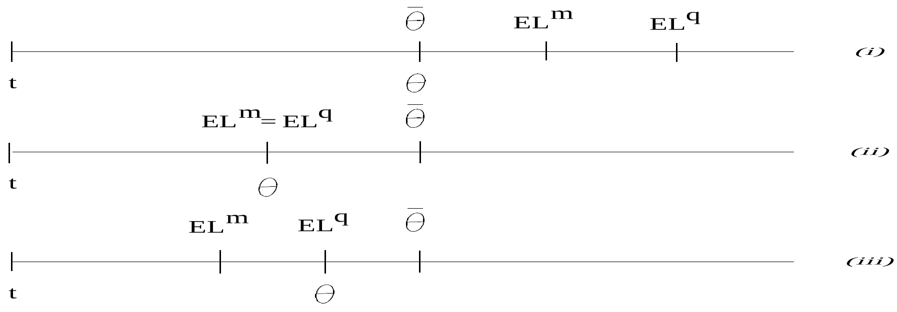

Figure 6.1. The length of the planning period (θ) and expected lifetimes in the case of negative quasi-rent scrapping (EL^q) and in the case of the Malcomson scrapping rule (EL^m).

In the macro-model, it is assumed that the number of firms are distributed with respect to risk aversion, which leads to a distribution that depends on expected profitability and on the available knowledge. The choice of the technology is not explicitly based on firm behaviour. The main difference between the two models is that the technology is given to each firm in the macro-model and the planning period is determined by a simultaneous solution of the labour intensity and the expected date of scrapping. In the present model, the choice of the technology and the expected date of scrapping are simultaneously determined. Moreover, the previous chapter has shown that the choice of the technology in the quasi-clay-clay model is a counterpart of the choice of the labour intensity in the putty-clay model.

Until now, we have assumed competitive output markets in which equipment is scrapped if the quasi-rents become negative.[223] In this chapter, we relax this assumption and we will assume that the output market can be described by monopolistic competition. This implies that the Malcomson scrapping rule is no longer comparable to the quasi-rent scrapping rule. This has two implications, first for the amount of scrapping, and secondly, for the expected lifetime.

The amount of scrapping is determined by comparing the total marginal costs of the newest vintage with the variable marginal costs of existing vintages. The Malcomson scrapping condition will lead to more scrapping if the market is less competitive, as a result of which firms will increase investment, ceteris paribus.[224]

The relation between the expected lifetime and the length of the planning period is less clear. If we assume that the planning period, which firms use to evaluate the expected profits, is equal to the expected lifetime, we have to determine the expected date of scrapping. However, since the date of scrapping depends on the total marginal costs of future vintages, we have to examine the initial labour productivity of future vintages. But the initial labour productivity of future vintages depends again on the expected lifetime of their successors, which means that we

223. Note that this is a special case of the Malcomson scrapping condition.

224. Although the total marginal costs of the newest vintage depends on the planning period, the relation between the planning period and the amount of scrapping is an indirect one.

must examine all future investment decisions to determine the expected lifetime of the current vintage. Thus, the Malcomson scrapping condition in the case of non-competitive markets and the assumption of consistent expectations implies that we have to use a dynamic or intertemporal model.

Note that such an approach implies that all future investment decisions have to be known before we can determine the expected lifetime of the current equipment. Although Malcomson (1975) investigates some numerical approaches to solve this problem, we will use a practical shortcut. As is done by van Zon (1989 and 1991) and by Meijers and van Zon (1991), for instance, we assume that *current* scrapping is based on the Malcomson scrapping condition, but that the *expected lifetime* is based on the quasi-rent scrapping rule. This implies that the total marginal costs are based on a (slightly) inconsistent planning period, also affecting the amount of scrapping to some extent.

Consider again Figure 6.1 to determine the consequences of this practical shortcut. If the expected lifetime exceeds the planning horizon, which is still bounded due to risk aversion and uncertainty, firms will use $\bar{\theta}$ as the planning period, i.e. case *(i)*, which implies that there is no difference between the two approaches in this case. If the expected lifetime is below the maximum planning period, we can distinguish two different cases. If output markets are competitive, both scrapping rules lead to the same expected lifetime and consequently to the same planning period (case *ii*). If the markets are non-competitive — which we assume to be the case in this chapter — the Malcomson scrapping rule will lead to shorter expected lifetimes than the negative quasi-rent scrapping rule, case *(iii)*. In this case, we will use EL^q as the planning period whereas it should be EL^m if we required consistent expectations, but which would lead to numerical solution methods in which we should take account of all future investment decisions.

There are some more differences between the two approaches, in which the user costs of capital being the most prominent. Because of its dynamic specification, the costs of capital will include opportunity costs which are related to future increases in profitability. In other words, technological expectations are included in the solution of the model. Although we will not completely solve the intertemporal version of the model, we will derive some results from the first-order conditions, thus shedding light on the difference between the dynamic and the static case, including the difference regarding to technological expectations. As in the previous chapter, we will start with the static version, to be followed by the intertemporal case.

Finally, Chapter 5 has shown that the solutions of the learning case can only be determined by simulation experiments. In this chapter, we concentrate on the non-learning case and will refer to the learning case parenthetically. In chapter 7, which addresses the behaviour of the quasi-clay-clay vintage model by presenting some simulation experiments, we will briefly reconsider the learning.

The next section describes a static (but non-myopic) vintage model in which firms maximize the expected discounted rents over a certain planning period. The properties of the static model outside the steady state are presented in chapter 7. The dynamic, or intertemporal, case is described in section 6.3, which ends with a discussion of the difference and the similarities between the static and the dynamic model.

As pointed out above, we assume monopolistic competition on the output market and we will use a specification which includes perfect competition and pure monopoly as special cases. This provides the opportunity to investigate the relation between the speed of diffusion and the market structure. Because both the static and dynamic versions are similar with respect to this particular point, and because the static model is far more easy to handle, we will examine this relationship in the static model only. This is done in sections 6.4 and 6.4.2. The diffusion pattern in section 6.4 is based on a bell-shaped distribution of the number of firms with respect to the planning period. This is comparable with the diffusion process in the previous chapter. However, monopolistic competition will lead to an S-shaped diffusion pattern which is *independent* of the distribution of firms with respect to the planning period. Section 6.4.2 elaborates such endogenous diffusion patterns.

6.2 A Static Vintage Model

As in the previous chapter, firms are assumed to maximize the present value of rents over a planning period which is assumed to vary among firms, but which is given to each firm. Whereas the output for each firm was treated as being given in the previous model, in this chapter we will introduce monopolistic competition where firms act as price setters and quantity takers. Furthermore, we will use the simplifying assumption that the expected lifetime of both the new and the existing capital stock is equal to or greater than the planning period.[225] This is the practical shortcut we will use to obtain the Malcomson scrapping condition in a static model. In the previous chapter, firms are assumed to maximize the net present value of rents of the newest investment. Now, we assume that they maximize the net present value of rents of *all* vintages. This leads to the Malcomson scrapping condition, as we will show below. Moreover, because the amount of output is now determined by the price, we have to evaluate the net present value of output in this model, in contrast to the net present value per unit of output in the previous chapters. Thus, firms are assumed to maximize:

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225. In terms of Figure 6.1, case *(iii)*, this implies that firms assume that all equipment will live for at least θ years in which $\theta = \min(EL^q, \bar{\theta})$.

$$PVX_\tau = \int_\tau^{\tau+\theta} e^{-r(t-\tau)}\{p_t X_t - w_t N_t\}dt - q_\tau^i I_{\tau,\tau}^i \tag{6.1}$$

subject to the output constraint:

$$\int_{t-T_t}^{t} X_{\tau,t}^i \, d\tau = X_t \tag{6.2}$$

in which all variables have been defined in the previous chapter. It is assumed that firms operate at full capacity at any point in time. The total demand for labour at time t is equal to the aggregate of the demand for labour for each individual vintage which is labelled $N_{\tau,t}^i$. The labour productivity depends, as in the previous chapter, on the incorporated technology but it is assumed that this productivity is constant in time, i.e. we assume the non-learning case. Furthermore, and again, similar to the previous chapter, we assume that the capital/output ratio is the same for all vintages and that the price of capital is given by: $q_t^i = q_t i^\gamma$. Throughout this chapter, it is assumed that capital depreciates exponentially at rate δ. Taken together, the above implies that:

$$N_t = \int_{t-T_t}^{t} N_{\tau,t}^i \, d\tau \ ; \quad N_{\tau,t}^i = \frac{X_{\tau,t}^i}{\lambda_\tau^{i_\tau}} = \frac{X_{\tau,t}^i}{\lambda_0 i_\tau^\mu} \ ;$$
$$X_{\tau,t}^i = \frac{I_{\tau,t}^i}{\psi} = \frac{I_{\tau,\tau}^i e^{-\delta(t-\tau)}}{\psi} \quad \text{and} \quad q_t^i = q_t i^\gamma \tag{6.3}$$

6.2.1 *The Final Demand Function in the Case of Monopolistic Competition*

In part II, we assumed that all firms operate in a competitive output market. Previously, we already argued that this is an unrealistic assumption if the costs structure between firms differs due to different process technologies. Moreover, the market may be less competitive due to geographical distribution, customer relations, differences with regard to service, etc. This chapter relaxes the assumption of competitive markets and assumes that each firm produces a specific consumer good.

The demand function for a specific firm is based on the model of Blanchard and Fisher (1989: 376-379), in which the consumer goods are imperfect substitutes and consumers maximize a utility function in which the elasticity of substitution between goods is constant.[226] Moreover, they assume that the aggregate price level is equal to a CES aggregate of the individual prices:

226. Cf. Dixit and Stiglitz (1977). A similar model is presented by Blanchard and Kiyotaki (1991).

$$\bar{P} = \left(\frac{1}{J} \sum_{j=1}^{J} (p^j)^{1-\eta} \right)^{\frac{1}{1-\eta}} \tag{6.4}$$

in which J denotes the number of consumer goods.
The demand for a consumer good j equals:

$$X_t^j = \left(\frac{p_t^j}{\bar{P}} \right)^{-\eta} \left(\frac{\bar{X}}{J} \right) \quad \text{where } \eta > 1 \tag{6.5}$$

where $\bar{X}$ stands for total market output.[227] The term η is the elasticity of substitution between goods in the utility function of consumers, but it is also equal to the price elasticity of demand. If η is large, goods are close substitutes and the price elasticity of demand is high leading to a more competitive market. A relative monopolistic case is obtained if $\eta \downarrow 1$. Similar to Blanchard and Fischer (1989) and Blanchard and Kiyotaki (1991), we assume that the number of firms is relatively large. Thus taking other prices as given is the same as taking the price level as given. Moreover, we assume that the expected aggregate price level grows at a rate π so that firms expect their future prices to grow at the same rate.

6.2.2 Optimal Firm Behaviour

The instrumental variables of the maximization problem are the price of output (p_t), the age of the oldest vintage (T_t), the choice of the technology (i_t) and the amount of investment ($I_{t,t}$). Finally, the planning period (θ) is an additional, but bounded, instrumental variable ($\theta \le \bar{\theta}$). The length of the planning period is related to risk aversion by the period in at which future rents are considered. Since the choice of the *current* technology is related to the length of the planning period, the first-order condition with respect to the length of the planning period holds for the newest vintage only. Using these assumptions, we can rewrite equation (6.1) as:[228]

$$\max_{p,I,i,T,\theta \,|\, \bar{\theta}} \int_t^{t+\theta} e^{-r(j-t)} \{ p_j X_j - w_j \int_{t-T_t}^{t} \frac{I_{\tau,\tau} e^{-\delta(j-\tau)}}{\psi \lambda_0 i_\tau^{\mu}} d\tau \} \, dj \; - \; q_t i^i I_{t,t} \tag{6.6}$$

subject to the planning period constraint: $\theta \le \bar{\theta}$ and to the output constraint:

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227. Because the level of risk aversion — or the length of the planning period — is a continuous distribution in our model, there is also a continuous range of different technologies as well as a continuous range of different products, which is slightly inconsistent with the demand function, in which the number of firms is equal to a finite number J. However, below we will show that this term does not arise in the solution of our model, whereas we will use a discontinuous version of the model in the simulations in chapter 7.

228. As before, we will drop the firm index (j) and use it only if necessary.

$$\int_{t-T_t}^{t} \frac{1}{\psi} I_{\tau,\tau} e^{-\delta(t-\tau)}\, d\tau = X_t \tag{6.7}$$

in which the amount of output is given by equation (6.5). The expected growth rate of prices of an individual firm is assumed to be equal to the growth rate of the aggregate price level (π) and this expected rate as well as the expected growth rate of nominal wages (ρ) are assumed to be constant. The solution of the model in terms of first-order conditions is presented in appendix 6A. The optimal technology index proves to be the same as that found in the previous chapter, which means that the labour intensity of the newest vintage is the same as that found before (cf. equation (5.33) on page 200). Moreover, the ratio of the discounted wage costs over the total costs of capital is again equal to γ/μ (cf. equation (5.14) on page 178). Thus, if μ and γ are constant, the ratio of wage costs over capital costs is the same for *all* vintages, which implies that this ratio is equal to the income distribution at the macro level (excluding profits).

Because the choice of technologies has been extensively discussed in the previous chapter, this chapter concentrates on the new elements. First, we will address the price setting behaviour, followed by the length of the planning period. Third, we will derive the scrapping condition in which we will show that the age of the oldest vintage is determined by the choice of the (current) technology. After that, we will derive the amount of output and the amount of investment. The previous chapter shows that the expected profits of the newest vintage and the level of risk aversion, or the length of the planning period, are positively related. At the end of this section, we will examine whether this holds true for the entire firm, i.e., for all vintages taken together.

Price-Setting Behaviour

From the final demand function (equation (6.5)), it follows that:

$$\frac{\partial X_t}{\partial p_t} = -\eta \frac{X_t}{p_t} \tag{6.8}$$

Substitution of this equation in the first-order condition with respect to the output price (equation (6A.2)) and solving for p_t yields:

$$p_t = \frac{\eta}{\eta-1}\frac{\zeta}{g(\theta)} \quad \text{or} \quad p_t\, g(\theta) = \frac{\eta}{\eta-1}\zeta \tag{6.9}$$

$p_t g(\theta)$ describes the total discounted returns per unit of output. From equation (6A.3), it follows that:

$$\zeta = \frac{w_t f(\theta)}{\lambda_0 i_t^{\mu}} + \psi q_t i_t^{\gamma} = \left(\frac{w_t f(\theta)}{\lambda_0}\right)^{\frac{\gamma}{\mu+\gamma}} \left(\frac{\psi q_t \gamma}{\mu}\right)^{\frac{\mu}{\mu+\gamma}} \left(1+\frac{\mu}{\gamma}\right) \tag{6.10}$$

in which we substituted the expression for the optimal technology for i_t. From the term in between the equal signs, it follows that ζ denotes the total marginal costs of the newest vintage (cf. equation (5.14) on page 178). Thus, the term $\eta/(\eta-1)$ reflects the mark-up ratio. So output prices are set by the firm by using a simple mark-up on the marginal total costs of the *newest* vintage.[229]

The Length of the Planning Period

The length of the planning period is determined by solving equation (6A.6):

$$X_{t,t}\left[p_t g_\theta - \frac{w_t f_\theta}{\lambda_0 i_t^{\mu}}\right] = 0 \tag{6.11}$$

Solving for the length of the planning period and applying the boundary condition yields:[230]

$$\theta = \min\left(\frac{1}{\pi-\rho}\ln\left[\frac{w_t}{\lambda_0 i^{\mu}}\frac{1}{p_t}\right],\ \bar{\theta}\right) \tag{6.12}$$

If θ is below $\bar{\theta}$, no firm will choose a longer planning period because this will decrease expected profits. On the other hand, if a firm is more risk-averse and the planning period $\bar{\theta}$ is shorter than the solution of the first-order condition, this firm will apply its maximum planning period. An interior (unbounded) solution is obtained if the term between brackets in equation (6.11) is equal to zero, that is, if the marginal change of the quasi-rents due to a change of the planning period is zero. This is exactly the same condition as that found in the previous chapter in the case where the growth rate of nominal wages exceeds the rate of inflation so that the utility function is backward bending. No firm will choose a certain planning period, and a corresponding technology, if it can increase its expected profits by lowering the planning period. Again, this is the same condition as that used to determine the expected lifetime in the macro-model (cf. equation (3.42), page 92).[231]

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229. Equation (6.9) corresponds with the, familiar, Amoroso-Robinson mark-up rule.

230. The optimal technology (i) depends on the length of the planning period, but it is impossible to solve this equation for the length of the planning period if the equation for optimal technology is substituted. Moreover, the price of output depends on the chosen technology in the case of non-competitive markets. Numerical solutions of this equation, in which the technology and the price are substituted, show that the planning period is finite if $\rho>\pi$. Moreover, the second-order condition is satisfied in this case.

231. Note that we do not include changes in working hours and disembodied technological change here.

The Scrapping Condition

The scrapping condition can be derived from equation (6A.5), which says that equipment is scrapped if:

$$I_{t-T_t,t-T_t} e^{-\delta T_t} \left[\frac{w_t f(\theta)}{\lambda_0 i_{t-T_t}^{\mu}} - \zeta \right] = 0 \tag{6.13}$$

holds, which is the case if the term between brackets is equal to zero. Thus, equipment is scrapped if the variable costs per unit of output of older vintages are equal to the total costs per unit of output of the newest vintage. This is the, familiar, Malcomson scrapping condition (cf. Malcomson, 1972 and 1975).

The optimal technology of the oldest vintage is equal to (cf. equation (5.33) at page 200):

$$i^*_{t-T_t} = \frac{w_{t-T_t} \mu f(\theta)}{\lambda_0 \gamma \psi q_{t-T_t}} \tag{6.14}$$

Substitution of equations (6.14) and (6.10) in (6.13), yields the scrapping condition, that is, equipment is scrapped if:

$$\frac{w_t \quad f(\theta,t) \quad q_{t-T_t}}{w_{t-T_t} \quad f(\theta,t-T_t) \; q_t} = \left(1 + \frac{\mu}{\gamma}\right)^{\frac{\mu+\gamma}{\mu}} \tag{6.15}$$

holds, in which the term $f(\theta,t)$ depends on the growth rate of nominal wages, on the discount rate and on the length of the planning period, all of them evaluated at time t.[232] If we assume that these terms are constant, the f-terms cancel out. This implies that, if the length of the planning period of a specific firm remains the same at several points in time, the lifetime of capital is equal for all firms because both wages and the non-technology specific part of prices of capital goods as well as μ and γ are the same for all firms. The lifetime can be calculated analytically in a steady state. Thus, assume constant rates of growth of the nominal wages (ρ) and of the general part of the price of capital goods (ν). Then, equation (6.15) is equal to:

$$\frac{w_0 e^{\rho t} \quad q_0 e^{\nu(t-T_t)}}{w_0 e^{\rho(t-T_t)} \quad q_0 e^{\nu t}} = \left(1 + \frac{\mu}{\gamma}\right)^{\frac{\mu+\gamma}{\mu}} \tag{6.16}$$

Solving for T_t yields:

232. Note that both terms depend on experience in the case of learning by doing. But because we do not know whether the firm has previously invested in the same technologies, and because we do not know the amount of previously produced output with each technology, we cannot analytically determine the age of the oldest vintage if learning by doing matters.

$$T = \frac{\left(1+\frac{\gamma}{\mu}\right)\ln\left(1+\frac{\mu}{\gamma}\right)}{\rho-\nu} \tag{6.17}$$

which is constant in time and identical for all firms. A necessary condition for a positive value of T is that $\rho>\nu$. This is not surprising as a positive lifetime implies that a firm must invest in newer, i.e., more advanced, technologies to make older investments obsolete. Now, we will show that for di^*/dt to be positive, the growth rate of nominal wages should be larger than the growth rate of the non-technology-specific part of the prices of capital goods.

In the steady state, the optimal technology is defined as:

$$i_t^* = \left(\frac{w_0 e^{\rho t}\mu f(\theta)}{q_0 e^{\nu t}\psi\gamma\lambda_0}\right)^{\frac{1}{\mu+\gamma}} = ce^{\frac{(\rho-\nu)t}{\mu+\gamma}} \tag{6.18}$$

which leads to:

$$\frac{\partial i^*}{\partial t}\frac{1}{i_t^*} = \frac{\rho-\nu}{\mu+\gamma} \tag{6.19}$$

with i_t^*, μ and γ all being positive. So $\rho-\nu$ has to be positive to ensure that newer equipment is more productive than older vintages and that the lifetime of the oldest vintage is positive and finite.

Finally, note that the Malcomson scrapping condition is independent of the price of output and therefore independent of the market structure. But if the output market is competitive, i.e. if $\eta = \infty$, the mark-up is zero, which implies that the price of output is equal to the marginal costs of the *newest* vintage. In other words, equating the marginal variable costs of the *oldest* vintage with the marginal total costs of the *newest* vintage is equal to equating the marginal costs of the *oldest* vintage with the price of output. This is the negative quasi-rent scrapping condition, which we employed in part II.

6.2.3 Output and Investment

One of the goals of this chapter is to derive a relation between the choice of the technology and the amount of investment. This section derives the amount of investment in the case of steady-state growth and in the case in which the price of capital goods deviates from the steady-state path. However, because the amount of investment depends on the amount of output, we will first consider the growth rate of output for each individual firm.

The Amount of Output

The amount of output is given by equation (6.5) which indicates that the growth rate of output depends on the growth of output prices and on the growth rate of aggregate demand ($\bar{X}$):

$$\frac{dX_t^j}{dt}\frac{1}{X_t^j} = -\eta\frac{\partial p_t^j}{\partial t}\frac{1}{p_t^j} + \frac{\partial \bar{X}}{\partial t}\frac{1}{\bar{X}} \tag{6.20}$$

Because aggregate demand equals the sum of the demand for each firm, the growth rate of output of each firm is constant if the growth rates of output prices and of aggregate demand are constant.[233] First, we will consider the growth rate of output prices.

The price of output is given by a mark-up on the marginal costs of the newest vintage, which means that the growth rate output prices depends on the growth rate of the marginal costs of the newest vintage, given a constant planning period for each specific firm. Since the wage rate and the price of capital are the only time-dependent variables, the growth rate of the marginal costs is equal to (cf. equation (6.10)):

$$\frac{d\zeta}{dt}\frac{1}{\zeta_t} = \frac{\gamma}{\mu+\gamma}\frac{\partial w_t}{\partial t}\frac{1}{w_t} + \frac{\mu}{\mu+\gamma}\frac{\partial q_t}{\partial t}\frac{1}{q_t} \tag{6.21}$$

which says that the growth rate of marginal costs is a weighted average of the growth rate of nominal wages and the growth rate of the non-technology-specific part of the price of equipment. If both rates are constant, the growth rate of marginal costs is constant and identical for all firms, which implies that the growth rate of prices is the same for all firms. Thus, the growth rate of output is the same for all firms and, by definition, equal to the growth rate of aggregate demand.

Now, consider a change in the prices of capital goods (q_t). The price of output will change according to:

$$\frac{dp_t}{dt}\frac{1}{p_t} = \frac{\mu}{\mu+\gamma}\frac{dq_t}{dt}\frac{1}{q_t} \quad \text{in which} \quad \frac{\mu}{\mu+\gamma} < 1 \tag{6.22}$$

We have shown previously that a firm will switch to a more labour-intensive technology (less advanced technology) if capital goods become more expensive (substitution effect). Equation (6.22) shows that the relative change of marginal total costs of the newest vintage due to an increase in prices of capital goods is smaller than one. This implies that, given the constant mark-up rule, the relative change in p_t is also smaller than the change in q_t. Substitution of equation (6.22) in (6.20) shows that the amount of output for an individual firm will decrease if the price of capital goods increases. However, if the price of capital goods increases for all technologies, all individual firms will face the same decrease in output, and their market shares remain the same. But because aggregate demand is exogenous, the output of

233. Note that we assume no entry or exit so that the total number of firms (J) is constant.

each firm will remain the same (or will grow at the same rate as aggregate demand).[234]

A change in the nominal wage rate will also lead to a substitution effect and a marginal cost effect:

$$\frac{dp_t}{dt}\frac{1}{p_t} = \frac{\gamma}{\mu+\gamma}\frac{dw_t}{dt}\frac{1}{w_t} \quad \text{in which } \frac{\gamma}{\mu+\gamma} < 1 \qquad (6.23)$$

which is, of course, the complement of the marginal costs effect due to a change in the prices of capital goods. Again, the expected output for each individual firm will decrease due to an increase of the wages, but the output remains the same if all firms face the same increase of wages and if aggregate demand does not change.

So, an individual firm will increase its output price if the price of capital and/or labour increases which leads to a decrease of its market share. But if all firms are affected in the same way, the output of each individual firm remains unchanged.

The Amount of Investment

This section determines the amount of investment both in steady state and in the case in which prices of capital goods deviate from the steady-state growth path. We will show that the demand function of capital goods is downward-sloping, but first, we will briefly describe the steady-state solution.

The amount of investment is derived from the output constraint and by using the property that the lifetime of equipment is constant in a steady state. The amount of investment is equal to (cf. equation (6B.6) on page 246):

$$I_{t,t} = X_t \psi\left(\frac{\chi+\delta}{1-e^{(-\chi-\delta)T}}\right) \qquad (6.24)$$

in which χ is the (exogenous) growth rate of aggregate demand. The term in the numerator describes the amount of investment due to expansion of output and due to depreciation of the existing capital stock, while the term in the denominator describes replacement investments of the part of the capital stock which is scrapped. The amount of investment is a constant share of total output, which implies that the growth rate of investment is equal to the growth rate of total output. This is not unexpected because the capital productivity is constant and because the lifetime of capital is constant in the steady state.

Equation (6B.6) is not defined if both the growth rate of output and the rate of depreciation are zero, or if $\chi+\delta=0$. But taking the limit of $\chi+\delta\downarrow 0$ shows that the amount of investment is equal to the amount of output times the capital/output

234. Note that the deviation between the initially expected decrease in output and the final conclusion that the amount remains the same is due to the fact that firms assume that their competitors do not change their price and that the influence of their own price-setting behaviour on the aggregate price level can be neglected.

ratio, divided by the lifetime of equipment.[235] So the amount of investment is constant in time and equal to the total capital stock of the firm divided by the lifetime of equipment if there is no output growth and no depreciation.

Notice that we derive the demand for capital goods in terms of the amount of capital, not in terms of the amount of investment in each *technology*. This is not an hard issue in the steady state. If firms move to more advanced technologies at a constant rate, the demand for each technology depends on the amount of investment and on the distribution of firms with respect to the length of the planning period. For instance, if the number of firms is distributed in a bell-shaped manner with respect to the planning period and if the amount of investment is a monotonically decreasing function of the planning period, the distribution of the amount of investments will still be bell-shaped. This distribution shifts to the right if firms buy more advanced technologies, so that the diffusion pattern remains S-shaped. This will be shown in section 6.4 below.

However, outside steady-state these reactions are less clear. An increase in the price of investment goods (q_t) leads to three reactions. First, all firms will choose a different technology according to equation (6A.7). Such a shift towards other technologies depends to a large extent on the distribution of firms with respect to the length of the planning period and cannot be determined analytically. This effect will be the subject of some simulation experiments in chapter 7.

Secondly, the marginal total costs of the newest vintage will increase due to an increase in the price of capital. This leads to less scrapping, and, thus, to a decrease in the amount of investment.

Thirdly, there is a demand effect. Each specific firm will set another output price due to a change of the marginal costs of the newest vintage. Consequently, investments will fall due to an increase in the costs of capital goods. It has been shown above that this holds true for all firms so that the market shares remain the same, which implies that the amount of output for each specific firm also remains the same, given exogenously determined aggregate demand. In this section, we will elaborate the investment behaviour of an individual firm, in which we assume that all other firms do not react. The aggregate investment effect, i.e., meaning that all firms will react to changes in investment prices, will be discussed in the next chapter.

To summarize the above, the amount of investment will change due to a change in the prices of capital goods for three reasons. Only the last two will be addresses in

235. Let $\chi+\delta$ be x, then the amount of investment is equal to: $I_{t,t} = X_t \psi x / (1 - e^{-xT})$. Taking the limit of $x \downarrow 0$ yields $\frac{x}{1-e^{-xT}} = \frac{x}{1-(1-xT)} = \frac{1}{T}$ which implies that, in this situation, the amount of investment is equal to $I_{t,t} = X_t \psi \frac{1}{T}$.

this section. Appendix 6B shows that the effect of a change in the price of capital goods can be described by (cf. equation (6B.15)):

$$\frac{\partial I_{t,t}}{\partial q_t}\frac{q_t}{I_{t,t}} = -\frac{\eta\mu}{\mu+\gamma} - \frac{1}{\rho-\nu}\frac{I_{t-T_t,t}}{K_t} \tag{6.25}$$

The first term at the right-hand side describes the demand effect, which is a combined effect of a change in the output price ($\mu/(\mu+\gamma)$) due to a change in the price of equipment, and an output effect due to a change of p_t. The second term at the right-hand side describes the lifetime effect and needs some more explanation.

According to the Malcomson scrapping condition, firms compare the total marginal costs of the newest vintage with the variable marginal costs of older equipment. Since equation (6.25) is based on a steady-state assumption, the growth rate of wages and the growth rate of price of equipment have been constant until time t. This implies that the current capital stock contains vintages in which the labour productivity of succeeding vintages (in terms of time of installation) has grown by:

$$\frac{\partial\lambda_j}{\partial t}\frac{1}{\lambda_j} = \frac{\rho-\nu}{\mu+\gamma} \quad \text{for} \quad j\in[T_t...t] \tag{6.26}$$

which is obtained from equation (6.19). Thus, if $\rho-\nu$ is relatively small, the difference between succeeding vintages in terms of labour productivity is small, and consequently, the difference in the marginal costs is relatively small. A change in the price of equipment will cause large scrapping effects in such a case. If $\rho-\nu$ was large in the past, the difference in existing vintages in terms of marginal costs is large to the extent that a firm will scrap less for the same change in q_t. Note that the labour productivity of all existing vintages is the same if the growth rate of wages has been the same as the growth rate of q_t, i.e., if all vintages embody the same technology. This implies that a firm will replace *all* existing capital if the marginal costs of the newest vintage decrease. So the term $\rho-\nu$ in equation (6.25) reflects the difference in the marginal costs within the existing capital stock. The last term denotes the relative size of the oldest vintage, which determines the size of the replacement investments per obsolete vintage.[236]

To summarize, this section shows that a change of the non-technology-specific part of price of equipment leads to three different effects. First, firms will buy other technologies, secondly, firms will change their output price which affects output, and thirdly, the amount of scrapping will change due to a change in the marginal costs of the newest vintage leading to a change in the replacement investments. We have investigated the last two effects and shown that both are negatively related to a change of q_t, resulting in a downward-sloping demand function for equipment. Moreover, we noticed that the output effect disappears if all firms change their price, as a result of which the market share of each specific firm does not change.

236. Note that we consider a marginal change of q_t, as a result of which the size of replacement investments is determined by the size of the oldest vintage.

But even then, the demand curve is downward-sloping due to the replacement effect, i.e., due to the Malcomson scrapping condition. Finally, it has been shown that the amount of scrapping is determined by the composition of the capital stock and, thus, depends on the technology index.

Finally, the previous chapter has shown that the expected profits per unit of output is a non-decreasing function of the length of the planning period. Firms maximize the expected profits of all vintages taken together whereas the output price is based on the marginal costs of the newest vintage. Appendix 6C shows that the relation between expected profits and the length of the planning period holds true for the present model. One main difference between the present model and the model in the previous chapter is that now, firms set their price according to a mark-up rule. This implies that even the most risk-averse firm, with a planning period near to zero, will expect small, but positive profits, whereas such a firm has been designated as being risk-averse in the previous chapter. This implies that the technology in which the most risk-averse firm will invest has a smaller index number than that found before.

6.3 Choice of Technologies in a Dynamic Vintage Model

The previous section has analyzed the behaviour of firms in a multi-period static vintage model. The Malcomson scrapping rule is derived by using the simplifying assumption that *both existing and new capital* will survive for at least the duration of the planning period. This assumption allows us to derive the scrapping condition but also introduces an inconsistency in the model. The lifetime of capital is shown to be constant in the steady state. This implies that firms will scrap some capital at each point in time, whereas it is assumed that this is not the case in the objective function. To be more precise, a firm expects that a vintage will exist for at least another θ years if this vintage is not scrapped at time t. For instance, the firm expects an $T_t - 1$ old vintage to be scrapped at or after time $t+\theta$. However, the lifetime is constant in a steady state, which implies that this vintage will be scrapped at time $t+1$, given the steady-state lifetime of T_t.

The importance of this inconsistency will be considered in this section, in which we will redo the same analysis, but now in an intertemporal setting. Again, firms are assumed to maximize the net present value of future rents, but will now consider current as well as future investments in their objective function. This implies that at time t_0, firms consider future production with the current capital stock *plus* future production with equipment which has to be installed after time t_0. For the rest, we will use the same assumptions in order to compare both models. The costs of capital, which are still assumed to be sunk costs, did not appear within the integral of the objective function in the previous section (cf. equation (6.1)). In the intertemporal setting, firms are assumed to consider these investment costs as long as they occur within the planning period. Thus, firms are assumed to maximize:[237]

$$PVX_{t_0} = \int_{t_0}^{t_0+\theta} e^{-r(t-t_0)} \{X_t p_t - w_t N_t - q_t^i I_{t,t}\} dt \tag{6.27}$$

subject to the output constraint:

$$X_t = \int_{t-T_t}^{t} X_{\tau,t}^i \, d\tau \quad \forall \; t \in [t_0 \ldots t_0 + \theta] \tag{6.28}$$

and in which total demand for labour, labour productivity, capital/output ratio and the costs of capital have already been defined in equation (6.3). As before, T_t describes the age of the oldest vintage at time t.

The way in which the Lagrange equation is obtained follows Malcomson (1972, 1975) to a large extent. Both the Lagrange equation and the first-order conditions are given in appendix 6D.

The optimal technology index is given by equation (6D.16), and reads:

$$i_t^* = \left(\frac{\mu}{\psi \lambda_0 \gamma q_t} \int_t^{t+L_t} w_\tau e^{(-\delta-r)(\tau-t)} \right)^{\frac{1}{\mu+\gamma}} = \left(\frac{w_t \mu \; f(L_t)}{\psi \lambda_0 \gamma q_t} \right)^{\frac{1}{\mu+\gamma}} \tag{6.29}$$

which is the same as that found before, with the exception of the expected lifetime in the $f()$-term. If the expected lifetime exceeds the length of the planning period ($\bar{\theta}$), there is no difference between the static model and the dynamic model. However, the expected lifetime in the case of the (expected) Malcomson scrapping rule will be smaller than the expected lifetime which results from (expected) quasi-rent scrapping. This implies that the $f()$-term will be smaller in the present model if $L_t < \bar{\theta}$. Note that the growth rate of the technology index, and thus the growth rate of labour productivity, is not affected in the steady state, i.e., if L_t is constant. Moreover, the f-term, which denotes the present value of future wage costs, depends on $\rho - \delta - r$. If this term is negative, which seems a reasonable assumption, the marginal contribution of the planning period will decrease for increasing values of the planning period. Consequently, if the difference between the expected lifetime and the planning period is relatively small, it is likely that the differences between both models will have minor effects on the choice of technologies.

In the introduction, we mentioned that technological expectations will appear in the dynamic case. We will elaborate this now. The Lagrange multiplier, ϕ_t, which

237. Note that taking the integral of equation (6.1) from t_0 to $t_0 + \theta$ would imply double counting of future quasi-rents which are generated by the current capital stock.

denotes the marginal costs of the newest vintage which will be installed at time t, and in which the costs are evaluated at time t_0, is given by equation (6D.13):

$$\phi_t = e^{-r(t-t_0)} \left\{ \frac{w_t}{\lambda_0 i_t^{\mu}} + \psi q_t i_t^{\gamma} \left[r + \delta - \hat{q}_t \right] + \hat{i}_t \left[\frac{w_t \mu f(L_t)}{\lambda_0 i_t^{\mu}} - \gamma \psi q_t i_t^{\gamma} \right] \right\} \tag{6.30}$$

(*a*) (*b*) (*c*)

The term (a) denotes the variable or operating costs of the newest vintage per unit of output at time t. (b) denotes the user costs of capital per unit of output at time t. This term includes the costs of investment ($q_t i^{\gamma}$) times the annual costs of interest payments, the costs of technical depreciation and a capital gain element, which reflects future opportunities if the price of capital changes.[238] The last term, (c), denotes the opportunity costs for *not* waiting another period and choosing another technology then. This last term depends on the gains of the integral variable costs over the expected lifetime and the loss of capital costs, and reflects technological expectations. If a firm expects the technology index to rise in the (near) future, for instance due to increases of the wage rate or due to a decrease of q_t, it can be better off by postponing current investment and waiting, and gain from these future opportunities. This effect becomes apparent if we examine the scrapping condition. In the present model, equipment is scrapped if (cf. equation (6D.18)):

$$\phi_t = \frac{w_t e^{-r(t-t_0)}}{\lambda_0 i_{t-T_t}^{\mu}} \tag{6.31}$$

If ϕ_t increases due to an increase of expected opportunities, a firm will scrap less and invest less, ceteris paribus. So, in the present dynamic model, technological expectations become important and cause a firm to postpone investment if it expects to gain from future circumstances. As a result, it will invest in more advanced technologies in the future and thus increase expected profits by waiting. A similar result is obtained by Balcer and Lippman (1984). They use a discontinuous model in which firms actually do not invest if they expect new technological opportunities to arise in the near future, and are able to increase profits by doing so. Our model is continuous in which the amount of scrapping, and therefore the amount of investment, is a function of technological expectations.[239] Note, however, that if the term (c) in equation (6.30) is large to the extent that the marginal total costs of the newest vintage exceed the marginal variable costs of the oldest vintage, a firm will not scrap at all. In that case, the amount of investment only depends on replacement investments due to depreciation and on changes in total

238. See for instance Jorgenson (1963, 1965), Malcomson (1975) or van den Noord (1990).

239. The work of Balcer and Lippman is exclusively concerned with technological expectations. Consequently, their article also concentrates on expectation formation with respect to technological innovations.

output. This is comparable to the zero-one decision (to invest or not to invest) in the model of Balcer and Lippman.[240]

Finally, note that ϕ_t depends on the expected lifetime of equipment L_t, provided that the technology index increases in time, i.e., if condition $\partial i / \partial t \geq 0$ is not strictly binding which we assumed to be the case. This implies that the expected lifetime of equipment, i.e., the expected date at which the equipment will be scrapped, depends on the expected lifetime of its successors. However, the expected lifetime of its successors depends on the expected lifetime of their own successors, and so on. This implies that the lifetime cannot be solved analytically in this model. Moreover, if $di / dt = 0$, the opportunity term (c) in the marginal costs equation (equation (6.30)) cancels out so that there are no expected technological improvements, which implies that a firm will not postpone investment to obtain future (expected) gains.

Comparison of the present marginal costs term with the marginal costs in the static model enables us to locate three main differences which are related to the difference between static and dynamic optimizing behaviour.[241] First, the user costs of capital term, second, the wage costs (term (a) in equation (6.30)), which does not include the f-term in the present model, and third, the opportunity costs term which is related to future technological change. The user costs of capital term now includes opportunity costs due to future changes in the price of capital goods. This term appears in the present model because firms consider future investment decisions as a result of which they may postpone investment, which is not possible in the static model. Another difference between the present model and the static model is that the user costs of capital denotes the costs of capital at one point in time, whereas it included *total* investment costs in the previous section. This difference is related to the second point, in which the f-term does not appear in term (a) in the present model, which means that the wage costs are also evaluated at one point in time. Thus, the marginal costs denote the costs of the newest vintage at one point in time whereas it denotes the marginal costs of the newest vintage during the entire planning horizon in the static model. Again, this is exactly the difference between static and dynamic behaviour. Moreover, note that the absence of the f-term in the scrapping condition is also the only difference between the dynamic and the static model. Finally, the opportunity costs due to technological expectations are, again, a result of the possibility to postpone investment decisions and to increase profits if future investments are more profitable.

Thus, although we find some differences between the static and the dynamic model, the choice of the technology is only affected if the expected lifetime is below

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240. Note that we do not allow for underutilisation of the capital stock, nor for supplying less than actual demand. Thus, firms cannot decide to postpone investment and supplying less than actual demand. Balcer and Lippman (1984) do not determine demand or output capacity at all. As a result, replacement investment and the costs of ‘selling no’ are not captured by their model.

241. Cf. Equation (6.10) in the previous section on page 222 for the marginal costs in the static model.

$\bar{\theta}$, and even then, it is likely that the difference between the technology index is small, at least if the difference of the expected date of scrapping between the quasi-rent scrapping rule and the Malcomson scrapping rule is limited.[242] The scrapping condition is comparable between both models and differs only with respect to the marginal costs of the newest vintage. These marginal costs now include opportunity costs due to (expected) changes of the price of equipment and due to (expected) changes resulting from technological prospects.

Because of the substantial similarities between both models and because of the (relative) analytical attractiveness of the static model, we will continue with the non-dynamic version of the quasi-clay-clay vintage model. The next chapter presents some simulation results, but before we turn to that subject, we will take a closer look at the diffusion process in a steady-state environment.

6.4 The Steady-State Diffusion Process

One of the goals of this chapter is to determine diffusion patterns in a quasi-clay-clay vintage model. We developed a model which determines both the choice of the technology and the amount of investment in that technology. Moreover, we introduced monopolistic competition, as a result of which the relation between the market share of a firm and the elasticity of substitution between consumer goods influences the relation between amount of investment and the chosen technology.

The previous chapter shows the diffusion process as a result of the choice of the technology solely, i.e., we assumed that each firm acquires only one unit of the capital goods. Now, we are able to determine the diffusion process in terms of amount of investment. However, because the model can be solved analytically for the steady state only we are restricted to such steady state results. The next chapter presents some results outside the steady-state, which have been obtained by performing some computer simulations. This section elaborates the diffusion pattern in two different ways. The previous chapter has shown that the model is able to generate S-shaped diffusion patterns if the number of firms with respect to the length of the planning period are distributed in a bell-shaped manner. The next section performs a similar analysis and examines the effect of the market structure on the speed of diffusion. However, the amount of investment in each technology depends on total output of each firm, which is in turn a function of the output price of each firm through the demand function. Section 6.4.2 will show that the model is able to generate S-shaped diffusion patterns *independently* of the shape of the distribution of the number of firms with respect to the length of the planning period. This will be the case if the growth rate of wages exceeds the growth rate of

242. Chapter 7 shows that this difference can be large if the rate of technological change is large and if the growth rate of *real* wages is small.

output prices, if the market is rather monopolistic, and if the length of the planning period of the least risk-averse firm is rather long.

6.4.1 The Market Structure and the Speed of Diffusion

Similar to the previous chapter, we assume the relative number of firms to be distributed with respect to the length of the planning period according to a Weibull pdf. Moreover, we assume that the growth rate of wages is equal to the growth rate of output prices, so that each firm will apply its maximum planning period ($\bar{\theta}$).[243] The amount of investment for each firm is determined by equation (6.24), in which the amount of output is determined by the price-setting behaviour — the mark-up rule — and therefore by the marginal costs, which depends on the chosen technology index.

To obtain the diffusion path of a specific technology, we must examine the amount of investment of that specific technology over time. In other words, we have to examine how the market share of each firm develops in time. However, it can be easily shown that the marginal costs are constant in time for each specific firm, and thus, that the market shares are constant in a steady state.[244] If we assume that aggregate demand ($\bar{X}$) is constant and that there is no entry or exit, the diffusion pattern of a certain technology can be obtained by examining the distribution of all technologies at one point in time.

Given the parameters and including the price elasticity of final demand, we can obtain the diffusion pattern for a specific technology. This is done in figure 6.2 for several values of the demand elasticity (η).[245] The original distribution of the (relative) number of firms for each planning period, which is shown in the previous chapter, is multiplied by the market share of each firm. The next section will show that the market share is a monotonically decreasing function of the level of risk aversion, or, to be more precise, a monotonically increasing function of the length of the planning period if the length of the planning period is smaller than about 50 years.[246] Thus, the amount of investment is an increasing function of the length of the planning period, and the adoption pattern is bell-shaped, which leads to an S-shaped diffusion pattern.

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243. Note that a zero growth rate of real wages leads to infinite expected lifetimes, at least if the expected lifetime is calculated by the quasi-rent scrapping rule, which we assume to be the case.

244. Cf. equation (6.21).

245. The values of the demand elasticity are 10 for curve (a), 5 for curve (b), 2 for curve (c) and 1+1E-09, as a proxy for the limit of $\eta \downarrow 1$, for curve (d). The values of the other parameters are the same as those used in Figure 5.7 in chapter 5 (cf. footnote 203 on page 193) and the diffusion curve is displayed for technology i=50.

246. The next section shows that the market share of firms with a planning period which is longer than 54 years is smaller than the market share of more risk-averse firms.

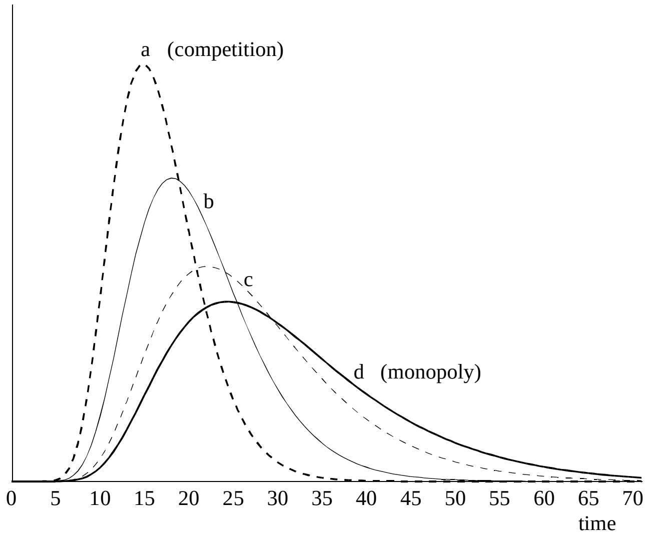

Figure 6.2. The adoption process in terms of the amount of investment in a technology

But because the relation between the amount of investment and the length of the planning period depends on the market structure, we are also able to relate the speed of diffusion to the market structure, or in this case, to the price elasticity of final demand. Curve (d) denotes the adoption pattern in the case where the demand elasticity is very low, which implies that the market is relatively monopolistic. As a result, each firm is able to maintain its own market, even if there are large price differences. Therefore, the relative difference between the technology index of the least and the most risk-averse firm, the technological distance for short, will be large. The figure is based identical values for all other parameters, with the exception of η. Thus, the speed at which firms buy more advanced technologies is the same in all cases. A large technological distance results in a slow speed of diffusion. If η increases, the market becomes more competitive which, implies that the market share for firms with relatively low marginal costs will increase at the costs of the market share of relatively risk-averse firms. Consequently, the technological distance becomes smaller and the distribution becomes more skewed to the right, which results in a faster speed of diffusion. This effect will continue for increasing values of η: the more competitive a market, the faster the diffusion process.[247] In the case of perfect competition, the firm with the lowest marginal costs will acquire the whole market, and the speed of diffusion becomes infinite.[248]

247. Although in a somewhat different setting, Fellner's (1951) theory on process innovation and market structures shows a similar relation.

248. Note that the adoption pattern is a single point in this.

6.4.2 Endogenous Diffusion Patterns

Until now, we have been able to obtain an S-shaped diffusion pattern by assuming that the relative number of firms is distributed in a bell-shaped manner with respect to the level of risk aversion. This section will show that an S-shaped diffusion pattern can be obtained *independently* of the shape of such an underlying distribution. However, this is only the case in a slightly modified version of the model and even then, only if the growth rate of real wages is positive and if the market is non-competitive.

The modification concerns the difference between firms with respect to the output they produce (including geographical distribution, service, customer relations, etc.). The previous sections assume that each firm produces a specific product, but now we will assume that each firm *type*, i.e., each group of firms with a specific planning period, produces a specific product. Moreover, we assume that if there are more firms with the same level of risk aversion, they will act like one firm, i.e. they will form a cartel in order to set the same price and will allocate the market share of the cartel among the individual firms. This implies that whatever the number of firms is with a specific planning period, the market share of the product they produce will be the same. As a result, the amount of investment remains the same. If this assumption holds, the amount of investment in an individual technology is independent of the number of firms. It only depends on the output price, and therefore on the marginal costs, given the constant mark-up rule.

An S-shaped diffusion pattern is obtained if the adoption pattern of one technology is bell-shaped (cf. Figure 6.2). As before, such adoption pattern is bell -shaped if the distribution of the amount of investment with respect to the technology index is bell shaped at one point in time, and if the rate at which firms buy new technologies is positive and constant.[249]

As before, we know that $\hat{i}_t$ is constant if the growth rate of wages and the growth rate of the non-technology-specific part of price of equipment is constant (cf. equation (6.19) on page 224). Therefore, a steady state assumption is sufficient to obtain an S-shaped diffusion pattern if the distribution of the amount of investment with respect to the technology index is bell-shaped at one point in time. The only thing we have to show is that the sign of the first derivative of the amount of investment with respect to the optimal technology index changes from positive to negative, which would indicate that the amount of investment is a bell-shaped distribution of the technology index. Because the technology index is a monotonic function of the length of the planning period, we have to show that the amount of investment is a bell-shaped function of the length of the planning period. But because the amount of investment is a constant share of the amount of output in a

249. Note that a constant rate is a sufficient condition, not a necessary one. However, a positive growth rate of the technology index is a necessary condition.

steady state, given the constant lifetime and a constant capital-output ratio, we have to show that the amount of output is a bell-shaped function of the length of the planning period. Moreover, we still require the expected profits to be an increasing function of the length of the planning period.

Unfortunately, it is not possible to establish such a relation analytically. However, we will show why such a bell-shaped distribution is possible and we will give a graphical example which is based on a simulation of the model. From appendix 6C, we know that the relative change of the amount of output due to a change of the planning period is (cf. equation (6C.12)):

$$\frac{dX_t^j}{d\theta}\frac{1}{X_t^j} = \eta\left(\frac{g_\theta}{g(\theta)} - \frac{\gamma}{\mu+\gamma}\frac{f_\theta}{f(\theta)}\right) \tag{6.32}$$

We have to show that this equation changes sign for some positive θ, under the condition that the marginal expected profits are still non-negative, i.e., (cf. equation (6C.13)):[250]

$$\frac{dPVX_t}{d\theta}\frac{1}{PVX_t} = \eta\left(\frac{g_\theta}{g(\theta)} - \frac{\eta-1}{\eta}\frac{\gamma}{\mu+\gamma}\frac{f_\theta}{f(\theta)}\right) \geq 0 \tag{6.33}$$

which holds true if the term between brackets is non-negative. Note that both equations are about the same, except for the term $(\eta-1)/\eta$ in the latter. The elasticity of substitution between different products is very high if the market is competitive (if $\eta\rightarrow\infty$). In other words, both equations are exactly the same, which in turn implies that the relative amount of investment is a positive function of the planning period for all (feasible) values of θ and that there is no S-shaped diffusion in a competitive market.

However, if the elasticity of substitution is finite, or close to one in the case of a monopolistic market, equation (6.32) can be negative even if (6.33) is positive. Moreover, if the marginal expected profits are zero, the marginal amount of output will be negative. This will happen if the (expected) growth rate of nominal wages is larger than the (expected) growth rate of output prices.[251] For the Dutch data, this is the case between 1960 and 1988, with the exception of four years in the eighties (cf. Figure A4.1 on page 145). Moreover, this will be the case if the growth rate of

250. Note that if these marginal profits are negative at the point at which the derivative of the amount of output changes sign, no firm would apply such a planning period, as a result of which the point of inflection of the diffusion curve would appear in an unfeasible region.

251. Note that the only difference between the functions $g(\theta)$ and $f(\theta)$ are the terms π and ρ.

nominal wages is larger than the growth rate of the non-technology-specific part of equipment.[252]

The previous section has shown the market share to be an increasing function of the length of the planning period and explained that this will be the case if the length of the planning period of the least risk-averse firm is shorter than 54 years. Figure 6.3 shows the amount of investment and the expected profits as a function of the length of the planning period. Given the present definition of the market share of each firm, this figure is based on a uniform distribution of the number of firms with respect to the length of the planning period. The maximum amount of investment is determined by the firm with the largest market share, which is the firm with a planning period of 54 years, for both values of the price elasticity of demand. The expected profits increase until a planning period of 60 years in the case of $\eta = 10$ and no firm will apply a longer planning. If the market is less competitive, for instance if $\eta = 5$, the corresponding planning period is 68 years.[253] This implies that the diffusion pattern is S-shaped if the length of the planning period of the least risk-averse firm is longer than 54 years.[254]

Note that for increasing values of the elasticity of substitution between consumer goods, the maximum value of the expected profits moves towards the maximum value of the amount of investment. Both will be equal if the market is competitive and the resulting diffusion pattern is not S-shaped any more.

Furthermore, the growth rate of output is implicitly assumed to be zero which implies that the amount of investment in a specific technology can be obtained using the market shares of each firm at one point in time. If output, and consequently the total amount of investment, expands in time, the amount of investment of each individual firm will increase. Because risk-averse firms will invest in a specific technology at a later point in time than less risk averse firms, their amount of investment will be larger than depicted by this figure. In other words, the length of the planning period of the firm that invests the largest amount in a specific technology, will be shorter than the length of the planning period of the firm that obtains the largest market share. In the present example, the length of the planning period of the firm that determines the point of inflection of the diffusion curve, is smaller than 54 years if the growth rate of aggregate output is positive. This phenomenon will be illustrated in the next chapter.

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252. Note that in a steady state (cf. equation (6.21)):

$$\pi = \frac{\partial p}{\partial t}\frac{1}{p} = \frac{\partial \zeta}{\partial t}\frac{1}{\zeta} = \frac{\gamma}{\mu+\gamma}\rho + \frac{\mu}{\mu+\gamma}\nu$$

such that $\pi < \rho$ if $\nu < \rho$.

253. The values for the planning period for $\eta = 2$ and for $\eta \downarrow 1$ are 96 and 990 years, respectively.

254. Note that the diffusion pattern of a certain technology is obtained by the cumulative amount of investment in that technology. The least risk-averse firm will be the first one which invests in a technology such that the diffusion pattern is obtained by aggregating the amount of investment from the right to the left, thereby starting at a planning period which corresponds to the maximum expected profits (in this figure 60 or 68 years).

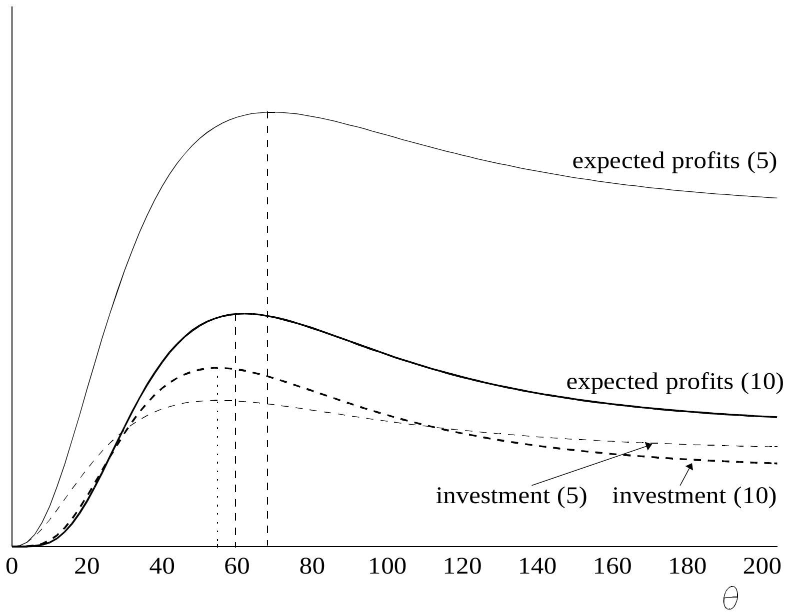

Figure 6.3. Amount of investment and expected profits for $\eta = 5$ and for $\eta = 10$[255]

Finally, we will examine the diffusion pattern if the market is nearly monopolistic. Moreover, we will assume the growth rate of wages to be large so that the market-share of less risk-averse firms are small. Figure 6.4 shows the amount of investment, and the expected profits as a function of the length of the planning period in the case where lim $\eta \downarrow 1$, and where the growth rate of nominal wages is rather large ($\rho = 10\%$). The previous chapter shows that the expected profits will reach a maximum value if the market is competitive, i.e., if prices are given (cf. curves (c) and (d) in the top graph of Figure 5C.1 on page 208). However, prices are now determined by a constant mark-up on marginal costs, so that expected profits are positive for all firms. Moreover, marginal costs are a decreasing function of the length of the planning period for relatively small values of the planning period. This is caused by the fact that firms with a longer planning period will invest in more productive equipment. But because the present value price of wages will increase if the planning period increases, and because this term increases faster than the present value of future output prices, there will be a minimum value of marginal costs as well as of the output price, and consequently, a maximum amount of output and of investment. This corresponds with point *a* in Figure 6.4 with a corresponding value of the planning period of 27 years. After that point, marginal costs increase due to an increasing planning period, leading to an increase in output prices, which causes a decrease in the amount of output, and therefore a

255. The values of the other parameters are the same as we use before, i.e., $\mu = 0.5$, $\gamma = 0.5$, $w_0 = 1$, $q_0 = 1$, $\lambda_0 = 1$, $\psi = 1$, $r = 6\%$, $\rho = 4\%$, $\nu = 0$, as in the previous chapter, we assume no depreciation ($\delta = 0$) and the growth rate of prices is equal to its steady state value: $\pi = \dfrac{\rho\gamma + \nu\mu}{\mu + \gamma} = 2\%$.

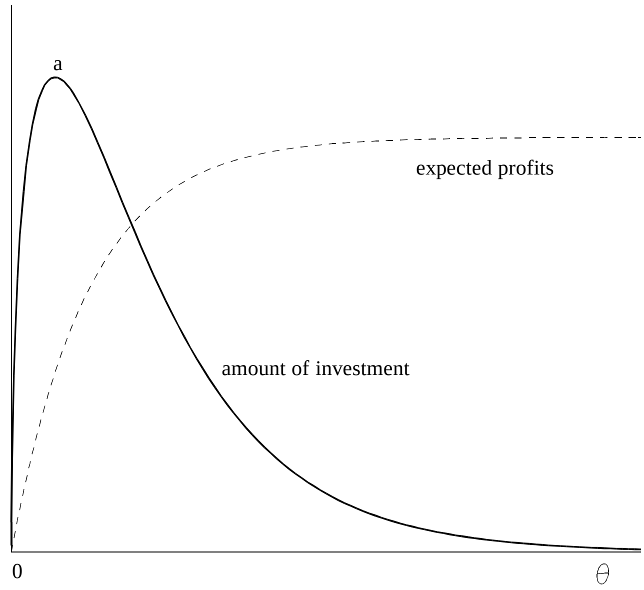

Figure 6.4. Endogenous diffusion pattern if $\lim \eta \downarrow 1$[256]

decrease in the amount of investment. This implies that the amount of investment is a bell-shaped function of the length of the planning period, whereas the expected profits are an increasing function of the planning period.[257]

To obtain an S-shaped diffusion pattern, we require firms to buy newer technologies over time, which is the case if the growth rate of nominal wages is larger than the growth rate of the non-technology-specific part of equipment. The diffusion pattern is obtained in the same way as before. Because firms buy more advanced equipment at a constant rate, the distribution of the amount of investment moves to the right, relative to the technology index. This implies that the diffusion pattern is obtained by the cumulative amount of investment in which we have to move from the right to the left in Figure 6.4. Obviously, this will lead to an S-shaped diffusion pattern. Note again that this pattern is *independent* of the distribution of firms with respect to the length of the planning period. It depends on the market structure which has to be non-competitive to obtain a sigmoid diffusion pattern.

Thus, in contrast to the diffusion pattern obtained in the previous section, and to most diffusion models found in the literature, the present model is able to generate S-shaped diffusion patterns if the output market is non-competitive, and if all firms with the same level of risk aversion — which invest in the same technology — will supply the same type of output and will act as one supplier with respect to price-setting behaviour. The length of the planning period has to be rather large to obtain

256. The values of the other parameters are: $\mu = 0.5$, $\gamma = 0.5$, $w_0 = 1$, $q_0 = 1$, $\lambda_0 = 1$, $\psi = 1$, $r = 6\%$, $\rho = 10\%$, $\nu = 0$, $\delta = 2\%$, and the growth rate of prices is equal to its steady-state value: $\pi = 5\%$.

257. In this example, expected profits will decrease if the planning period is longer than 650 years.

this result. However, chapter 7 shows that in a growing economy, the planning period that determines the point of inflection is about ten to twenty years.

6.5 Conclusions

This chapter incorporates the basic model of the previous chapter into a vintage framework. For analytical reasons, we used the model in which the length of the planning period is treated as a measure of risk aversion and for the same reason, we did not incorporate stochastic variables in our model. We showed that, if we require consistent expectations with respect to the length of the planning period, we have to use a dynamic optimization problem. However, because of its incorporated simultaneities, we employed a practical shortcut by utilizing a static model in which firms maximize the present value of rents of both the newly installed and the existing vintages. This leads to an inconsistency in the model as regards the expected and the realized lifetimes. The expected lifetime is based on the negative quasi-rent scrapping condition, whereas the current amount of scrapping is based on the Malcomson scrapping condition. We distinguish two situations: one in which the expected lifetime (according to the Malcomson scrapping condition) exceeds the maximum length of the planning period, and one in which it is less than this maximum. Since firms consider their maximum planning period in the first case, the difference between both expected lifetimes has no effect on firm behaviour. However, if the expected (Malcomson) lifetime is shorter than the maximum planning period, we introduce an inconsistency, because in general, the quasi-rent scrapping rule will lead to longer expected lifetimes than the Malcomson rule does. Although the choice of technologies is affected by this inconsistency, we showed that it is plausible that this error has marginal impacts on the chosen technology index.

Due to our practical shortcut, we are able to derive the Malcomson scrapping condition in the static model such that the marginal total costs of the newest vintage determines the amount of scrapping. The choice of the technology affects the amount of scrapping and, consequently, the amount of investment in which that technology is incorporated. Moreover, by assuming a non-competitive market structure we introduced another relation between the amount of investment and the choice of the technology. Without elaborating this, it is assumed that firms differ from one another with respect to the output they produce and we used a simple demand function in which the market share of the firm depends on its own price relative to the aggregate price, and on the price elasticity of demand. This leads to a simple mark-up rule in which the output price, and therefore the amount of output, depends on the marginal costs of the newest vintage. Buying another technology implies other marginal costs, which will affect the amount of output, and which in turn affects the amount of investment. So the amount of investment is affected by the choice of the technology in two ways: first, through the scrapping condition and, secondly, through price-setting behaviour. These two effects are demonstrated by assuming a deviation of the price of equipment from its steady-state path. Besides illustrating the interdependency of the choice of the technology and the amount of investment, this derivation shows that the demand for capital goods is downward-sloping.

With respect to the differences between the static and the dynamic model, we have already mentioned the choice of technologies. Another interesting difference is the presence of technological expectations in the dynamic model. If a firm expects that it will invest in more advanced technologies in the future, for instance due to an expected decrease in the price of equipment, it will (partially) postpone current investment so as to increase profits by waiting. We showed that this effect becomes apparent because technological expectations emerge as opportunity costs in the marginal costs of the newest vintage, which determines the amount of scrapping and, consequently, the amount of investment.

The previous chapter presents the diffusion pattern of new technologies as being the result of the choice of technologies, without investigating the amount of investment in each technology. We were able to obtain an S-shaped diffusion pattern by assuming a bell-shaped distribution of the number of firms with respect to risk aversion. Now, after we determined the amount of investment, we can determine the diffusion pattern as being the amount of investment in a specific technology. This is done in two different settings, depending on the interpretation of the difference between consumer goods and the firms that produces these goods.

In the first version, it is assumed that each firm produces a unique consumer good, for instance due to customer relations, service, etcetera. Because each firm has some monopolistic power, it is able to preserve its own market share. We can obtain S-shaped diffusion patterns by assuming a bell-shaped distribution of firms with respect to risk aversion, which is the same assumption as that used in the previous chapter. An interesting difference is that the speed of diffusion depends on the market structure and we showed that a more competitive market, i.e., a market in which the elasticity of substitution between several consumer goods is relatively high, leads to more rapid diffusion than a more monopolistic market structure.

The second version assumes that firms with the same level of risk aversion, which will invest in the same technology at each point in time, produce the same type of output. Moreover, we assume that these firms co-operate as a cartel. They set one price and distribute the market share of the cartel among the individual firms. Given this setting, we are able to derive an endogenous diffusion pattern which is S-shaped if the growth rate of wages is larger than the growth rate of output prices and if the market is not (perfectly) competitive. A smooth diffusion pattern is obtained if the market is almost monopolistic, whereas a more competitive market structure leads to a sudden start of the diffusion curve, but which is still S-shaped. Both the most and the least risk-averse firms will have relatively large marginal costs and, consequently, a small market share. The most risk-averse firms will invest in a relatively less productive technology and will have large annual wage costs. The least risk-averse firms invest in advanced technologies and will have large annual costs of capital. The moderate firms will gain the lowest annual marginal costs and, therefore, the largest market share. Note that firms with a long planning horizon, i.e., the least risk-averse firms, will still expect to obtain the largest profits, which are measured over the whole planning period of these firms.

To conclude, we are not able to determine the amount of investment outside the steady state. Moreover, the difference between a vintage model and an aggregate production function model becomes especially relevant outside the steady state. The next chapter presents some simulation experiments to highlight the properties of the model in a more turbulent (and more realistic) environment. We will also present a variant in which we will simulate the productivity slowdown, which emphasizes some differences between the quasi-clay-clay vintage model and the putty-clay diffusion model from part II.

Appendix 6A. The Solution of the Static Model

The Lagrange equation reads:

$$\mathcal{L}_t = p_t g(\theta) X_t - w_t f(\theta) \int_{t-T_t}^{t} \frac{I_{\tau,\tau} e^{-\delta(t-\tau)}}{\psi \lambda_0 i_\tau^\mu} \, d\tau - q_t i_t^\gamma I_{t,t} - \zeta \left[X_t - \int_{t-T_t}^{t} \frac{1}{\psi} I_{\tau,\tau} e^{-\delta(t-\tau)} d\tau \right] \tag{6A.1}$$

with: $g(\theta) = \int_0^\theta e^{(\pi-\delta-r)t} \, dt = \dfrac{e^{(\pi-\delta-r)\theta}-1}{\pi-\delta-r}$ and $f(\theta) = \int_0^\theta e^{(\rho-\delta-r)t} dt = \dfrac{e^{(\rho-\delta-r)\theta}-1}{\rho-\delta-r}$

and in which ξ is the Lagrange multiplier.

The first order conditions are:

$$\frac{\partial \mathcal{L}}{\partial p_t} = g(\theta) X_t + p_t g(\theta) \frac{\partial X_t}{\partial p_t} - \zeta \frac{\partial X_t}{\partial p_t} = 0 \tag{6A.2}$$

$$\frac{\partial \mathcal{L}}{\partial I_{t,t}} = -\frac{w_t f(\theta)}{\psi \lambda_0 i_t^\mu} - q_t i_t^\gamma + \frac{\zeta}{\psi} = 0 \tag{6A.3}$$

$$\frac{\partial \mathcal{L}}{\partial i} = I_{t,t} \frac{w_t \mu f(\theta)}{\psi \lambda_0 i_t^{\mu+1}} - I_{t,t} q_t \gamma i_t^{\gamma-1} = 0 \tag{6A.4}$$

$$\frac{\partial \mathcal{L}}{\partial T_t} = -I_{t-T_t,t-T_t} e^{-\delta T_t} \frac{w_t f(\theta)}{\psi \lambda_0 i_{t-T_t}^\mu} + I_{t-T_t,t-T_t} e^{-\delta T_t} \frac{\zeta}{\psi} = 0 \tag{6A.5}$$

and the last first order condition, which holds only for the newest vintage:

$$\frac{\partial \mathcal{L}}{\partial \theta} = p_t g_\theta x_{t,t} - I_{t,t} \frac{w_t f_\theta}{\psi \lambda_0 i_t^\mu} = 0 \tag{6A.6}$$

and the appropriate complementary slackness equations for the output and the planning period constraint.

The Choice of the Technology and the Initial Labour Intensity
From equation (6A.4), the optimal technology is given by:

$$i_t = \left(\frac{w_t \mu f(\theta)}{\psi \gamma \lambda_0 q_t} \right)^{\frac{1}{\mu+\gamma}} \tag{6A.7}$$

which is the same as we found in the previous chapter.[258] From equation (6A.4), we can derive the ratio of total labour costs per unit of output over total capital costs of the newest vintage. This term is equal to:

$$\frac{\left(\dfrac{w_t f(\theta)}{\lambda_0 i_t^\mu} \right)}{\psi q_t i_t^\gamma} = \frac{\gamma}{\mu} \tag{6A.8}$$

This implies that this ratio is the same for all firms, irrespective of the length of the planning period or of their level of risk aversion. Recall the production function view of

258. Here, the function f(θ) depends not only on the growth rate of nominal wages and the discount rate, but also on the rate of depreciation, whereas this latter term was assumed to be zero in the previous chapter.

the present model (equation (5.30) on page 198). The exponent of capital is equal to $\beta = \mu\ /(u+\gamma)$ which shows that the ratio of the labour share of income over the capital share of income is equal to $\mu\ /\gamma$. But note that this ratio is equal for all technologies and therefore equal for all vintages, given constant values for μ and γ. This implies that the macro-economic shares of income are equal to the same ratio.

Finally, note that the labour intensity is equal to:

$$\iota_t \equiv \frac{1}{\lambda_t^i \psi} = \frac{1}{\lambda_0 i^{\mu} \psi} = \left(\frac{1}{\psi \lambda_0}\right)^{\frac{\gamma}{\mu+\gamma}} \left(\frac{q_t \gamma}{w_t \mu f(\theta)}\right)^{\frac{\mu}{\mu+\gamma}} \tag{6A.9}$$

which implies that if, for instance, wages or the elasticity μ increase, all firms will choose a more labour-extensive way to produce output, and thus choose a more advanced technology. An increase of q_t or γ will lead to an increase of the labour intensity and thus of a decrease of the technology index. Note that the choice of technologies is very similar to the choice of the production technique, i.e., the initial labour intensity, in the putty-clay model described in part II.

Appendix 6B. Output and Investment

Output

For each firm, the amount of investments can be derived by derivation of the output constraint:

$$X_t = \frac{1}{\psi} \int_{t-T_t}^{t} I_{\tau,\tau} e^{-\delta(t-\tau)} d\tau \tag{6B.1}$$

with respect to time, so:

$$\frac{dX_t}{dt} = \frac{1}{\psi}\left[I_{t,t} - I_{t-T_t,t-T_t}\, e^{-\delta T_t} \left(1 - \frac{dT_t}{dt}\right)\right] - \frac{\delta}{\psi} \int_{t-T_t}^{t} I_{\tau,\tau} e^{-\delta(t-\tau)} d\tau \tag{6B.2}$$

in which the last term is equal to the amount of output multiplied by the rate of depreciation. Solving for $I_{t,t}$ yields:

$$I_{t,t} = \psi\left(\frac{dX_t}{dt} + \delta X_t\right) + I_{t-T_t,t-T_t} e^{-\delta T_t}\left(1 - \frac{dT_t}{dt}\right) \tag{6B.3}$$

We have previously shown that the lifetime is constant in a steady state. Dividing equation (6B.3) by the amount of output of the newest vintage yields:

$$\frac{I_{t,t}}{X_{t,t}} = \psi\left(\frac{dX_t}{dt}\frac{1}{X_{t,t}} + \delta \frac{X_t}{X_{t,t}}\right) + \frac{I_{t-T_t,t-T_t}}{X_{t-T_t,t-T_t}} \frac{X_{t-T_t,t-T_t}}{X_{t,t}} e^{-\delta T_t} \tag{6B.4}$$

In the steady state, total output grows at a constant rate χ, the capital output ratio is constant and the growth rate of output for each vintage is constant, due to a constant planning period. This implies that:

$$\frac{I_{t,t}}{X_{t,t}} = \frac{X_t}{X_{t,t}} \psi[\chi + \delta] + \psi e^{-(\chi+\delta)T} \tag{6B.5}$$

Solving for the amount of investment of the newest vintage yields:

$$I_{t,t} = X_t \psi \left(\frac{\chi + \delta}{1 - e^{(-\chi-\delta)T}} \right) \tag{6B.6}$$

which is shown in the main text.

Investment

A change of the amount of investment due to a change of the price of equipment can be obtained by differentiating equation (6B.6) towards q_t:

$$\begin{aligned} \frac{dI_{t,t}}{dq_t} &= \psi \left(\frac{\chi + \delta}{1 - e^{(-\chi-\delta)T_t}} \right) \frac{\partial X_t}{\partial q_t} - X_t \psi \left(\frac{(\chi+\delta)^2 e^{(-\chi-\delta)T_t}}{(1 - e^{(-\chi-\delta)T_t})^2} \right) \frac{\partial T_t}{\partial q_t} \\ &= \frac{I_{t,t}}{X_t} \frac{\partial X_t}{\partial q_t} - \frac{I_{t-T_t,t}}{K_t} \frac{\partial T}{\partial q_t} \end{aligned} \tag{6B.7}$$

in which K_t stands for the capital stock and $I_{t-T_t,t}$ denotes the amount of capital of the oldest vintage, which still exists at time t. The first term at the right-hand side of this equation denotes the output effect and the second term represents the lifetime effect. From equations (6.8) and (6.22) we already know that:

$$\frac{\partial X_t}{\partial q_t} = \frac{\partial X_t}{\partial p_t} \frac{\partial p_t}{\partial q_t} = -\eta \frac{X_t}{p_t} \frac{\mu}{\mu+\gamma} \frac{p_t}{q_t} = -\frac{\eta \mu}{\mu+\gamma} \frac{X_t}{q_t} \tag{6B.8}$$

which is negative as expected; because an increase of the costs of capital will lead to an increase of the marginal costs, firms will, given their constant mark-up ratio, increase the output price. This will reduce the final demand for the individual firm.

The lifetime of the oldest vintage depends on the price of equipment through the Malcomson condition. A change of q_t will change the marginal total costs of the newest vintage, which will then determine the lifetime of the oldest vintage:

$$\frac{\partial T_t}{\partial q_t} = \frac{d\zeta_t}{dq_t} \frac{dT_t}{d\zeta_t} \tag{6B.9}$$

From the marginal costs function, equation (6.10), it follows that:

$$\frac{d\zeta_t}{dq_t} = \frac{\mu}{\mu+\gamma} \frac{\zeta_t}{q_t} \tag{6B.10}$$

and from the scrapping condition (cf. equation (6.13)), we know that equipment is scrapped if:

$$\frac{w_t\, f(\theta)}{\lambda_0 i_{t-T_t}^{\mu}} = \zeta_t = \left(\frac{w_t\, f(\theta)}{\lambda_0} \right)^{\frac{\gamma}{\mu+\gamma}} \left(\frac{\psi q_t \gamma}{\mu} \right)^{\frac{\mu}{\mu+\gamma}} \left(1 + \frac{\mu}{\gamma} \right) \quad \text{with} \quad i_{t-T_t} = \left(\frac{w_{t-T_t} f(\theta, t-T_t)}{q_{t-T_t} \lambda_o \psi \gamma} \right)^{\frac{1}{\mu+\gamma}} \tag{6B.11}$$

Using the constant growth rates of wages (ρ) and of price of equipment (ν), we can solve the lifetime of the oldest vintage:

$$T_t = \frac{-1}{\rho - \nu} \ln \left[q_t \psi \gamma \left(\frac{w_t\, f(\theta)}{\lambda_0} \right)^{\frac{\gamma}{\mu}} \zeta^{-\left(\frac{\mu+\gamma}{\mu}\right)} \right] \tag{6B.12}$$

in which we assumed that the length of the planning period is the same for vintage $t-T_t$ and for the newest vintage at time t. Differentiating yields:

$$\frac{dT_t}{dq_t} = \frac{\mu}{\mu+\gamma}\frac{\zeta_t}{q_t} \tag{6B.13}$$

Substituting in equation (6B.9) yields:

$$\frac{\partial T_t}{\partial q_t} = \frac{1}{\rho-\nu}\frac{1}{q_t} \tag{6B.14}$$

leading to:

$$\frac{\partial I_{t,t}}{\partial q_t}\frac{q_t}{I_{t,t}} = -\frac{\eta\mu}{\mu+\gamma} - \frac{1}{\rho-\nu}\frac{I_{t-T_t,t}}{K_t} \tag{6B.15}$$

which is shown in the main text (equation (6.25)).

Appendix 6C. Expected Profits of all Vintages and the Length of the Planning Period

This appendix shows that, in a steady state, the expected profits of a firm increase if the length of the planning period increases. Chapter 5 shows that the expected profits of the newest vintage increase if the length of the planning period increases. Here, we will show the result of the whole firm, i.e., all vintages taken together.
The expected profits are defined as:

$$PVX_t = p_t g(\theta) X_t - w_t f(\theta) \int_{t-T_t}^{t} \frac{I_{\tau,\tau} e^{-\delta(t-\tau)}}{\psi\lambda_0 i_\tau^{\mu}} d\tau - q_t i_t^{\gamma} I_{t,t} \tag{6C.1}$$

Substitution of the optimal technology yields:

$$PVX_t = p_t g(\theta) X_t - \frac{w_t f(\theta)}{\psi\lambda_0} \int_{t-T_t}^{t} I_{\tau,\tau} e^{-\delta(t-\tau)} \left(\frac{w_\tau \mu f(\theta)}{\psi\gamma q_\tau \lambda_0}\right)^{\frac{-\mu}{\mu+\gamma}} d\tau - q_t I_{t,t} \left(\frac{w_t \mu f(\theta)}{\psi\gamma q_t \lambda_0}\right)^{\frac{\gamma}{\mu+\gamma}} \tag{6C.2}$$

Using the steady-state assumption that the growth rate of nominal wages (ρ) as well as the growth rate of the non-technology-specific part of capital goods prices (ν) are constant in time, we obtain:

$$PVX_t = p_t g(\theta) X_t - \left(\frac{w_t f(\theta)}{\psi\lambda_0}\right)^{\frac{\gamma}{\mu+\gamma}} \left(\frac{\mu}{\gamma q_t}\right)^{\frac{-\mu}{\mu+\gamma}} \int_{t-T_t}^{t} I_{\tau,\tau} e^{-\delta(t-\tau)} e^{\frac{-\mu}{\mu+\gamma}(\nu-\rho)(t-\tau)} d\tau - q_t I_{t,t} \left(\frac{w_t \mu f(\theta)}{\psi\gamma q_t \lambda_0}\right)^{\frac{\gamma}{\mu+\gamma}} \tag{6C.3}$$

The amount of investment in a steady state is defined by equation (6B.6). Substitution of this equation and making use of the constant growth rate of total output, equation (6C.3) becomes:

$$PVX_t = X_t \left[p_t g(\theta) - \left(\frac{w_t f(\theta)}{\lambda_0}\right)^{\frac{\gamma}{\mu+\gamma}} \left(\frac{\psi q_t \gamma}{\mu}\right)^{\frac{\mu}{\mu+\gamma}} \frac{(\chi+\delta)}{1-e^{(-\chi-\delta)T_t}} \left[z(t,T_t) + \frac{\mu}{\gamma} \right] \right]$$

$$\text{with} \quad z(t,T_t) = \int_{t-T_t}^{t} e^{(-\chi-\delta+\frac{\mu}{\mu+\gamma}(\rho-\nu))(t-\tau)} d\tau = \frac{e^{(-\chi-\delta+\frac{\mu}{\mu+\gamma}(\rho-\nu))T_t} - 1}{-\chi-\delta+\frac{\mu}{\mu+\gamma}(\rho-\nu)} \tag{6C.4}$$

in which the first term between brackets ($p_t g(\theta)$) denotes the present value of marginal returns, whereas the second term denotes the present value of marginal costs.

The price of output is equal to the marginal costs of the newest vintage times a mark-up factor. Substitution of the output price yields:

$$PVX_t = X_t\left(\frac{w_t f(\theta)}{\lambda_0}\right)^{\frac{\gamma}{\mu+\gamma}}\left(\frac{\psi q_t \gamma}{\mu}\right)^{\frac{\mu}{\mu+\gamma}}\left[\frac{\eta}{\eta-1}\left(1+\frac{\mu}{\gamma}\right) - \frac{(\chi+\delta)}{1-e^{(-\chi-\delta)T_t}}\left[z(t,T_t) + \frac{\mu}{\gamma}\right]\right] \tag{6C.5}$$

which means that the relative change of the expected profits due to a change of the planning period is:

$$\frac{dPVX}{d\theta}\frac{1}{PVX} = \frac{\partial X}{\partial\theta}\frac{1}{X} + \frac{\partial PV}{\partial\theta}\frac{1}{PV} \tag{6C.6}$$

in which PV denotes the present value of expected profits *per unit of output*.

The relative change of the expected profits per unit of output due to a change of the length of the planning period is equal to:

$$\frac{dPV}{d\theta}\frac{1}{PV} = \frac{\gamma}{\mu+\gamma}\frac{f_\theta}{f(\theta)} > 0 \tag{6C.7}$$

However, the market share and, thus, the amount of output, do not necessarily increase as the length of the planning period increases. The amount of output of firm j is equal to:

$$X_t^j = \left(\frac{p_t^j}{\bar{P}}\right)^{-\eta}\left(\frac{\bar{X}_t}{J}\right) \tag{6C.8}$$

and the change of the expected amount of output due to a change in the length of the planning period is equal to:

$$\frac{dX_t^j}{d\theta}\frac{1}{X_t^j} = -\eta\frac{dp_t^j}{d\theta}\frac{1}{p_t^j} \tag{6C.9}$$

in which the output price is equal to (cf. equation (6.9)):

$$p_t = \frac{\eta}{\eta-1}\frac{\zeta_t}{g(\theta)} \tag{6C.10}$$

The relative change of the price of output is:

$$\frac{dp}{d\theta}\frac{1}{p} = \frac{\gamma}{\mu+\gamma}\frac{f_\theta}{f(\theta)} - \frac{g_\theta}{g(\theta)} \tag{6C.11}$$

which can be positive or negative. The relative change in the amount of output due to a change in the length of the planning period is thus equal to:

$$\frac{dX_t^j}{d\theta}\frac{1}{X_t^j} = -\eta\left(\frac{\gamma}{\mu+\gamma}\frac{f_\theta}{f(\theta)} - \frac{g_\theta}{g(\theta)}\right) \tag{6C.12}$$

Thus, the sign depends on the sign of the change of the output price.
The relative change of the expected profits due to a change of the length of the planning period is:

$$\frac{dPVX_t}{d\theta}\frac{1}{PVX_t} = \frac{dX_t}{d\theta}\frac{1}{X_t} + \frac{dPV_t}{d\theta}\frac{1}{PV_t} = \eta\left(\frac{g_\theta}{g(\theta)} - \frac{\eta-1}{\eta}\frac{\gamma}{\mu+\gamma}\frac{f_\theta}{f(\theta)}\right) \tag{6C.13}$$

Now, we will prove that the term within brackets is non-negative, which leads to the conclusion that total profits are non-decreasing as the length of the planning period increases.

This can be shown by using the last first-order condition of the maximization problem (equation (6A.6)). This condition implies that a firm will extend its planning period as long as the change of the expected profits of the newest vintage due to a change of the length of the planning period is positive, cf. equation (6.11):

$$p_t g_\theta - \frac{w_t f_\theta}{\lambda_0 i_t^\mu} \geq 0 \tag{6C.14}$$

Substitution of the optimal technology and the price of output yields:

$$\frac{g_\theta}{g(\theta)} - \frac{\eta-1}{\eta}\frac{\gamma}{\mu+\gamma}\frac{f_\theta}{f(\theta)} \geq 0 \tag{6C.15}$$

which implies that equation (6C.13) has to be non-negative. Note that the relative change of the expected profits is positive if the length of the planning period is equal to its upper boundary, i.e. if the length of the planning period is determined by the maximum level of risk the firm is prepared to take.

Appendix 6D. Solution of the Dynamic Model

Substitution of equations (6.28) and (6.3) in (6.27) gives the Lagrange equation:

$$L_{t_0} = \int_{t_0}^{t_0+\theta} \{ e^{-r(t-t_0)} \left[X_t p_t - q_t i_t^\gamma I_{t,t} \right] - \phi_t X_t - e^{-r(t-t_0)} w_t \int_{t-T_t}^{t} \frac{I_{\tau,\tau} e^{-\delta(t-\tau)}}{\kappa \lambda_0 i_\tau^\mu} d\tau + \frac{\phi_t}{\kappa} \int_{t-T_t}^{t} I_{\tau,\tau} e^{-\delta(t-\tau)} d\tau \} \, dt \tag{6D.1}$$

in which ϕ_t describes the (time-dependent) Lagrange multiplier. It is assumed that if a vintage is scrapped, it will be scrapped for ever. In other words, the change of the age of the oldest vintage cannot be larger than the change in time, $\dot{T}_t \leq 1$, in which a dot denotes the time derivative. The control variables of this problem are included in the inner integrals, and the expected lifetime is not present in the problem at all. Following Malcomson (1972, 1975), we will transfer the outer integral to the integral over all (existing and future) vintages. The expected lifetime (L_t) of a vintage is introduced in order to make this step possible. The integral from $t-T_t$ to t is transferred to the integral from t^* to $t^*+L_{t^*}$. So $t-T_t = t^*$ and $t = t^* + L_{t^*}$ which leads to $L_{t^*} = T_{t^*+L_{t^*}}$ or $L_t = T_{t+L_t}$. This is only valid if older vintages are scrapped prior to newer ones, which we assume to be the case in this model. The restriction $\dot{T}_t \leq 1$ is then equivalent to $\dot{L}_t \geq -1$.[259]
The Lagrange equation can be rewritten as:[260]

259. Cf. Malcomson (1972). This condition can be made more clear as follows: suppose that a firm invests in year t and expect that this vintage will be scrapped at t+L(t). After some time Δ, so at time t+Δ, the firm invests in another vintage with t+Δ+L(t+Δ) as the expected date of scrapping. The condition is that the first vintage has to be scrapped before the second one, thus t+Δ+L(t+Δ) ≥ t+L(t). This implies that L(t+Δ)-L(t)≥-Δ. Dividing by Δ and taking the limit of Δ↓0 yields the condition as shown in the text.

260. Cf. Malcomson (1975: 38).

$$L_{t_0} = \int_{t_0 - T_{t_0}}^{t_0+\theta} \{ \Xi_t e^{-r(t-t_0)} \Big[X_t p_t - q_t i_t^{\gamma} I_{t,t} \Big] - \phi_t \Xi_t X_t -$$

$$\frac{I_{t,t} e^{-r(t-t_0)}}{\psi \lambda_0 i_t^{\mu}} \int_t^{t+L_t} w_\tau \Xi_\tau e^{(-\delta - r)(\tau - t)} d\tau + \frac{I_{t,t}}{\psi} \int_t^{t+L_t} \phi_\tau \Xi_\tau e^{-\delta(\tau - t)} d\tau \} dt \quad \text{where } \Xi_t \begin{cases} = 1 \text{ if } t \geq t_0 \\ = 0 \text{ if } t < t_0 \end{cases} \tag{6D.2}$$

In this dynamic problem, L_t and i_t can be regarded as state variables while $I_{t,t}$ and p_t are control variables. Two surrogate control variables are introduced, which affect the state variables: $c_t^L = dL/dt$ and $c_t^i = di/dt$. From $\dot{L}_t \geq -1$ it follows that $c_t^L \geq -1$, which implies that $-(1+c_t^L) \leq 0$.

Above we assumed that older vintages are scrapped before newer ones. Thus, without disembodied technological progress, we have to assume that firms buy technologies which are at least as good as the existing ones, which implies that $c_t^i \geq 0$. Furthermore, we assume that $p_t > 0$ and $L_t > 0$ for all t.

Now, two cases arise, the first in which it is assumed that firms will always buy new technologies, i.e., $di/dt > 0$, and the second in which firms may choose to invest in the same technology at different points in time. Recall from the previous section that the first case will lead to a finite lifetime of equipment, whereas the lifetime is infinite in the second case. Below, we will show a similar result in this dynamic model.

The Lagrange equation of the dynamic model can be written as:

$$\mathfrak{L} = F(p,I,i,L,\phi)dt + \Gamma_t^L c_t^L + \Gamma_t^i c_t^i + \theta_1 (c_t^L + 1) + \theta_2 c_t^i + \theta_3 I_t$$

$$\begin{aligned} s.t. \quad \dot{L}_t &= c_t^L \\ di_t / dt &= c_t^i \\ -(c_t^L + 1) &\leq 0 \\ -c_t^i &\leq 0 \\ -p_t &< 0 \\ -I_t &\leq 0 \\ -i_t &< 0 \\ -L_t &< 0 \end{aligned} \tag{6D.3}$$

in which $F()$ represents the term within the outer integral of equation (6D.2). The costate variables are denoted by Γ_t^L and Γ_t^i.

The first-order conditions for this problem are:

$$\frac{\partial \mathcal{L}}{\partial \Gamma^L} = \frac{dL}{dt} \qquad (a)$$

$$\frac{\partial \mathcal{L}}{\partial \Gamma^i} = \frac{di}{dt} \qquad (b)$$

$$\frac{\partial \mathcal{L}}{\partial c^L} = 0,\ \theta_1 \geq 0,\ (c^L+1) \geq 0,\ \theta_1(c^L+1) = 0 \qquad (c)$$

$$\frac{\partial \mathcal{L}}{\partial c^i} = 0,\ \theta_2 \geq 0,\ c^i \geq 0,\ \theta_2 c^i = 0 \qquad (d)$$

$$\frac{\partial \mathcal{L}}{\partial I} = 0,\ \theta_3 \geq 0,\ I_t \geq 0,\ \theta_3 I_t = 0 \qquad (e) \qquad (6D.4)$$

$$\frac{\partial \mathcal{L}}{\partial p} = 0\ ;\ p_t > 0 \qquad (f)$$

$$\frac{\partial \mathcal{L}}{\partial \phi} = 0 \qquad (g)$$

$$\frac{\partial \mathcal{L}}{\partial L} = -\frac{d\Gamma_L}{dt}\ ;\ L(t) > 0 \qquad (h)$$

$$\frac{\partial \mathcal{L}}{\partial i} = -\frac{d\Gamma^i}{dt}\ ;\ i_t > 0 \qquad (i)$$

Note that $\partial \mathcal{L} / \partial c^L = \Gamma^L_t + \theta_1 = 0\ \forall\ t$, which is equal to $\partial \mathcal{L} / \partial c^L = \Gamma^L_t = 0\ \forall\ t$ if the constraint $\dot{L}_t \geq -1$ is not strictly binding. This is equivalent to not wishing to scrap older equipment before newer vintages, which we excluded to be the case. Consequently, we assume that $\Gamma^L_t = 0\ \forall t$, so that the transversality condition $\Gamma^L_{t=\theta} = 0$ holds, which also implies that $d\Gamma^L / dt = 0$ so that first order condition (h) becomes: $\partial \mathcal{L} / \partial L = 0$.

The complementary slackness variables in first-order condition (d) leads to three different cases. The first in which firms will always buy more advanced technologies, the second, in which firms buy the same technology, and the last case in which firms will buy less advanced technologies. We cannot exclude the possibility that firms buy the same technology as they did before, but we will exclude the situation in which firms will buy less advanced equipment.

Moreover, first-order condition (e) leads to two cases: one in which $I_t > 0$, and the second in which the amount of investment is zero. The case in which $I_t = 0$ is described in for instance Nickell (1975) and van den Noord (1990). Here, we will assume that the amount of investment is positive at each point in time.

First, we will describe the case in which a firm always buys newer equipment, i.e., the constraint $di_t / dt \geq 0$ is not strictly binding. Secondly, we will describe the case in which $di_t / dt = 0$. In both cases, we find $\partial \mathcal{L} / \partial c^i = \Gamma^i_t = 0\ \forall t$, which implies that the transversality condition $\Gamma^i_{t=\theta} = 0$ holds.

In the first case, ($di_t / dt > 0$), the last two conditions can be rewritten as: $\partial \mathcal{L} / \partial L \leq 0\ ;\ L_t \geq 0$ and $\partial \mathcal{L} / \partial i = 0;\ i_t > 0$. The fifth condition ($e$) is transferred to $\partial \mathcal{L} / \partial I = 0;\ I_t > 0$. From the first-order conditions, it follows that:

$$\frac{\partial \mathcal{L}}{\partial p} = 0 \Rightarrow e^{-r(t-t_0)}[X_t + \frac{\partial X}{\partial p} p_t] - \phi_t \frac{\partial X}{\partial p} = 0 \qquad (6D.5)$$

$$\frac{\partial \mathcal{L}}{\partial I} = 0 \Rightarrow \quad -e^{-r(t-t_0)} q_t i_t^{\gamma} - \frac{e^{-r(t-t_0)}}{\psi \lambda_0 i_t^{\mu}} \int_t^{t+L_t} w_\tau e^{(-\delta - r)(\tau - t)} d\tau + \frac{1}{\psi} \int_t^{t+L_t} \phi_\tau e^{-\delta(\tau - t)} d\tau = 0 \tag{6D.6}$$

$$\frac{\partial \mathcal{L}}{\partial i} = 0 \Rightarrow \quad -e^{-r(t-t_0)} q_t \gamma i_t^{\gamma-1} I_{t,t} + \frac{\mu I_{t,t} e^{-r(t-t_0)}}{\psi \lambda_0 i_t^{\mu+1}} \int_t^{t+L_t} w_\tau e^{(-\delta - r)(\tau - t)} d\tau = 0 \tag{6D.7}$$

$$\frac{\partial \mathcal{L}}{\partial L} = 0 \Rightarrow \quad -\frac{I_{t,t} e^{-r(t-t_0)}}{\psi \lambda_0 i_t^{\mu}} w_{t+L_t} e^{(-\delta - r)L_t} + \frac{1}{\psi} I_{t,t} \phi_{t+L_t} e^{-\delta L_t} = 0 \tag{6D.8}$$

and the output constraint.

Multiplying equation (6D.6) by ψ gives:

$$-e^{-r(t-t_0)} \psi q_t i_t^{\gamma} - \frac{e^{-r(t-t_0)}}{\lambda_0 i_t^{\mu}} \int_t^{t+L_t} w_\tau e^{(-\delta - r)(\tau - t)} d\tau + \int_t^{t+L_t} \phi_\tau e^{-\delta(\tau - t)} d\tau = 0 \tag{6D.9}$$

Differentiating this equation to t gives:

$$\begin{aligned} & e^{-r(t-t_0)} r \psi q_t i_t^{\gamma} - e^{-r(t-t_0)} \frac{dq_t}{dt} \psi i_t^{\gamma} - e^{-r(t-t_0)} q_t \psi \gamma i_t^{\gamma-1} \frac{\partial i_t}{\partial t} + \frac{\mu}{\lambda_0 i_t^{\mu+1}} \frac{\partial i_t}{\partial t} \int_t^{t+L_t} w_\tau e^{(-\delta-r)(\tau-t)} d\tau - \\ & \frac{e^{-r(t-t_0)}}{\lambda_0 i_t^{\mu}} \left[w_{t+L_t} e^{(-\delta-r)L_t} \left(1 + \frac{dL}{dt}\right) - w_t + (\delta + r) \int_t^{t+L_t} w_\tau e^{(-\delta-r)(\tau-t)} d\tau \right] + \\ & \phi_{t+L_t} e^{-\delta L_t} \left(1 + \frac{dL}{dt}\right) - \phi_t + \delta \int_t^{t+L_t} \phi_\tau e^{-\delta(\tau-t)} d\tau = 0 \end{aligned} \tag{6D.10}$$

From equation (6D.8) it follows that:

$$w_{t+L_t} e^{(-\delta-r)L_t} = \phi_{t+L_t} \lambda_0 i_t^{\mu} \frac{e^{-\delta L_t}}{e^{-r(t-t_0)}} \tag{6D.11}$$

By substitution of this equation into equation (6D.10), two terms cancel out. By making use of equation (6D.6), equation (6D.10) simplifies to:

$$\begin{aligned} & e^{-r(t-t_0)} r \psi q_t i_t^{\gamma} - e^{-r(t-t_0)} \frac{dq}{dt} \psi i_t^{\gamma} - e^{-r(t-t_0)} q_t \psi \gamma i_t^{\gamma-1} \frac{\partial i_t}{\partial t} + \left[r + \frac{\mu}{i_t} \frac{\partial i}{\partial t} \right] \frac{e^{-r(t-t_0)}}{\lambda_0 i_t^{\mu}} \int_t^{t+L_t} w_\tau e^{(-\delta-r)(\tau-t)} d\tau + \\ & \delta \psi e^{-r(t-t_0)} q_t i_t^{\gamma} - \frac{e^{-r(t-t_0)}}{\lambda_0 i_t^{\mu}} \left[r \int_t^{t+L_t} w_\tau e^{(-\delta-r)(\tau-t)} d\tau - w_t \right] - \phi_t = 0 \end{aligned} \tag{6D.12}$$

Solving for ϕ_t gives:

$$\phi_t = e^{-r(t-t_0)} \left\{ \frac{w_t}{\lambda_0 i_t^{\mu}} + \psi q_t i_t^{\gamma} \left[r + \delta - \hat{q}_t \right] - \hat{i}_t \left[\frac{-\mu}{\lambda_0 i_t^{\mu}} \int_t^{t+L_t} w_\tau e^{(-\delta-r)(\tau-t)} d\tau + \gamma \psi q_t i_t^{\gamma} \right] \right\} \tag{6D.13}$$

This equation is shown in the main text (equation (6.30)).

The second case is obtained by assuming that firms buy the same technology in succeeding years, i.e. $di_t/dt=0$. However, as the change of the technology index is still assumed to be non-negative, all first-order conditions remain the same, except for the fourth first-order condition (d), for which both the complementary slackness variable and c^i will be zero. As $\hat{i}_t = 0$, ϕ_t is now equal to:

$$\phi_t = e^{-r(t-t_0)} \left\{ \frac{w_t}{\lambda_0 i_t^{\mu}} + \psi q_t i_t^{\gamma} \left[r + \delta - \hat{q}_t \right] \right\} \tag{6D.14}$$

which is independent of the expected lifetime of equipment. This can be explained as follows: if a firm will choose the same technology for more than one period, there are no opportunity costs of waiting one period to gain from choosing a more advanced technology. Therefore, the last term of the original definition of the marginal costs (cf. equation (6D.13)) disappears. Because this term disappears and the labour productivity does not change over time, the marginal costs of an older vintage are always below the marginal costs of the newest vintage. The expected lifetime will then be infinite and a firm will always apply its maximum length of the planning period ($\bar{\theta}$).

Optimal Technology Index

The optimal technology index is obtained by solving equation (6D.7):

$$e^{-r(t-t_0)} q_t \gamma i_t^{\gamma-1} = \frac{\mu e^{-r(t-t_0)}}{\psi \lambda_0 i_t^{\mu+1}} \int_t^{t+L_t} w_\tau e^{(-\delta-r)(\tau-t)} d\tau \tag{6D.15}$$

Solving for i gives:

$$i_t = \left(\frac{\mu}{\psi \lambda_0 \gamma q_t} \int_t^{t+L_t} w_\tau e^{(-\delta-r)(\tau-t)} \right)^{\frac{1}{\mu+\gamma}} = \left(\frac{w_t \mu f(L_t)}{\psi \lambda_0 \gamma q_t} \right)^{\frac{1}{\mu+\gamma}} \tag{6D.16}$$

where the function $f()$ is the same as that used in the previous section and in chapter 5. Equation (6D.16) is shown in the main text (equation (6.29)).

Scrapping Condition

The scrapping condition can be derived from equation (6D.8). From this equation it follows that:

$$I_{t,t} \frac{e^{-\delta L_t}}{\kappa} \left\{ \phi_{t+L_t} - \frac{w_{t+L_t} e^{-r(t+L_t-t_0)}}{\lambda_0 i_t^{\mu}} \right\} = 0 \tag{6D.17}$$

which holds for all values of t. Equipment is scrapped if the term between brackets is equal to zero. Replacing t by $t-T_t$, and thus $t+L_t$ by t, this term is equal to:

$$\phi_t - \frac{w_t e^{-r(t-t_0)}}{\lambda_0 i_{t-T_t}^{\mu}} = 0 \tag{6D.18}$$

which is the scrapping condition.

7 Simulation Results of the Quasi-Clay-Clay Vintage Model

This chapter presents some simulation results of the static quasi-clay-clay diffusion model. The main purpose of these simulation experiments is to highlight both the characteristics of typical vintage features, such as the lifetime of equipment, and characteristics of the diffusion process if the model deviates from the steady-state growth path. The first experiment is to investigate whether the present model can describe the productivity slowdown. In part II, we explained the productivity slowdown by a decrease in the growth rate of wages. It was argued that the incentive to innovate will decrease and firms will decrease the rate of investment in new technologies. In the present simulation experiment, we will impose a decline upon the growth rate of nominal wages and we will investigate what the present model predicts with respect to the productivity slowdown. We will compare the quasi-clay-clay model with a standard putty-clay model in order to analyze the differences.

The second experiment involves a simulation of such endogenous S-shaped diffusion patterns as described in the previous section. Such an experiment enables us to examine the differences with regard to market shares and expected profits between different firms. Moreover, we will show that the parameters needed to generate such S-shaped diffusions pattern are not that exceptional as suggested in the previous chapter. This experiment is combined with a shock of the non-technology-specific part of prices of capital goods. Contrary to a decrease in the growth rate of wages, a shock in q_t will affect all firms in the same way.

The third and last experiment concerns a reduction in the price of one technology. This is done to get some insights in the reactions with regard to the amount of investment on the price of equipment so that we can determine the slope of the demand curve by means of a numerical example. The result is used in the final section of this chapter: the supply of new technologies.

In part II as well as in the present part, it is assumed that equipment is more expensive if the incorporated technology is more advanced. Moreover, the present model generates positive technological change if, and only if, the growth rate in the non-technology specific part of equipment is less than the growth rate in wages. Although we will not present a formal model, section 7.5 gives some possible explanations of the supply-side in which both properties are likely to hold.

Besides the non-learning version of the quasi-clay-clay vintage model, we experimented with the learning-by-doing case. One main goal was to obtain S-shaped intra-firm diffusion for this case. However, without making additional assumptions, such as the introduction of adjustment costs à la Stoneman (1981), the intra-firm diffusion patterns are not S-shaped and this experiment gives no additional insights into the results already obtained in chapter 5. All firms invest in the same technology for some time until the growth rate of labour productivity which is caused by learning-by-doing effects decreases as a result of which investment in a new technology becomes profitable. Because the capital stock contains a large number of equally productive vintages, the amount of scrapping appears to be very large if a firm switches to a new technology so that the initial amount of investment in the new technology is relatively large. After a firm switches to that new technology, no equipment is scrapped until the specific firm switches to another, more advanced technology again. This implies that the initial amount of investment is rather high whereas investment in succeeding periods is only needed to keep the capital stock in line with the growth rate of output. This implies that the intra-firm diffusion patterns start with a huge jump and increase at a constant rate afterwards so that the model as it stands now is not capable to describe an S-shaped intra-firm pattern. So, the learning-by-doing version is not described and this final chapter of this part concentrates on the results of the non-learning case.

7.1 The Simulation Models and Some Steady State Results

Before we will turn to the actual simulation results, this section discusses the way in which we translated the theoretical models into models to be used for simulation purposes. Moreover, we will calibrate the quasi-clay-clay and the putty-clay models in such a way that the steady-state growth rates as well as some levels, e.g. employment, are the same for both. Finally, we will examine the steady-state diffusion process of the quasi-clay-clay model and compare this with the diffusion process presented in the previous chapter.

7.1.1 The Quasi-Clay-Clay Model

The quasi-clay-clay model, QCC model for short, is defined in continuous time and incorporates an infinite number of different technologies and firms. However, the simulation model is discontinuous in nature and it is impossible to simulate an infinite number of different firms. Moreover, the technologies are indexed by non-integer numbers, which makes the determination of the diffusion process impossible. This section discusses some (minor) modifications that make the model usable for simulations purposes.

The experiments are carried out for eleven different firm types, and the diffusion process can be calculated for seven different technologies.[261] A firm type may represent more than one firm, but all these firms have identical levels of risk aversion and, therefore, identical planning horizons, which means that they will invest in the same technology. As noted previously, they differ from each other with respect to customer relations, service, geographical distribution, etc. Thus, we have to allocate a planning period to each firm type. In order to obtain a more or less linear distribution of the chosen technologies and realistic diffusion patterns, we used a loglinear distribution of the length of the planning period.[262] In the previous chapter we used a Weibull distribution of the number of firms for each length of the planning period. This assumption will be maintained in the simulation experiments. The length of the planning period and the corresponding number of firms are displayed in Figure 7.1.[263]

The simulation is carried out in two steps to avoid severe deviations from the steady-state path in the first periods. The steady-state growth rates as well as the amount of investment are calculated in the first step. From the amount of investment in the last period, the amount of investment for the initial vintages is calculated by using the average growth rate. In the second step, the initial capital stock is built up by using the predetermined amount of investment. The model runs in the simulation mode (the second step) from period L^{max} onwards, in which L^{max} denotes the maximum number of vintages allowed for. Furthermore, from the first step, we can calculate the range of technologies in which all firms will invest so that we are able to determine for which technologies we will examine the diffusion path. This is discussed at the end of this section.

261. The total number of firm types and technologies is limited due to limited computer memory, and has been chosen to obtain ‘realistic’ diffusion patterns, i.e., diffusion patterns that are comparable with the patterns we showed in the previous chapter.

262. If we used a linear distribution of the length of the planning period instead, the difference between the succeeding technologies would decline for increasing values of the planning period. This would result in severe discontinuities in the diffusion pattern.

263. The length of planning period of the most risk-averse firm is chosen to be 5 periods, whereas the east risk-averse firm has a planning horizon of 35 periods. The length of the planning period for the j’th firm type is defined by: $\theta^j = \theta_{low} e^{(j-1)*\alpha}$ with $\alpha = \frac{1}{(J-1)} \ln(\theta_{high} - \theta_{low})$ in which capital J denotes the number of firm types.

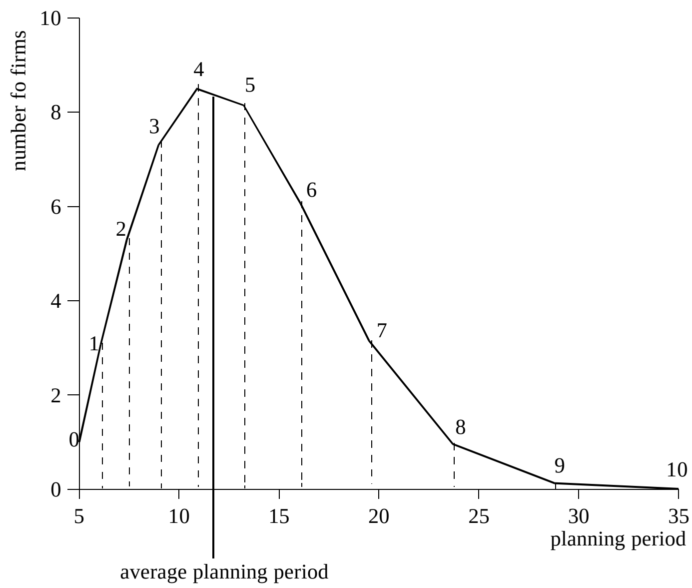

Figure 7.1. The length of the planning period and the number of firms

The first simulation experiment yields a steady-state growth path without any shocks. This is done to calibrate the quasi-clay-clay and the putty-clay model and to illustrate the diffusion process.[264] The parameters for the quasi-clay-clay model are listed in Table 7.1. The growth rate of the non-specific part of capital goods prices is set to zero and the growth rate of the nominal wages is 4%. The values for μ and γ are chosen in such a way that this results in a realistic lifetime of equipment.[265] These values of parameters result in a growth rate of the labour productivity of 1%, and a 2.5% growth rate of output prices. Moreover, the discount rate is assumed to be 6%, as a result of which the optimal technologies will asymptotically reach an upper boundary as the planning period increases ($r > \rho$). These growth rates and the value of the discount rate seem realistic if one period corresponds to one year. The growth rate of output is 1¼%, which means that the demand for labour will grow at a rate of ¼% per year, given the growth rate of labour productivity of 1%. The maximum number of vintages allowed for is 99. In other words, the first period for which the simulation can be carried out is 100. The last period is chosen to be 350.

Y_0	10.0	μ	1	r	6%	ψ	0.5	η	3.0	S^c	10
w_0	1.0	γ	3	δ	5%	λ_0	5	$\bar{\theta}_{low}$	5.0	S^h	2
q_0	1.0	ν	0%	ρ	4%	χ	1¼%	$\bar{\theta}_{high}$	35.0	S^l	4.5

Table 7.1. The parameters for the quasi-clay-clay model

264. It also enabled us to determine the correspondence between the steady-state growth rates of the 'true' model and the simulation model. All growth rates appeared to be exactly the same.

265. Which is about 28 periods in this example.

7.1.2 *The Reference Putty-Clay Model*

Our goal is to investigate the similarities and differences between the quasi-clay-clay model and a standard putty-clay model if the economy deviates from a steady-state growth path. In order to do so, we must calibrate both models to achieve identical steady-state growth patterns.

The reference standard putty-clay model, PC model for short, is comparable to the non-diffusion model of Chapter 3. The main difference is that we exclude dis-embodied technological change and that we do not allow for changes in working/operating hours in the present version of the model. Another, slight, modification is that the present model is defined in continuous time.

Chapter 5 shows that the choice of the technologies in the quasi-clay-clay model can be interpreted as the choice of the production technique in a standard putty-clay model. The labour intensity in the QCC model is comparable to the labour intensity of a standard putty-clay model if the elasticity of substitution is equal to $\mu/(\mu+\gamma)$ (cf. equation (5.33) at page 200). This implies that we have to use a CES production function in the putty-clay model with a substitution elasticity of 0.25.

The rate of embodied labour-augmenting technological change is equal to 1% to obtain a 1% growth rate of labour productivity. The capital/output ratio is constant in the quasi-clay-clay model, thus excluding embodied capital-augmenting technological change in the putty-clay model. The growth rate of wages is the same for both models, but the growth rates of the price of equipment are different. From the quasi-clay-clay model, we know that the growth rate of the price of capital is equal to the growth rate of the non-technology-specific part of these prices plus an incorporated quality effect. ν is assumed to be zero and thus the first effect is zero, but because the growth rate of the technology index is equal to 1% — which is the same as the growth rate of labour productivity — and because $\gamma=3$, the price of capital will grow at 3% per year in the quasi-clay-clay model. Consequently, the price of equipment has to grow 3% per year to make both models comparable.

The last parameter — with the exception of the scale parameters in the CES function (A_0 and B_0) which are used to calibrate some levels — is the length of the planning period in the putty-clay model. In the macro-model, we determined the length of the planning period by computing the expected date of scrapping. If the resulting expected lifetime is below a maximum value of the planning period, it is assumed that firms will take that value as the appropriate planning period; otherwise, they will employ the maximum value. The planning period in the quasi-clay-clay model is obtained in a similar way but because firms differ with respect to the level of risk aversion, their maximum value of the planning period will be different. To make both models comparable, we assume that the maximum value of the planning period in the PC model is equal to the weighted average value of the maximum planning horizon in the QCC model, in which the weights are equal to the relative number of firms in the quasi-clay-clay model.[266] According to the Weibull distribution, the average maximum planning period in the PC model is about 12 years (cf. Figure 7.1).[267] If the expected lifetime is below this maximum value, firms will employ the shorter lifetime as their planning period, thus making the putty-clay model comparable to the quasi-clay-clay model, and also to the macro-models used in part II. The parameters of the putty-clay model are listed in Table 7.2.

Y_0	10.0	σ	0.25	ν	3%	ρ	4%	$\bar{\theta}$	11.8
w_0	1.0	μ_n	1%	r	6%	χ	1¼%	A_0	5.5
q_0	1.0	μ_i	0%	δ	5%	η	3.0	B_0	3.1

Table 7.2. The parameters for the putty-clay model

7.1.3 Both Models Compared in a Steady State

This section presents some steady-state results for both models to illustrate the result of the calibration process. We calibrated the model in such a way that the aggregate data on employment, capital stock, amount of investment, price level as well as labour intensity and growth rates of output prices, labour productivity, are about the same. Whereas the growth rates are exactly the same for both models, we also require that the wage rate and the price of equipment to be identical. The degrees of freedom is consequently limited to two scale parameters of the CES production function of the putty-clay model, given the parameter values of the quasi-clay-clay model. This implies that the results with respect to the levels are not exactly the same, but the deviations are relatively small. This is shown in Table 7.3 for the demand for labour, the labour intensity of the newest vintage, the amount of investment and the labour productivity, respectively. Table 7.3 presents the aggregate labour productivity of all vintages taken together as well as the labour productivity of the newest vintage. Note that we obtained the aggregate levels in the quasi-clay-clay model by aggregating over all firms, that is by aggregating the relevant variables of all (eleven) firm types multiplied by the number of firms within each type.

The lifetime of equipment for both models is equal to 28 years. Moreover, the marginal costs are nearly the same so that the price levels are almost identical as well. Finally, the capital output ratio is 0.5 in the quasi-clay-clay model whereas it

266. Another possibility is to use the relative amount of output (or investment) as weights. This would lead to a slightly longer planning period (12.1 instead of 11.8).

267. Note that we applied a maximum planning period of 15 years in the macro-model.

is equal to 0.51 in the putty-clay model. This explains the small deviation with respect to the amount of investment.

	Quasi-Clay-Clay		Putty-Clay		Relative difference of levels between QCC and PC model (in %)
	level in period 100	% growth rate from 100-350	level in period 100	% growth rate from 100-350	
Demand for labour	2.8137	0.2500	2.8249	0.2500	-0.4
Labour intensity	0.1475	-1.0000	0.1443	-1.0000	2.2
Amount of investment	1.2479	1.2500	1.2811	1.2500	-2.6
labour productivity:					
—aggregate	12.2508	0.1000	12.2023	0.1000	0.4
—newest vintage	13.5598	0.1000	13.5061	0.1000	0.4

Table 7.3. Quasi-clay-clay model and Putty-Clay model compared

7.1.4 The Steady-State Diffusion Process

Some Measurement Issues

The last results of the steady-state reference simulation concerns the diffusion process. In order to determine the diffusion pattern, we have to make some additional assumptions. Because the number of firm types is limited, the diffusion of a certain technology represented by a real, i.e., a non-integer, number, would be of no use as the probability that a firm will invest in precisely that technology is very small. To overcome this problem, we define technology ranges and assume that all technologies which are captured within such a range are treated as the same technology. Note that this holds true only for the determination of the diffusion process and does not have any effect on the investment decisions of the firms. The actual optimal technology indices are used to determine the labour productivity as well as the price of capital goods.

The optimal technologies for the most (i_{10}^*) and the least (i_0^*) risk-averse class of firm types are displayed in Figure 7.2. The annual rate of growth of the index is equal to 1% and is the same for all firms. The ranges of the least and the most advanced technology are also displayed in this figure. If the number of different firms were infinite and if time were continuous, the technology index could be represented be a single (horizontal) line. Each firm would then choose each technology within the range A in Figure 7.2 once, which would lead to the diffusion curves as shown in the previous chapter. The technology ranges have been chosen in such a way that the amount of investments in each technology corresponds more or less with the 'true' model. This implies that the width of the less advanced technologies, e.g. distance b in Figure 7.2, will be smaller than the width of the most advanced technology, distance a.[268]

Another aspect involves the distribution of all technologies within the range $\bar{i}_0$–$\bar{i}_6$. Because of the constant rate of growth of the technology index, a linear distribution implies that the time period between two succeeding technologies decreases in the course of time. Although this is a realistic description of the actual model, this implies that the time period between technologies $\bar{i}_0$ and $\bar{i}_1$ is about 50 years, whereas it is less than 10 years for technologies 5 and 6. In the simulation experiments, this leads to some difficulties regarding the visualization of the diffusion process and changes of the speed of diffusion. To avoid such problems, we define the technologies such that the time periods between the adoption of succeeding technologies are constant. Note that these assumptions concern the measurement of the diffusion process which does not affect the actual technologies chosen nor the amount of investment in each technology.

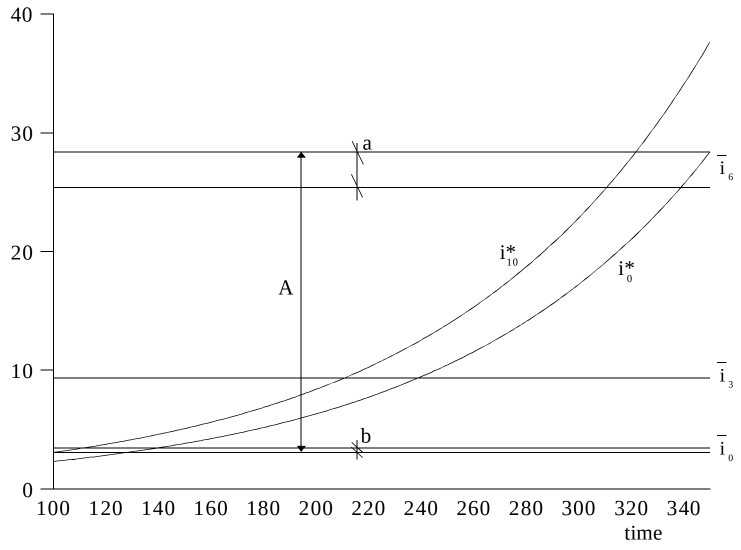

Figure 7.2. The optimal technologies and the technology ranges

268. See appendix 7A for a detailed explanation.

The Diffusion Process

As shown previously in part II, the diffusion pattern can be discussed in relation to three different figures: First, the amount of investment in each technology, secondly, the cumulative amount of investments, and finally, the relative amount of output produced with each technology. The steady state diffusion process will be visualized for all three variants, but the description below, where we show the diffusion process outside the steady state, will be restricted ourselves to one or two variants. The diffusion pattern in terms of the amount of investment in each technology is presented in Figure 7.3 for all technologies. The least risk-averse firms will invest in a technology first, but the amount of investment is rather limited because this firm type represents just a few firms. The amount of investment increases if the medium risk-averse firms start to invest in this technology. Finally, the most risk-averse firms, which again represent a minority, will invest in the technology in the last stage of the diffusion process. This bell-shaped investment figure will lead, of course, to an S-shaped diffusion pattern. The investment patterns are not smooth because of the limited number of firm types. The total amount of investments in each technology increases over time because we imposed a 1¼% growth in total output, so that the growth rate of the amount of investment in each technology will also be about 1¼%.[269]

The resulting diffusion pattern in terms of the cumulative amount of investment in each technology is presented in Figure 7.4. So, whereas the amount of investment shows some discontinuities, the cumulative amount of investment is rather smooth.[270]

Finally, the relative amount of output produced with each technology is given in Figure 7.5. The non-smooth shape of the curve is due to inaccuracies of the simulation model. The same holds true for the height of the patterns, which are not all the same in the simulation results, but which should be all the same in the 'true' model. The relative amount of production with each technology increases along an S-shaped path. The production declines and fades out for two reasons. First, due the fact that firms will invest in newer technologies, and second due to the fact that vintages will be scrapped both due to wear and tear and due to economic obsolescence.

The three figures show that the distance in time between two succeeding technologies is constant. Although firms invest in newer technologies at a constant rate ($\hat{i}_t$ is constant), leading to a decline in the time distance between succeeding technologies if the technology indices are defined on a linear scale, here, we defined the technology indices for which we will examine the diffusion process in such a way that the distance is constant.

269. Note that the amount of investment is below 1¼% if we used a constant technology range (cf. appendix 7A).

270. Of course, it contains the same discontinuities, but these are less visible.

Although there are some discontinuities, we can conclude that the results of the simulation model provide a correct representation of the theoretical model if compared with those of the previous chapter. This is mainly obtained by the introduction of variable technology ranges. There still exist some minor differences between both models, such as the lifetime of equipment and the amount of investment in each technology, but the magnitude of these differences is very small compared to the deviations which will result from the shock experiments described below.

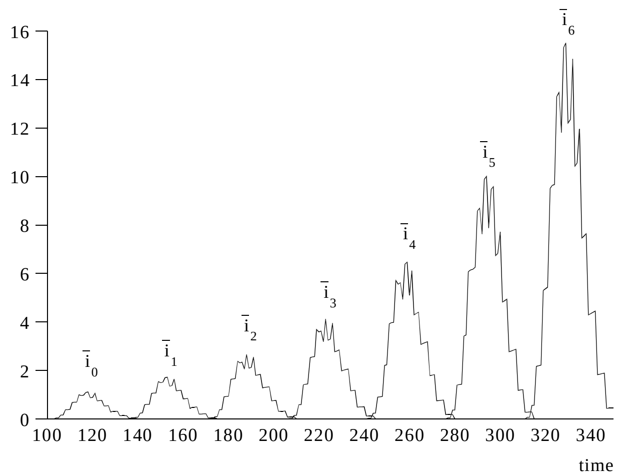

Figure 7.3. The amount of investments in each technology

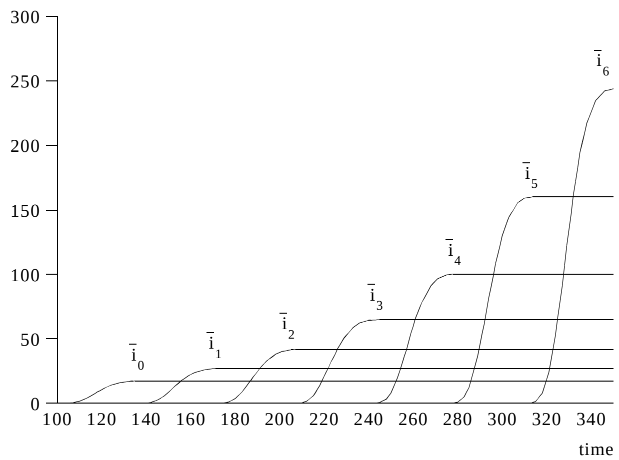

Figure 7.4. The cumulative amount of investment in each technology

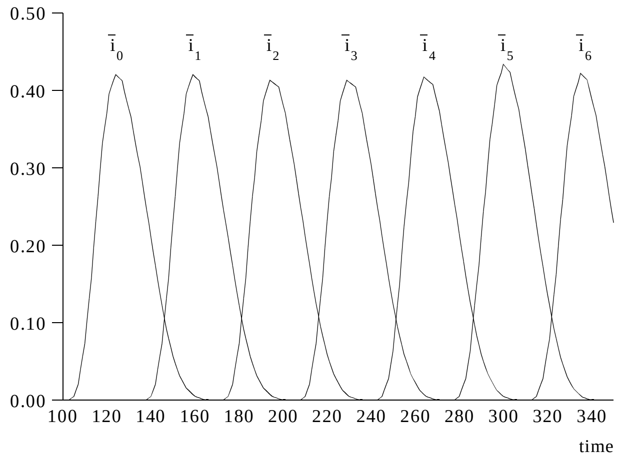

Figure 7.5. The relative amount of production with each technology

7.2 A Replay of the Productivity Slowdown

One of the objectives of the present simulation experiments is to compare the quasi-clay-clay model with the putty-clay *diffusion* model with respect to the productivity slowdown. However, the putty-clay diffusion model is not suited to incorporate the Malcomson scrapping condition. Moreover, the putty-clay diffusion model is rather comprehensive so that a simulation would be restricted to just a few firms and technologies, and even then, we cannot simulate for very long periods. Below, we will show that long time periods, about 50 to 100 years, are needed after a shock before the economy returns to its steady-state path. The comparison between the quasi-clay-clay model and the putty-clay diffusion model with respect to the simulation results will be limited to a replay of the productivity slowdown with the former one. However, we will compare the results of the quasi-clay-clay model with the standard putty-clay model, and investigate whether the quasi-clay-clay model can better explain the productivity slowdown than the putty-clay model. Moreover, we will examine whether labour productivity and employment will be restored if we apply an opposite shock after some years.

In the macro-model, we concluded that a decrease in the growth rate of wages in the mid seventies and eighties was responsible for the productivity slowdown to a large extent. Here, we will simulate this result by assuming that the growth rate of nominal wages decreases from 4% to 3% in year 125. To investigate whether the economy recovers after a similar shock, we increase the growth rate of nominal wage from 3 to 4% in year 225. The next section describes the results of the quasi-clay-clay model with respect to the choice of technologies and the diffusion process. After that, Section 7.2.2 compares the quasi-clay-clay model with the putty-clay model in terms of some aggregate variables.

7.2.1 The Diffusion Pattern

From the definition of the optimal technology index (cf. equation (5.33), page 200), it is obvious that the growth rate of the technology index (the speed of innovations) decreases if the growth rate of wages slows down. This implies that the amount of investment in a specific technology is delayed. Another implication of a decrease in the growth rate of the technology index is that the diffusion process takes more time so that the cumulative amount of investment in each technology increases. Because we assume a positive growth rate of final output, both effects will increase the total (cumulative) amount of investment in each technology. However, the previous chapter shows that the lifetime of equipment increases if the marginal costs of the newest vintage decreases. This causes a decrease of the amount of investment in a particular technology and the present simulation experiment will determine the relative size of both effects.

Next to the impact on the diffusion of technologies, a decrease in the growth rate of wages will have a permanent effect on the choice of the technologies, even if the growth rate in wages is restored to its original value. This is caused by the fact that the (level of) nominal wages will not return to their original, steady-state, values. The next section shows that this is one of the main differences between the quasi-clay-clay and the putty-clay model.

So, we can expect two effects of the diffusion of technologies. First, firms will delay investment in new technologies and thus delay the diffusion of technologies after the first shock in which the growth rate in wages is decreased. Because the index of the chosen technologies remains below the steady-state technology indices after the second, opposite, shock, this delay persists.

The second effect concerns the amount of investment in each technology. As explained previously, there are two opposite effects. Because the speed at which firms buy new technologies slows down, the amount of investment in a specific technology will increase after the first shock. But the lifetime of the oldest vintage increases which in turn decreases the amount of investment. Figure 7.7 displays the result of these effects. The diffusion pattern of technology 0 is not affected until 125, but firms will still invest in it after the first shock leading to an increase in the ceiling level.[271] The diffusion patterns of technologies 2 and 4 are both delayed and increased. Note that a delay of diffusion also implies an increase in the amount of investment because the aggregate output, and consequently the amount of investment, grows at a constant rate. From this, one could wonder whether the increase of the ceiling level of technology 4, is a consequence of the delay in the diffusion process or a reflection of an increase in the amount of investment due to other reasons. Figure 7.7 is based on the same simulation, but now, zero growth in

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271. The original diffusion patterns are denoted by $\bar{i}_0$, $\bar{i}_2$ and $\bar{i}_4$, whereas the patterns in the shock experiment are indicated by an asterisk.

aggregate output ($\chi = 0$) is imposed. From this figure, it becomes clear that the ceiling level of technology 4 is not affected at all and the diffusion process is only delayed.

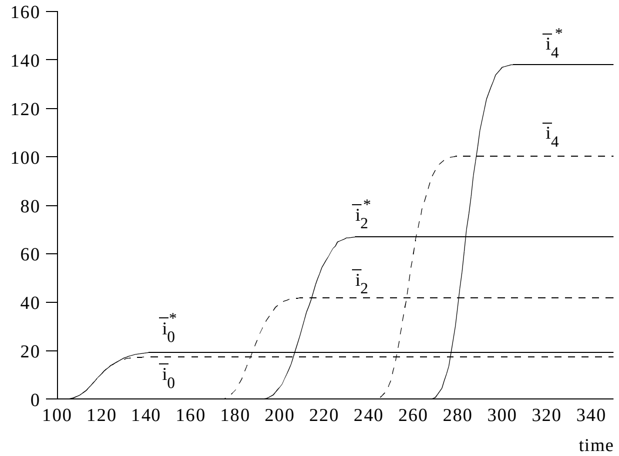

Figure 7.6. The cumulative amount of investment for several technologies (original patterns (dashed) and patterns obtained after shock in the wage rate (solid))

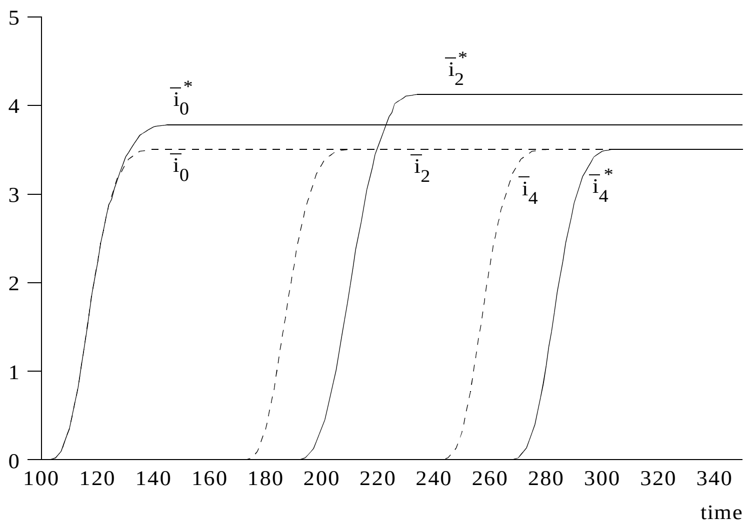

Figure 7.7. The cumulative amount of investment for several technologies with zero output growth (original patterns (dashed) and patterns obtained after shock in the wage rate (solid))

7.2.2 Exogenous versus Endogenous Technological Change

Above, we have shown that firms will decrease the speed at which they buy new technologies if the growth rate of nominal wages decreases by 1%-point. Now we will consider other effects and we will compare the quasi-clay-clay model with a standard putty-clay model.

First of all, the labour intensity will increase in both models and decreases the labour productivity. Because we calculated the rate of substitution of the putty-clay model in such a way that it is comparable to the quasi-clay-clay model, one would expect the same behaviour with respect to the labour intensity. Moreover, and once again because of the same elasticity of substitution, one would expect about the same reactions with respect to the labour productivity, at least for the newest vintage. The lifetime effect is less clear and so is the a priori difference between both models of the growth rate of the aggregate labour productivity.

The Growth Rate of Labour Intensity

For both models, the labour intensity increases by the elasticity of substitution times the change of the wages rate, i.e., by $0.25 * \Delta\rho = 0.25\%$-point. This is shown in Figure 7.8, in which the growth rate of the labour intensity increases from −1% to −0.75%. However, there are two main differences. First, the initial reaction, which is positive in the putty-clay model (the growth rate increases to 0.5% in period 125), and which is first negative in the quasi-clay-clay model (-2.5% in 125) but positive in the next year (about 2% in 126). The second difference is that the putty-clay model does not show any fluctuations after the initial shock, while the growth rate of the labour intensity in the quasi-clay-clay model fluctuates about 35 years after the shock and becomes stable afterwards.

Both effects depend on the way in which the growth rate of labour intensity is measured. One possibility is to calculate the growth rate of the labour intensity for each firm and determine the aggregate growth rate by a weighted sum of the growth rates of all firms. Another possibility is to aggregate the demand for labour and the amount of investment over all firms and then determine the aggregate labour intensity and the corresponding growth rate. Because it is far more easy to calculate this measure at an aggregate level, and because it is likely that one would employ aggregate data in actual — non-simulation — estimates, we will employ the second method. If the weights for each individual firm remain constant, both methods will lead to the same aggregate data (labour intensity, labour productivity, etc.). However, both methods will result in different aggregates if the weights are not constant. This is exactly what happens in the quasi-clay-clay model.

The first difference is due to the fact that the market shares of firms change in the QCC model, whereas all firms are assumed to be the same in the PC model. In the QCC model, all firms will choose a less advanced technology but the least risk-averse firms will react more fiercely because of their longer planning horizon (the

f-term, which denotes the present value of integral labour costs over the planning period, is larger for less risk-averse firms). This implies that the marginal costs will reduce to a larger extent for the least risk-averse firms, resulting in an increase in the market share of the least risk-averse firms. The market share of the most risk-averse firms will decrease. This implies that the distribution with respect to the amount of investment changes, which leads to changes in the weights of the aggregate growth rate of labour intensity. In other words, the QCC model differs from the PC model at an aggregate level. The pattern of the growth rate of labour intensity of each *individual* firm is the same for all firms and about the same as the reaction in the Putty-Clay model, but the aggregate growth rates differ due to changes in the weights.[272]

The second difference — the fluctuations after the shock — originates from the same source. However, different reactions with respect to scrapping of equipment are responsible for differences in the amount of investment here, and, consequently, for differences in the weights of the aggregate measure for the QCC model. Below, we will show that the lifetime of the oldest vintage becomes the same for all firms after a while, so that the fluctuations evaporate.

To summarize, the (average) growth rates of the labour intensity are the same for both the quasi-clay-clay and the putty-clay model, but the growth rates fluctuate in the QCC model due to changes in the relative amount of investment for each individual firm.

The Growth Rate of Labour Productivity

With respect to the development of the labour productivity, we can distinguish two effects. First, the change of the labour productivity of the newest vintage — which will decrease due to a decrease in the growth rate of wages — and secondly, the reaction of the labour productivity due to scrapping effects — the lifetime of equipment will increase as a result of which the growth rate of the labour productivity will decrease. Above, we argued that the growth rate of labour productivity of the newest vintage, i.e. the first effect, will be the same for both models. However,

272. This can be illustrated by a simple example. Suppose that there are two firms, a and b. At time 1, the labour intensity is equal to $l_1^a = 1$ and $l_1^b = 4$ for firm a and b, respectively, whereas both increase by 50% to $l_2^a = 1.5$ and $l_2^b = 6$ in year 2. The growth rate of the aggregate labour intensity, measured as the average growth rates of both firms is, of course, equal to 50%. Assume that the amount of investment of firm a changes from $I_1^a = 1$ to $I_2^a = 4$, whereas the amount of investment of firm b is constant $I_1^b = I_2^b = 2$. The aggregate demand for labour at time 1 is then equal to $l_1^a I_1^a + l_1^b I_1^b = 9$ and the aggregate amount of investment is equal to 3. At time 2, these figures are 18 and 6 for demand for labour and investment, respectively. So, at the aggregate level, labour intensity is equal to 3 in both years and therefore constant, which is far below a growth of 50%. If the amount of investment of firm a had increased more, for instance to 5, the aggregate labour intensity would have decreased from 3 in year 1 to 2.785 in year 2, a relative change of −12.5%, which shows that the aggregate growth rate can even be the opposite of the growth rates of individual firms.

Figure 7.9 shows that this is not true. Besides the fluctuations in the QCC model, which originate from the same source as those in the growth rate of the labour intensity, the growth rate of labour productivity decreases to a larger extent in the QCC model. The difference can be attributed to the difference between exogenous technological change in the putty-clay model and endogenous technological change in the quasi-clay-clay model.

In the putty-clay model, the production isoquant shifts towards the origin at a constant rate, independently from factor costs, etc.. We already know that the growth rate of the labour intensity increases by 0.25%-point (from −1% to −0.75%). As a result, given the constant shifts of the isoquant, the growth rate of labour productivity will decrease by less than 0.25%-point. Moreover, the capital productivity is constant in the steady state but will increase after the shock in the wages.

In the QCC model, there is no exogenous shift. The labour productivity is determined by the behaviour of firms with respect to the technologies they buy. Because labour becomes cheaper, relative to capital, the incentive to buy more advanced technologies decreases and the growth rate of the labour productivity will slow down. Moreover, because there is no exogenous shift of a production isoquant and because the capital productivity is constant by assumption, the growth rate of labour productivity will decrease by the same amount as the growth rate of the labour intensity. Thus, the growth rate of labour productivity will decrease more in the QCC model in the putty-clay model. This is the reason why the diffusion process of new technologies is delayed as we have seen above. This is also the reason why standard putty-clay models are less appropriate to explain the productivity slowdown.

The second source of differences between both models with respect to the labour productivity is the change in the age of the oldest vintage. This is shown in Figures 7.10 and 7.11. The first figure shows the annual growth rates of labour productivity at the aggregate level, i.e., for all firms and for all vintages together, and the second figure displays the ten-year moving average of this measure. In the QCC model, all firms adjust the age of the oldest vintage, but because they will not do this simultaneously, the effect cancels out somewhat. As a result, the fluctuations of the growth rate of labour productivity at the aggregate level are less for the QCC model than for the PC model. Again, the lifetime becomes stable after a while, so that the growth rate becomes equal to the growth rate of the newest vintage. The adjustment of the age of the oldest vintage takes much more time in the putty-clay model, where the fluctuations persist.

The fluctuations after the second shock fade more rapidly because firms are able to adjust the age of the oldest vintage downwards for more than one per year whereas it is impossible to increase the age by more than one per year.[273]

273. Note that we exclude investment in second-hand machinery.

The Age of the Oldest Vintage

Because the growth rate of wages slows down, and because the growth rate of labour productivity decreases less than the wage rate, the age of the oldest vintage will increase for both models. This is shown in Figure 7.12. The new steady-state value of the lifetime of the oldest vintage is 38 years in the quasi-clay-clay model. In other words, it takes 38 years for the whole capital stock to be adjusted. Figure 7.12 shows the development of the age of the oldest vintage for the most risk-averse (firm 0) and for the least risk-averse (firm 10) firm. Previously, we mentioned that the marginal productivity will be adjusted more for the least risk-averse firm, which means that the age of the oldest vintage is higher during the adjustment process. Moreover, Figure 7.12 shows that the lifetime slightly overshoots the (new) steady state for both firms and that the amount of overshooting is larger for the least risk-averse firm. This is caused by the fact that the last vintage installed before the shock in the wage rate is relatively productive compared to the first vintage installed after the shock. Consequently, the lifetime of the pre-shock vintage is longer than its successors and the age of the oldest vintage decreases at the end of the adjustment process.

In the initial steady state, the growth rate of the wages is 4%, the increase of the labour productivity is 1%, and the marginal costs of the newest vintage increases by 3%, so that the lifetime is constant.[274] This holds true for both models. In the quasi-clay-clay model, a new constant lifetime is obtained after the shock because the growth rate of labour productivity decreases towards 0.75%, the growth rate of wages is set to 3% and the marginal costs decrease towards 2.25% per year. Thus again, the growth rate of the marginal costs is equal to the growth rate of wages minus the growth rate of the labour productivity.

With respect to the putty-clay model, the growth rates differ after the shock. The labour productivity decreases towards 0.93% in 126 but decreases towards 0.89% in year 225. This non-steady-state value is caused by the fact that the decrease of the labour intensity is less than the shift of the production isoquant, as a result of which both the growth rate of the labour productivity and the growth rate of the capital productivity are no longer constant. The marginal costs decrease from the steady-state value of 3% towards about 2.25% in 125, but increase afterwards towards about 2.43% in 225. This implies that the growth rate of the marginal costs of the newest vintage exceeds the growth rate of the marginal costs of the oldest vintage (which is 3%-0.93%=2.07% in 125 and 2.11% in 225), so that the age of the oldest vintage increases unbounded.

The opposite shock decreases the lifetime of equipment in both models. Because in the quasi-clay-clay model, the original growth rates are restored, the lifetime will return to the initial value. However, this is not the case for the putty-clay model.

274. The growth rate of the marginal costs for the quasi-clay-clay model is obtained by using equation (6.21) on page 225.

Although the growth rates of the marginal costs and the labour productivity are restored to their original values, and thus the lifetime will be constant after the adjustment process, it does not return to its original level. Again, this is caused by the impact of exogenous technological change, as a result of which the productivity gap between the newest and the oldest vintage has increased.

Demand for Labour

Finally, the demand for labour, which is determined by the labour productivity — given the exogenous growth rate of output — is presented in Figure 7.13. As expected, the demand for labour is affected to a larger extent in the quasi-clay-clay model than in the putty-clay model. The steady-state growth rate before the shock in the wage rate is 0.25% for both models, and the same growth rate is obtained after the second opposite shock. However, because the labour productivity is influenced by the exogenous rate of embodied technological change in the PC model, the labour productivity does not decline as much as in the QCC model. The increase of the aggregate demand for labour is about fifty percent of the increase of the demand for labour in the quasi-clay-clay model. This result is caused by the fact that the labour productivity has decreased to a larger extent in the QCC model. Moreover, note that the growth rate of aggregate demand of output is fixed by assumption, which means that this (partial) model is not able to determine the labour demand effects through final demands and / or income effects.

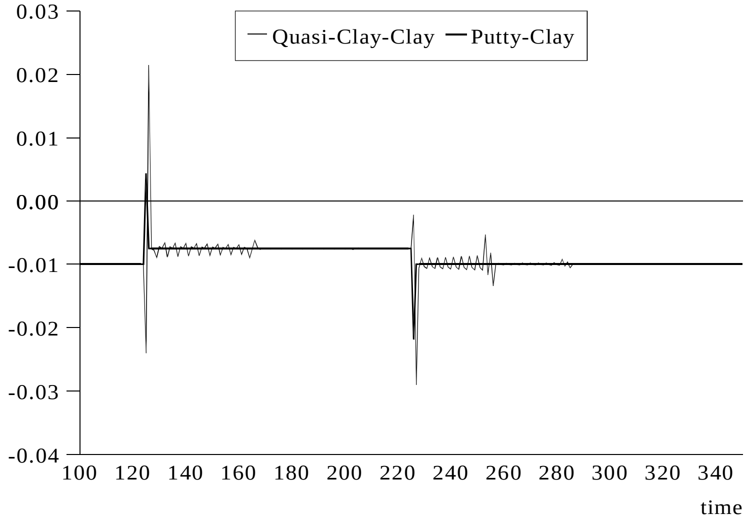

Figure 7.8. Growth rate of the labour intensity of the newest vintage

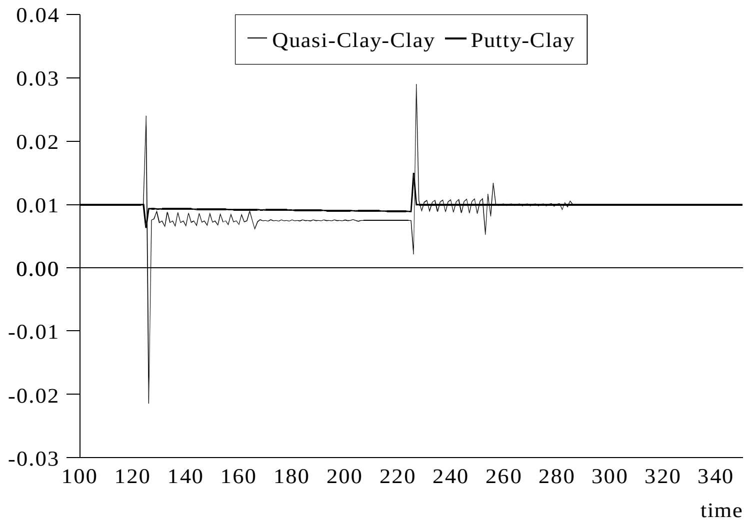

Figure 7.9. Growth rate of labour productivity of the newest vintage

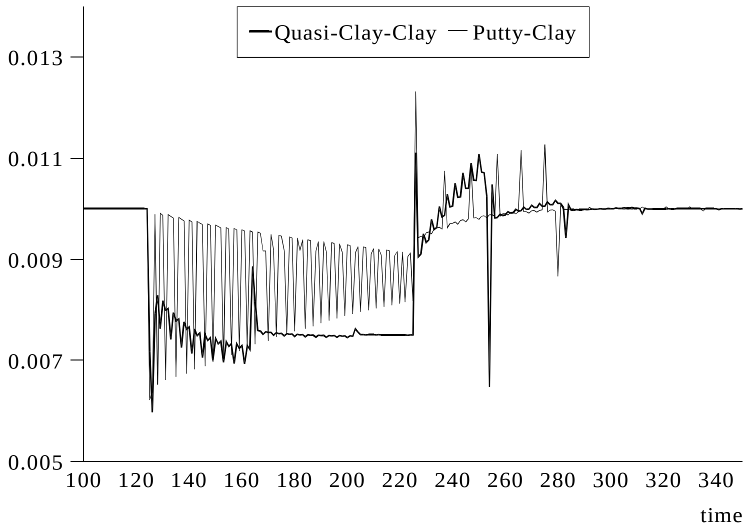

Figure 7.10. Growth rate labour productivity at the aggregate level

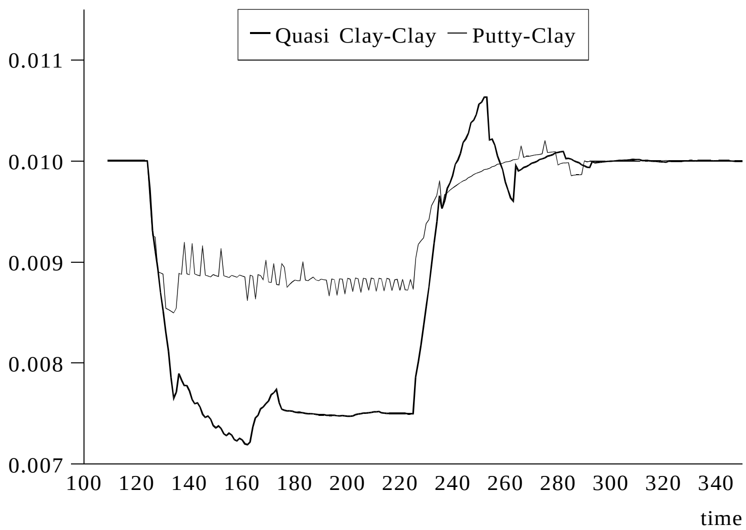

Figure 7.11. Ten-year moving average of the growth rate of the labour productivity at the aggregate level

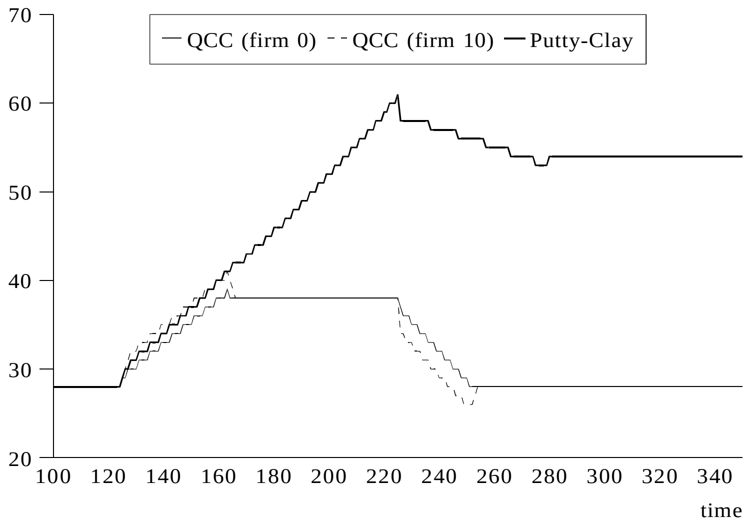

Figure 7.12. Lifetime of oldest vintage
(firm 0: most risk-averse; firm 10: least risk-averse)

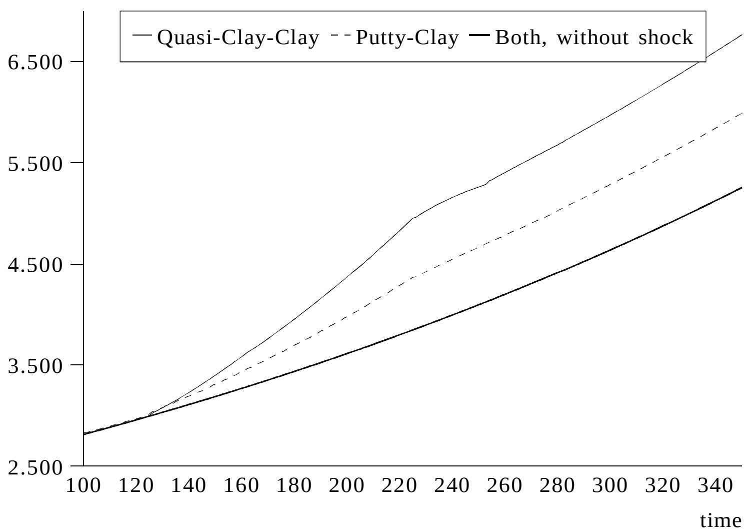

Figure 7.13. Aggregate demand for labour

7.2.3 Conclusions

This experiment has shown that the growth rate of labour productivity is affected to a considerably larger extent in the quasi-clay-clay model than it is in a standard putty-clay model. This phenomenon is explained by the difference between exogenous technological change in the putty-clay model and endogenous technological change in the quasi-clay-clay model. The diffusion pattern is affected in two ways, the adoption of new technologies is delayed and the amount of investment in a certain technology increases.

Compared to the putty-clay diffusion model used in part II to explain the productivity slowdown, there is one main similarity. Although the rate of technological change is exogenous in that model, the distribution of firms with respect to the technology in which they invest depends on profitability and on learning effects. A decrease in the growth rate of wages decreases the profitability differences, causing firms to delay investment in new technologies. This effect is comparable to the effect in the quasi-clay-clay model. In both models, the growth rate of labour productivity slows down to a larger extent than in standard putty-clay models.

Two main differences are that the rate of technological change is constant in the putty-clay diffusion model, and that there are path dependencies through learning effects in that model. The constant rate of technological change will have the same effect as the present non-diffusion putty-clay model, but learning effects will delay the movement towards new technologies. This implies that the effects in the short run will differ from the long-run effects. In the short run, the growth rate of labour productivity will be below the growth rate of the labour productivity in the standard putty-clay model if the growth rate of wages slows down. However, it is not clear whether this growth rate will be below or above that in the present quasi-clay-clay model. In the long run, the labour productivity growth of the putty-clay diffusion model will move towards the labour productivity growth of the standard putty-clay model, which means that the putty-clay diffusion model will predict a higher long run labour productivity growth than the present quasi-clay-clay model. Again, this is caused by the difference between exogenous technological change in the putty-clay diffusion model and endogenous technological change in the present quasi-clay-clay model.

7.3 Endogenous Diffusion Patterns

Chapter 6 presents a case in which the output market is near to monopolistic and in which all firms with the same level of risk aversion — and which consequently invest in the same technology at any point in time — operate as a cartel, so that the market share of a cartel is given by the demand function. Compared to the original interpretation of the demand function, there are no differences between firms in terms of service, customer relation and geographical distribution with the exception of their marginal costs and their output price. This resulted in a diffusion pattern which is independent of the distribution of firms with respect to the length of the planning period. It is shown that the diffusion pattern is S-shaped if the growth rate of wages is larger than the growth rate of output prices, which is the case if the growth rate of the non-technology-specific part of the price of equipment is smaller than the growth rate of wages. This section presents a similar result, obtained by using the simulation program, and enabling us to investigate the differences with respect to the expected profitability between firms. Moreover, we will combine this purpose with a shock of the price of equipment in which we assume that all suppliers lower the price of capital by 10%.

The main difference between a shock in the wages and a shock in the price of equipment is that all firms are now affected in the same way, because the capital productivity is identical for all firms. Whereas firms differ with respect to the labour productivity, and, thus, a change of the wage rate has different effects on different firms, this is not the case in a shift of the price of equipment, at least if the relative price difference between technologies, the parameter γ, is not affected, which we assume to be the case. In other words, because the market shares do not change, the diffusion patterns are only affected by changes in the technology index and by changes in the amount of investment through lifetime effects.

In order to highlight the endogenous diffusion patterns, we changed the parameters, thus making differences between firms more visible. In the previous section, we assumed that $\rho = 4\%$ and that the discount rate is equal to 6%. Thus, differences between firms through the f-terms are relatively small.[275] To increase this difference, we imposed a growth of nominal wages of 7%. Because the growth rate of output prices is given by $\pi = \rho \cdot \gamma / (\gamma + \mu)$, given that $\nu = 0$, we obtain a growth rate of output prices of 5¼%, so that the real discount rate is still positive. Moreover, to increase differences between firms, we imposed a minimum planning period of 1 year on the most risk-averse firm and a maximum planning period of 75 periods on the least risk-averse firm. To obtain a nearly monopolistic market, we changed the price elasticity of final demand to about 1. The parameters of the present simulation experiment are summarized in Table 7.4. The price of equipment is lowered by 10% for the period 125 to 225.

Because the growth rates of the technology index are not affected by this shift, the effects of this shock are very limited. The lifetime is reduced from 26 years to 24 years for a relatively short period of 26 years. After that period, the whole capital stock is adjusted and the lifetime increases towards 26 years. Thus, contrary to the ‘productivity slowdown experiment’ in which the growth rates are affected in such a way that the lifetime is increased during the whole period from 125 to 225, the present shock leads to minor adjustments of the age of the capital stock, and the period of adjustment is relatively short.

Y_0	10.0	μ	1	r	6%	ψ	0.5	η	1.00000001	S^c	--
w_0	1.0	γ	3	δ	5%	λ_0	5	$\bar{\theta}_{low}$	1.0	S^h	--
q_0	1.0	ν	0%	ρ	7%	χ	1¼%	$\bar{\theta}_{high}$	75.0	S^l	--

Table 7.4. The parameters for the quasi-clay-clay model (endogenous diffusion pattern simulation)

275. Recall that the f-term denotes the present value of integral future labour costs, relative to the present labour costs. This term depends on the length of the planning period (cf. equation (6A.1) on page 244).

The technology index decreases due to a decreased price of equipment, but again, because the growth rates are not affected, the effect on the amount of investment is very limited. The ceiling level of the diffusion pattern of the first technology, which is chosen at the time the prices are lowered, is decreased by about 5%. The diffusion of the other technologies starts and ends one year earlier than would be the case without shock, so that the ceiling levels are nearly unaffected.[276] Altogether, the market shares of firms are not affected, the growth rates do not change, and the diffusion patterns somewhat decrease, but the differences are small to the extent that this effect is almost not visible in the diffusion pattern figures, as we will show below.

Now, we will turn to the main point of this section, endogenous S-shaped diffusion patterns. Because the rationale behind such patterns has already been described in the previous chapter, this section is restricted to a graphical presentation. Figure 7.14 presents the market shares of all eleven firm types. The least risk-averse firm employs a planning period of 75 years.[277] Since firm number 7 acquires the largest market share, this firm determines the point of inflection of the diffusion curve. It has a planning period of about 20 years, which means that we can obtain a sigmoid diffusion pattern if the planning period of the least risk-averse firm is longer than 20 years. This holds true if total final demand does not grow. But because we imposed a 1¼% annual growth rate of output in this simulation experiment, firms which invest in a specific technology at a later point in time will invest a relatively larger amount than firms who invest earlier, even if their market shares were the same. Thus, the firm with the largest (absolute) amount of investment in a certain technology will have a smaller planning period than firm 7. To be more precise, firm 5 invests the largest amount in every technology and employs a planning period of about 9 years. We are able to obtain an S-shaped diffusion pattern in the present example if the planning period of the least risk-averse firms exceeds 9 years. We employed a relatively long planning period of 75 years for the least risk-averse firm because then the point of inflection will be somewhere in the middle of the diffusion pattern. Lowering the longest planning period will shift the point of inflection to the left.

The expected profits increase for firms with a longer planning period. In Figure 7.15, we plotted the expected profits of all firms relative to the most risk-averse

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276. There is a small effect because the growth rate of total output, and therefore the growth rate of investment, is positive, as a result of which the ceiling levels, in terms of absolute amount of cumulative investment, decrease because the diffusion starts and ends earlier.

277. We also experimented with a version in which the expected lifetime is below the maximum planning period, but the planning period for which the marginal expected profits are zero is about 1000 years. This large number if caused by the relatively high growth rate of output prices which limits the growth rate of real wages to 1¾%. Another option is to increase the growth rate of wages, but the planning period of the least risk averse firm decreases from its maximum value of 100 to 91 years if the growth rate of nominal wages is 10% per year. So, to limit our analysis to reasonable parameter settings, we will not present these cases.

firm, firm 0. Note that the expected profits of firm 10 are about three times as high as those of firm 0, which implies that the average risk premium, defined as the relative increase of expected profits per additional year of the planning period, is equal to about 0.04.

To return to the resulting diffusion pattern, Figure 7.16 shows the adoption patterns, i.e., the amount of investment in each technology.[278] Although there are severe discontinuities due to the fact that the simulation is limited to eleven firm types, the envelope of each adoption pattern increases in the first stage and decreases afterwards.[279] This implies that the diffusion patterns are S-shaped, as can be seen in Figure 7.17. This figure shows that the decrease in the price of capital goods has only minor effects on the diffusion patterns.

To summarize, this section shows that the effect of a decrease in prices of equipment has very limited effect on the choice of technologies and the amount of investment. Moreover, because all firms are affected in the same way, the market share of each firm remain unchanged. A more important conclusion is that we are able to obtain S-shaped diffusion patterns if the market is nearly monopolistic without imposing a huge growth rate of nominal wages. We increased the growth rate of wages to highlight the effect, but the growth rate of real wages appears to be about 2% per year whereas the discount rate is still positive, which indicates that the parameters of this simulation experiment are not that exceptional. The firm with the largest market share employs a planning period of about 20 years, while the firm which invests the largest amount in a specific technology, and which consequently defines the point of inflection of the diffusion pattern, appears to have a planning period of about 9 years, given a growth rate of output (and investment) of 1¼% per year. Although a planning horizon of 75 years of the least risk-averse firm is rather long, a planning horizon of about 15 or 20 years seems to be reasonable. Moreover, the point of inflection is determined by firms with a planning period of 9 years which also seems to be reasonable.

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278. We plotted the investment for the even-numbered technologies only, because a plot of all technologies is less clear due to large overlaps between technologies.

279. Note that the amount of investment of firm 10 (the first buyer of each technology) is about the same as the amount of investment of firm 0 (the last buyer) whereas the market shares differ considerably between these two firms. This is due to increasing output and increasing investment over time.

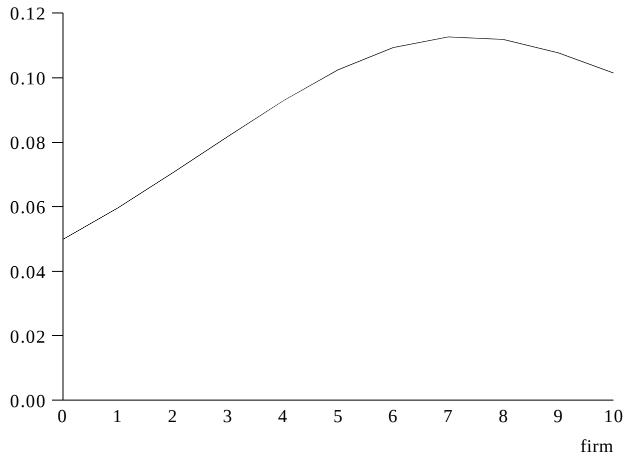

Figure 7.14. Market shares for all firms

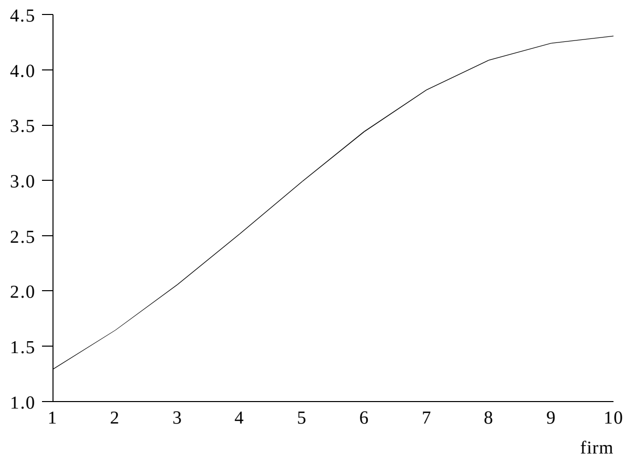

Figure 7.15. Expected profits, relative to the expected profits of firm 0

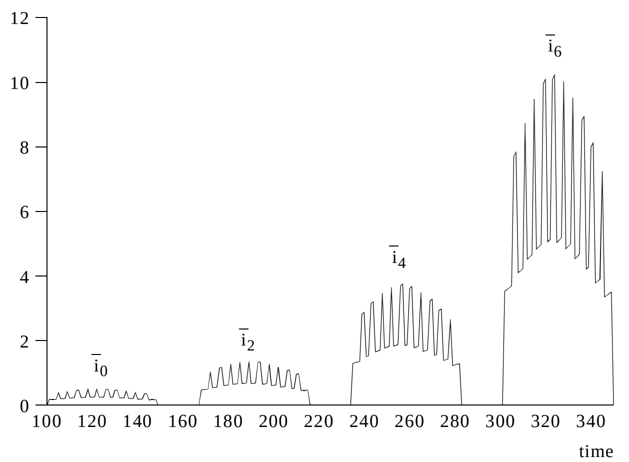

Figure 7.16. The amount of investment in several technologies

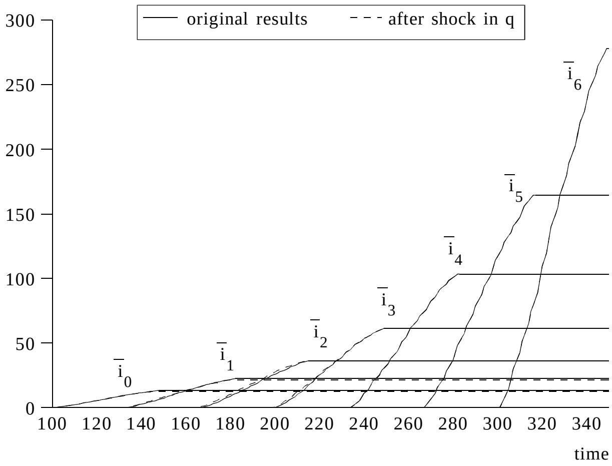

Figure 7.17. Endogenous diffusion patterns

7.4 A Discount on the Price of One Technology

In the present model, the price of equipment is defined as the general, non-technology-specific, price multiplied by a technology-specific part. It is assumed that the costs of producing a capital good incorporating a specific technology are related to a general part, for instance wages, and a technology-specific part. As a result, a relative improvement of the productivity of equipment of μ costs an extra amount of inputs of γ. Moreover, it is assumed that, given this cost structure, the supplying industry sets an output price which is a mark-up on the marginal costs. The next section will elaborate the price-setting behaviour, but here, we will determine the market reactions if one supplier offers a permanent discount on its capital good. The changes of the demand for that specific product can provide some insights into the market structure of the supplying industry. This result will be used in the next section.

Thus, assume that the supplier of technology $\bar{i}_3$ offers a 10% discount and that the price of all other technologies do not change. What will happen? First of all, firms who would buy another technology if there was no discount, they would buy technology $\bar{i}_2$, for instance, will now examine whether investing in technology $\bar{i}_3$ is more profitable. If this is the case, they will invest in technology $\bar{i}_3$ rather than in technology $\bar{i}_2$, but it is possible that, at the prevailing wage rate and discount rate, technology $\bar{i}_2$ is still more profitable. If wages rise, relative to the non-technology-specific price of capital goods, there will be a point in time at which technology $\bar{i}_3$ becomes more profitable than technology $\bar{i}_2$, where this point in time is reached before the firm in question would switch to the new technology if there was no discount. Moreover, as the least risk-averse firm invests in the most advanced technology at all points in time, this firm will probably invest in the discount technology before others will do. This brings us to the second point.

If not all firms invest in technology $\bar{i}_3$ at the same point in time, the relative marginal costs will changes, and thus, given the constant mark-up rule and the price elasticity of final demand, the market shares will change, at least as long as some firms benefit from the discount rate. If the least risk-averse firms invest in the new technology before the others do, they will increase their market share as a result of which the amount of investment in that technology will increase, at the expense of the amount of investment in other technologies. So the demand for technology $\bar{i}_3$ will increase because firms will choose that technology for more than one year, and it will increase because the amount of investment of each firm will increase.

Figure 7.18 presents the technology index for the least risk-averse firm (firm 10), the most risk-averse firm (firm 0), and for a firm with a risk aversion between these extremes (firm 5).[280] First, the least risk-averse firm switches to technology $\bar{i}_3$ and invests in that technology for more than 25 years (from 63 to 88). Before and after this period, the firm invests in the same technology as it would do without discount. This implies that it will skip some technologies before as well as after choosing technology $\bar{i}_3$. More risk-averse firm will do exactly the same, but they switch to the 'discount technology' some years later. Note that at the time when the most risk-averse firm jumps to technology $\bar{i}_3$, the least risk-averse firm is already investing in more advanced technologies. This implies that the market of capital goods is not a perfectly monopolistic one in the sense that total demand will be in technology $\bar{i}_3$ for some time.[281]

Before we will turn to the diffusion pattern, we will examine what happens to the market share of each firm, the lifetime of equipment, and aggregate demand for labour. The growth rate of the price of output, which is equivalent to the growth rate of marginal costs on the newest vintage, is displayed in Figure 7.19 for firm 10 and firm 0. This figure also presents the growth rate of the aggregate price level of output ($\bar{P}_t$). The price of output decreases if the firm switches to the 'discount technology' but increases afterwards due to an increasing wage rate while the labour productivity remains the same. This holds true for all firms, but because the least risk-averse firm switch to the new technology prior to others and because the

280. To obtain representative graphs of this experiment, we changed the number of technologies from 7 to 15. Given the amount of available computer memory, we reduced the length of the simulation period to 200 and decreased the maximum lifetime to 50 (the actual maximum lifetime is less than 45 years in this experiment), so that the simulation runs from year 50 to year 200. All parameters are the same as those used for the simulation in section 7.1.

281. Note that the interval between the point in time at which the least risk-averse firm chooses another technology and the point at which the least risk-averse firm switches to the 'discount technology' depends on the height of the discount (here 10%) and on the difference in planning period between these firms (here 35 years for the least risk-averse and 5 years for the most risk-averse firm).

market shares and the number of firms are not the same for all firm types, the growth rate of the aggregate price level appears to be a smooth cycle. Because of this pattern, the market share of the least risk-averse firm will increase as soon as it invests in technology $\bar{i}_3$, but will decrease afterwards and is even below its steady-state market share because other firms also switch to that cheaper technology. The market shares of the most risk-averse firms show opposite patterns, which is displayed in Figure 7.20.

The development of the lifetime of equipment is the same for all firms. First, the lifetime will decrease because old equipment is replaced by the new technology whose marginal costs are relatively low. The marginal costs of the newest vintage increase due to increasing wage costs while the labour productivity remains the same, which causes an increase of the lifetime. As long as a specific firm buys technology $\bar{i}_3$, the labour productivity of the vintages in which that technology is embodied is the same. This implies that the lifetime increases until the firm buys a new technology. This causes a huge drop in the lifetime because that part of the capital stock in which technology $\bar{i}_3$ is embodied will be scrapped at one point in time. In the end, the lifetime will increase until its steady-state value. This development is presented in Figure 7.21 for firm 10 and for firm 0.

Finally, the growth rate of aggregate demand for labour will initially fall because firms invest in a more productive technology ($\bar{i}_3$) than they would without a discount. But after a while the opposite holds, as firms would have invested in more advanced technologies but buy technology $\bar{i}_3$ because of the discount. The growth rate of aggregate labour demand is displayed in Figure 7.22. The huge decrease in the lifetime of equipment implies that there is a large capacity gap at that moment, as a result of which the amount of investment will be large, the labour productivity increases, and the demand for labour decreases sharply due to the scrapping effect. Note that it takes a long time for the labour demand to reach its steady-state path. This is a typical vintage model effect. Because a specific vintage will be relatively large, the amount of investment will also be large if that vintage is scrapped. After a while, the relatively large vintage is scrapped and replaced by a new, and again relatively large, vintage. This causes peaks in the amount of investment but also in the growth rate of labour demand. The effect decreases in time because the amount of capital of a specific vintage decreases due to depreciation. Without depreciation, the large fluctuations would persist forever.

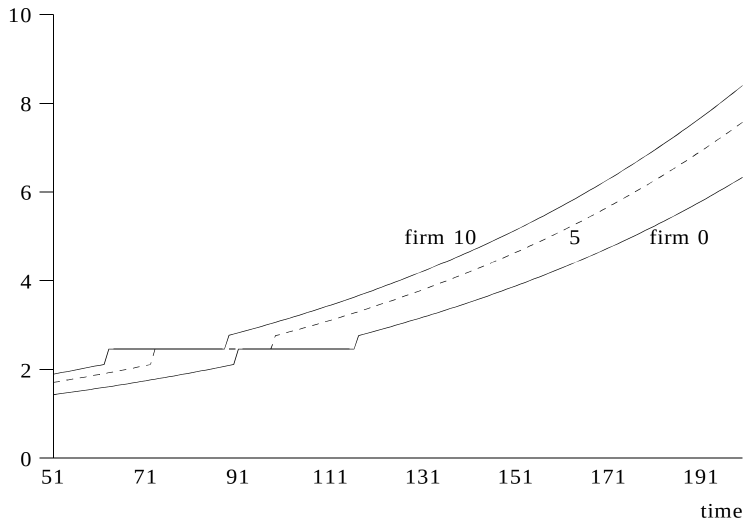

Figure 7.18. The technology index chosen by firms 0, 5 and 10

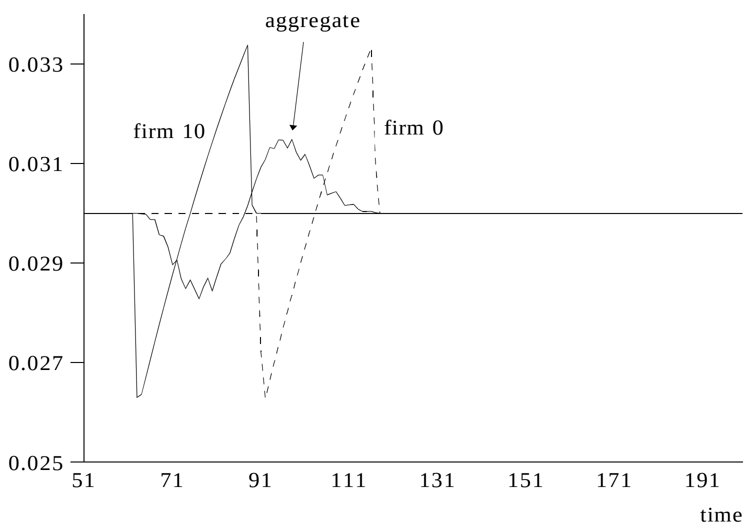

Figure 7.19. The growth rate of output prices

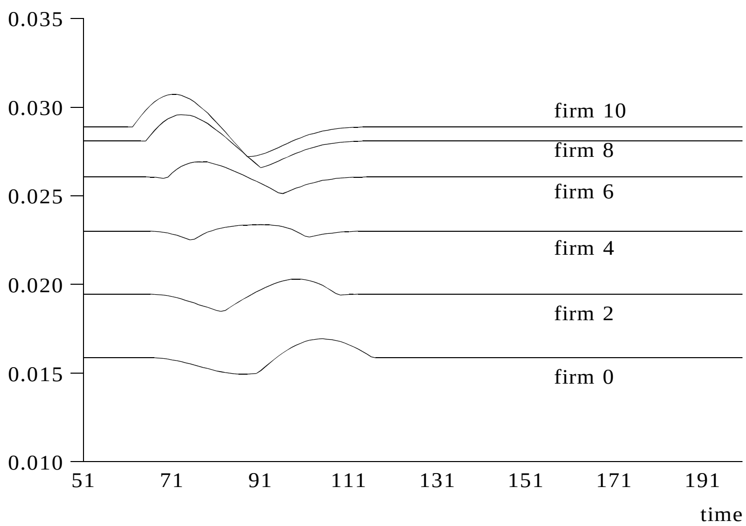

Figure 7.20. The market shares of several firms

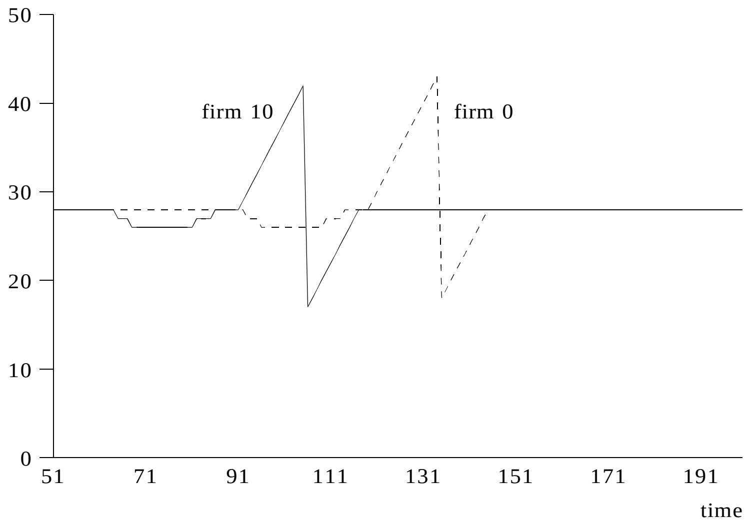

Figure 7.21. The lifetime of equipment

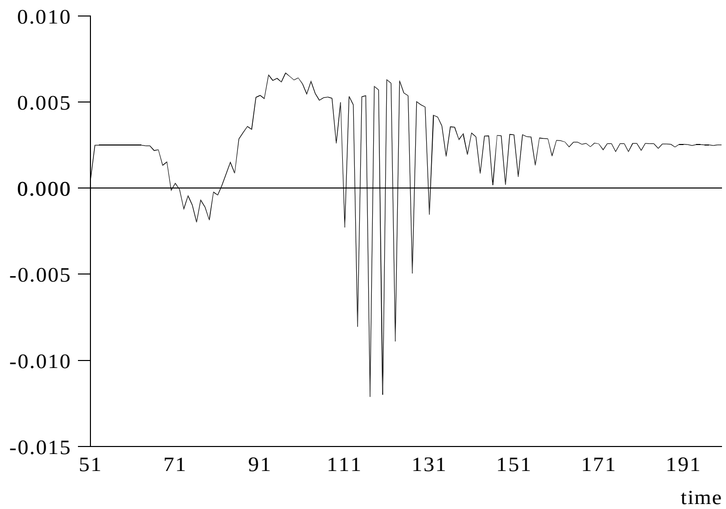

Figure 7.22. Growth rate of aggregate demand for labour

7.4.1 The Diffusion Pattern

The diffusion pattern is the result of the choice of technologies and of the amount of investment in each technology. We have shown previously that all firms invest in the 'discount technology' earlier that in a technology without a discount. Moreover, we have shown that they invest in that technology for a longer period and that the amount of investment increases, at least during the first years of investment in that technology. Thus, we expect the diffusion pattern of technology $\bar{i}_3$ to start sooner and that the ceiling level, i.e., the cumulative amount of investment in that technology, is raised. In Figure 7.23, we see that this is indeed the case. The diffusion pattern starts at time 63 whereas it would begin at 77 without a discount. The ceiling is increased from 4.4 to 28.6, an increase of 550%. If we define the elasticity of demand on the ultimate ceiling levels, this implies a price elasticity of -55.[282] So, whereas the supplier of technology $\bar{i}_3$ is not exclusively selling its capital goods to the final goods sector, the slope of the demand curve for each individual technology is very flat, which indicates that the market for capital goods is rather competitive. But because each technology is supplied by one firm, for instance due to property rights on the blueprints of that specific technology, the market of capital goods can be described by monopolistic competition. This finding will be used in the next section, where we will discuss the supply of technologies.

Note that the increase in the amount of investment in technology $\bar{i}_3$ decreases the amount of investment in technologies $\bar{i}_1$ and $\bar{i}_7$. The amount of investment in technologies $\bar{i}_2$ and $\bar{i}_4$ are zero and are not shown in the figure. Technology $\bar{i}_{14}$ is not affected by the discount, but the amount of investment in technology $\bar{i}_{10}$ has increased compared to the non-discount simulation. This seems counter-intuitive at first sight, but becomes clear if we recall the scrapping behaviour discussed above. Because all firms invest large amounts in technology $\bar{i}_3$, a large part of the capital stock is scrapped if that technology becomes obsolete. This implies that the amount of replacement investment is large. Most firms invest in technology $\bar{i}_{10}$ if this happens as a result of which the supplier of that technology coincidentally benefits from the discount provided (and paid for) by the supplier of technology $\bar{i}_3$.

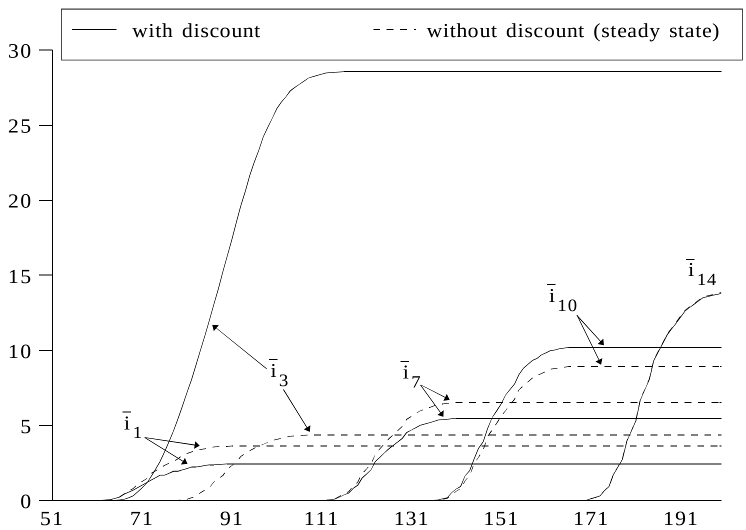

Figure 7.23. Diffusion patterns of several technologies, with and without a discount

282. Discounts of 1% and 5% resulted in elasticities of -103 and -71, respectively.

7.5 The Supply of Technologies

Above, we have shown that the slope of the demand curve for an individual supplier of capital goods is very flat and we concluded that the market for capital goods is characterized by monopolistic competition. In the macro-model in part II as well as in the present part, we assume that the price of equipment increases as the incorporated technology increases. Moreover, the present model generates positive growth of labour productivity if, and only if, the growth rate of nominal wages is larger than the growth rate of the price of capital goods for each individual technology.[283] This section will motivate that this is likely to be the case. We will not develop a model as such, but provide some possible directions for further research in which the supply side is incorporated into the model.

One possible explanation of a smaller growth rate in prices of capital goods than the growth rate of wages can be found in Stoneman and Ireland (1983). They assume that the demand for equipment in which a specific technology is incorporated is given by a bell-shaped distribution which originates from the probit-type models of David (1969) and Davies (1979). Stoneman and Ireland assume that each firm buys only one unit of the capital good, as a result of which the demand is equal to the number of firms which will adopt a technology. Their model comes in two versions: one in which the supplier is a monopolist and one in which there are a few oligopolistic suppliers.

Because they assume that each firm buys only one unit of the capital good, Stoneman and Ireland can derive an inverse demand function in a straightforward manner. In the monopolistic case, the supplier sets the price of the capital good in such a way that it maximizes total, present and future, profits. Moreover, it is implicitly assumed that the supplier is able to decrease the price of the capital good continuously, i.e., with infinitely small steps, so that it can exercise perfect intertemporal price discrimination. Because each demanding firm buys the capital good as soon as the price of that capital good reaches the firm-specific critical value, each demanding firm pays exactly its highest acceptable price. The distribution of firms with respect to the price they are willing to pay for the capital good is assumed to be fixed, which implies that the supplying industry has to decrease its price to sell it product. In terms of our model, this implies that the growth rate of the price of the capital good must be below the growth rate of the wages, otherwise there would be zero demand. Stoneman and Ireland show that the resulting diffusion pattern is S-shaped if the costs structure of the supplying firm includes a minimal optimal scale and if there are learning-by-doing effects.

There exist several differences between their model and our quasi-clay-clay model. First, in our model the demand in terms of the amount of investment of an

283. Note that the observed price of equipment can grow due to increasing technology indices, i.e., due to an increasing quality embodied in capital goods.

individual firm depends on the price of that capital good. Secondly, firms may buy that technology more than once, and thirdly, there are many other investment opportunities which means that the supplying industry is far from monopolistic. The oligopolistic case of Stoneman and Ireland describes the same demand structure, but now there are more firms which produce the same technology. Because the same discrepancies hold true here, their model is not suitable to describe the supply side in the present study.[284] Although it is easy to incorporate the demand function of our model into the analysis of Stoneman and Ireland if we assume that each firm buys only one unit of the investment good and if each firm invests only once in that technology, these limitations are crucial to the extent that this is not a very useful approach explaining price-setting behaviour in our model. We tried to extend their model by replacing their demand function by a function which originates from our quasi-clay-clay model. However, the main, and unsolved, problem is that there is no simple way to derive an inverse demand function, and thus this strategy failed. Therefore, we are not able to present a formal model in this thesis, but below, we will provide some possible directions in which a supply side could be integrated into our model. As previously mentioned, these extensions are left for further research.

One possible approach is to integrate our model into Romer's endogenous growth model. The model of Romer (1990) incorporates three different sectors: the R&D sector, which produces new process designs or blueprints; the intermediate good sector, which buys designs and produces capital goods; and a final good sector, which produces consumer goods with capital goods being one of the inputs. Technological change enters Romer's model because it is assumed that the productivity of the research sector depends on the accumulated knowledge. If a researcher produces a new design, he/she can prevent others from imitating this design by means of patents. Yet, other researchers can learn from the design and are thus able to increase their productivity. Or, in the words of Romer: *"If an inventor has a patented design for widgets, no one can make or sell widgets without an agreement of the inventor. On the other hand, other inventors are free to spend time studying the patent application for the widget and learn knowledge that helps in the design of a wodget. The inventor of the widget has no ability to stop the inventor of a wodget from learning from the design of a widget. This means that the benefits from the first productive role for a design are completely excludable, whereas the benefits from the second are completely nonexcludable."* Romer (1990: S84). In more formal terms, Romer assumes that the total number of different designs evolves according to: $\dot{A} = \varrho H_A A$, in which A denotes the total number of designs, H_A denotes the amount of human capital employed in the R&D sector and ϱ is a productivity parameter. Human capital is the only factor of input in the research sector.

284. An alternative view is that our model is not appropriate to be incorporated into their model, of course.

The intermediate good sector buys (or rents) a design and produces capital goods which are based on this design. The intermediate good sector is assumed to be rather monopolistic at the output side, which means that these firms maximize expected profits, conditional on the inverse demand function of the final goods sector. The resulting price is a mark-up on marginal costs. At the input side, the research sector is competitive and thus intermediate firms compete to buy new designs. This results in a price which equals the present value of expected profits which an intermediate good producing firm can realize.

Finally, technological change — which is modelled by the number of different designs — enters the consumer goods producing sector by using the Ethier (1982) production function.[285] This functional form says that the productivity of all capital goods is the same but that the productivity of all capital goods increases if the number of different types of equipment — the variety of production possibilities — increases. The first characteristic implies that a capital good built on an old design (e.g., a steam engine) is as productive as a capital good built on a new design (e.g., an internal combustion engine). However, this is rather counter-intuitive and not supported by empirical results.

In our model, the capital goods in the final goods producing sector differ from each other with respect to the embodied labour productivity and their price. Moreover, the number of different types of equipment does not tend to increase. Old equipment is simply scrapped and replaced by new machinery and we showed that the lifetime is constant in a steady state. This is one of the main differences between both models. Now, we will tentatively examine whether (parts of) the Romer model can be used to underpin the supply side in our model. As stated above, we have to examine two different properties: the relative price difference between types of equipment in which different technologies, or designs, are embodied and the movement of the price of one specific capital good in time. We will show that the first property can be extracted fairly easily from the Romer model but that the second property involves some problems.

An important consequence of the production function in the research sector is that one unit of human capital becomes more productive if the number of designs increases. Let the different capital goods, or designs incorporated into these goods, be indexed by i and let A_t be the index number of the newest design at time t. Then, the Romer model says that the amount of labour needed to produce a new design is constant. Consequently, if we define μ as being the relative increase in the productivity of a capital good which embodies that new design, the costs involved with the production of this new design is equal to $w_H/(\varrho A_t)$ where w_H denotes the prevailing wage rate in the research sector. Because everyone can enter the research sector, this sector is competitive and, thus, the price of the newest

285. As already noted in Chapter 2, this production function is based on the 'love of variety' idea of Dixit and Stiglitz (1977).

design is equal to $p_A = w_H/(\varrho A_t)$. This result is taken from the Romer model. The relative price difference between two succeeding designs is then equal to $\hat{p}_A = \hat{w}_H - \hat{A}_t = \rho_H - \varrho$ in which ρ_H denotes the growth rate of wages in the research sector. So the intermediate good sector can buy a new design for price p_A and the growth rate of this price is equal to the growth rate of the wages in the research sector minus the productivity of that sector. If the intermediate sector is rather competitive, which is indeed the case as we have shown above, the price of capital goods (as an output of the intermediate goods producing sector) will be a simple mark-up on marginal costs. Assume that the price of a design is the only difference of the costs structure in producing different types of capital goods. The price difference between capital goods which are based on different designs will then be the same as the price difference between the costs of buying these designs. This, in turn, implies that the parameter γ in our model is equal to $w_H - \varrho$.

If the growth rate of wages in the research sector increases, γ will increase because the relative costs of producing new designs increase and is negatively related to the productivity of the research sector ϱ. One interesting feature is that the relation between μ and γ determines the elasticity of substitution in the final goods producing sector. Chapter 5 has shown that this elasticity is equal to $\mu/(\mu+\gamma)$ which is exogenously given for the final goods producing firms. However, the relation between μ and γ is determined by the relative costs involved in producing, or inventing, new designs. The elasticity of substitution is therefore not a technical parameter but is based on the growth rate of wages in the research sector. If ρ_H increases, γ will increase and the elasticity of substitution decreases. This causes a slowdown in the rate of technological change in the final goods producing sector. In the above mentioned ‘productivity slowdown simulation’, as well as in the macro-economic diffusion model, we concluded that a decrease in the growth rate of wages will decrease the rate of technological change. However, if the wage rate of the research sector is positively correlated with the wage rate in the final goods producing sector, the relation between the growth rate of wages and the rate of technological change becomes less clear. However, from a policy point of view — an issue which has not been discussed until now — the rate of technological change can be increased a by relatively high growth rate of wages in the final goods producing sector and relatively low wage rates in the research sector, for instance due to wage subsidies or income tax differentials between both sectors of production.[286]

From this, it follows that the relative price differences between several capital goods can be modelled by making use of Romer’s production function of new

286. A simulation of an increase of γ is fairly complex, because the costs of capital goods are no longer a continuous function of the technology index. This would imply that we have to consider investment in technologies invented before the shock, and investment in technologies invented after the shock. Because there are infinite investment possibilities, this would request an entire revision of the simulation program.

designs.[287] The development of the price of a specific capital good over time is less clear, however. There are several possibilities to explain why the price of a certain capital good increases less than the wage rate of the final goods producing sector. Without being decisive, we will briefly discuss two possibilities.

The first one corresponds to the Romer model, where the intermediate sector uses designs and capital to produce new types of equipment. Because the price of a design is determined at the moment a intermediate goods producing firms buys that design, it can be interpreted as an ordinary investment good, which means that the annual costs are the same if the interest rate is constant. This implies that the price of a specific investment good is fixed and that the final goods producing firms will invest in more advanced technologies if the growth rate of nominal wages is positive. The main 'trick' to obtain this result is, of course, the absence of labour as an input of the intermediate good producing sector. Although it corresponds to the Romer model, this seems to be an unrealistic assumption.

The second possibility stems from the Stoneman and Ireland model. If we assume that the price of capital goods is related to the marginal costs of the intermediate goods producing sector, and if we assume that there are learning-by-doing effects in this sector, the marginal costs will decrease relative to the wage rate, as more capital goods are produced. If we assume that the production of capital goods on a new design implies that the learning process starts all over again, the relative difference of the price between two different types of capital goods is unaffected. So 'design-specific' learning by doing in the intermediate goods producing sector will decrease the price of capital relative to the prevailing wage rate, whereas the relative price difference between different technologies is unaffected.

Thus, the Romer model enables us to derive the desired property that the price of a specific capital good decreases relative to the wage rate in the final goods producing sector, but this is initiated by the absence of labour in the capital goods producing sector. A more elegant, or less crude, solution is to assume technology-specific learning by doing in the intermediate good producing sector. Because this reduces marginal costs, the price of capital goods in which a specific technology, or design, is embodied decreases over time, relative to the development of the wage rate.

Of course, the possibilities discussed in this section are not represented in a formal model, but they can be seen as possible extensions to the present, demand-based, quasi-clay-clay model. The inclusion of an R&D sector in which the productivity of researchers depends on the number of designs produced provide an opportunity to build an endogenous growth model which describes the generation of new technologies as well as the spread of the capital goods in which these new technologies are embodied. Moreover, the present production structure of the final goods producing sector relaxes Romer's unrealistic assumption that all capital

287. Which originates from Judd's (1985) study on the production of new patents.

goods, whether invented now or a couple of decades or centuries ago, are equally productive. Of course, it still has to be proved that this approach will lead to stable growth paths.

7.6 Conclusions

This chapter highlights some properties of the quasi-clay-clay vintage model if the economy is outside the steady state. We presented three different simulations. The first one involves a replay of the productivity slowdown, in which we compare our model with a standard putty-clay model. The parameters of the putty-clay model are calibrated in such a way that both models are comparable in a steady state. A comparison between both models in the steady state shows that the growth rates are exactly the same whereas the relative differences between most variables are very limited. In the second part of this thesis, we concluded that the slowdown in the growth rate of real wages is responsible for the productivity slowdown for a large extent. The present chapter shows that the quasi-clay-clay model is able to describe such a productivity slowdown. Whereas a standard putty-clay model shows a decrease in the growth rate of labour productivity, the reduction in the labour productivity in the quasi-clay-clay model is about twice as high. This is attributed to the difference between endogenous technological change in our quasi-clay-clay model and exogenous technological change in the standard putty-clay model. An interesting result is that the productivity in the quasi-clay-clay model remains below the labour productivity of the putty-clay model if the growth rate of wages is restored to its original value.

Comparing these results with the difference between the diffusion and the non-diffusion putty-clay model in the second part of this thesis, we find that both diffusion models can explain the productivity slowdown to a larger extent than the non-diffusion models. In both diffusion models, this is caused by a decrease in the profitability of new types of equipment, which leads to a decrease in the incentive to innovate.

The diffusion patterns are S-shaped in this particular simulation because we assumed a bell-shaped distribution of firms with respect to the length of the planning period. Estimation results of the macro model indicate that the ceiling levels of the diffusion patterns increase if the rate of adoption decreases. This holds true for the present model. One main difference between the macro-economic putty-clay diffusion model and the quasi-clay-clay model is that the former includes path dependencies through learning effects. In other words, firms will stick to old technologies if the relative profitability between old and new types of equipment decreases. In the present model, a similar result is obtained if the gains from investing in new types of equipment decreases relative to the costs. In the learning-by-doing version of the quasi-clay-clay model, Chapter 5 shows that firms will invest in the same capital good for a considerable period of time. The average rate of labour productivity growth is the same as in the non-learning case if measured over a long period in time. If the growth rate of wages decreases, firms will invest in the same technology for a longer period, so that the growth rate of labour productivity also slows down in the learning-by-doing version of our model. We have not presented a simulation of the learning-by-doing case because this would not add new insights. Inter-firm diffusion patterns remain S-shaped whereas intra-firm diffusion patterns appeared to be nearly linear, which has already been shown in chapter 5. To obtain S-shaped intra-firm diffusion patterns, we would have to include such adjustment costs in our model as used by Stoneman (1981).

Returning to the simulation results, the second simulation involves a presentation of endogenous diffusion patterns. In chapter 6, we were not able to proof that the diffusion pattern is S-shaped whereas the expected profits are non-decreasing for less risk-averse firms. Although a simulation is still not a solid proof, we showed that the expected profits increases as the length of the planning period increases, whereas the market shares appeared to be a bell-shaped function of the length of the planning period. This results in S-shaped diffusion patterns and we showed that this result can be obtained without assuming extraordinary parameter values.

The endogenous diffusion pattern simulation is combined with a decrease in the non-technology-specific part of capital good prices. In contrast to shocks in the wage rate, which affect relatively labour-intensive producing firms to a larger extent, the non-specific part of capital goods influences all firms in the same way. This implies that the market shares do not change. Moreover, because the growth rates are not affected, there is just a short lifetime effect. Altogether, we showed that this experiment did not substantially alter the diffusion patterns, and consequently has a limited effect on the growth rate of labour productivity.

The third and last simulation result presented in this chapter involves a discount on the price of only one technology. This experiment provides some insights into the slope of the demand curve for investment goods. We showed that a discount of 10% leads to an overall increase in the amount of investment in that technology of 550%. Consequently, the slope of the demand curve is very flat, which means that the market for capital goods is rather, but not perfectly, competitive. An interesting feature of the vintage structure of the model is that a supplier of a more advanced technology benefits from the discount of another supplier, because the amount of investment is relatively high if the ‘discount technology’ becomes economically obsolete and is scrapped. Moreover, the vintage structure involves a long period of adjustment, so that it takes a long time for the economy to restore to its steady-state value.

The result of the rather competitive market for capital goods is used to give some possible directions for further research to incorporate a supply side of new technologies into our model. We showed that the model of Stoneman and Ireland is a less fruitful approach because their assumption that each firm buys a capital good only once and buys only one unit of that good appeared to be a crucial assumption in order to obtain an inverse demand function of the technology-using sector. With respect to the price differences between distinct technologies, we used some concepts of the endogenous growth model of Romer (1990). Because the generation of new technologies increases the total (public) stock of knowledge in the research sector, the productivity of a researcher is positively related to the number of designs. Given this production structure of the research sector, we are able to show that the relative costs of producing a new design depends on the growth rate of wages in the research sector. If this term is constant, the relative costs involved in the invention of a new design are constant, and this model is able to describe relative differences between the price of different types of equipment and the incorporated technologies. An interesting result is that the elasticity of substitution, which is given exogenously to the final goods producing firms, can be related to the costs involved in producing a new capital good. From that point of view, the elasticity of substitution is not just a technically determined parameter.

To obtain technological progress in our model, we required the growth rate of the non-technology-specific part of prices of capital goods to be less than the growth rate of wages in the final goods producing sector. Without developing a model into detail, we suggested two different ways in which the supply side could be modelled to obtain this result. A less plausible way is to follow Romer and to assume that designs and capital are the only factors of input to produce durables. A more likely explanation is that the production of equipment exhibits learning-by-doing effects, causing the marginal costs of producing durable to decrease relative to the growth rate of wages. Although this is not demonstrated in a formal way, this approach can be used to incorporate the supply side of new technologies into our model. Moreover, this will lead to a model which incorporates both endogenous growth and diffusion of new technologies. Or, to put it differently, such a model can describe both the generation of new technologies and the transmission of these new types of equipment through the economy.

Appendix 7A. The Determination of Technology Ranges

If we assume that all technology ranges are be equal, i.e., if the distance a and b in Figure 7.2 are the same, the amount of investment in each technology would decrease relative to the actual amount of investment due to the fact that the slope of intersection between the optimal technologies and the horizontal technology ranges increases over time. The total amount of investments in each technology increases over time because we imposed a 1¼% growth of total output. The interval between the point in time at which the least risk-averse firm invests in a technology and at which the most risk-averse firm invests in the same technology is constant in time in the theoretical model, which implies that the amount of investment in each technology should increase by 1¼%.[288] This notion has two implications. First, the speed of diffusion, measured as the time interval between first and last adoption, is constant in time, and secondly, the amount of investment in a technology increases at the same rate as the growth total output. If we use a constant range, we would measure a growth rate of about 0.6%, which is far below 1.25%. This is caused by the fact that the number of times a firm would invest in a technology declines over time if the technology ranges are the same for all technologies. The relative amount of output, produced with each technology, would decrease over time in such a case. This is shown in Figure 7A.1, in which the technology range is kept constant for all technologies. In order to correct for this measurement error, the technology range should increase as the slope of intersection between the optimal technology and the horizontal technology range increases. The range of the least advanced technology (b in Figure 7.2) is assumed to be 0.10% of the total range (A). The number of times that a firm invests in this technology is kept constant for all technologies, resulting in increasing technology ranges.

Finally, Figure 7A.1 is based on a linear distribution of the technologies within the range (A) in Figure 7.2, as a result of which the interval between succeeding technologies decreases over time. The diffusion patterns in the main text are obtained by the condition that the time interval between succeeding technologies is constant.

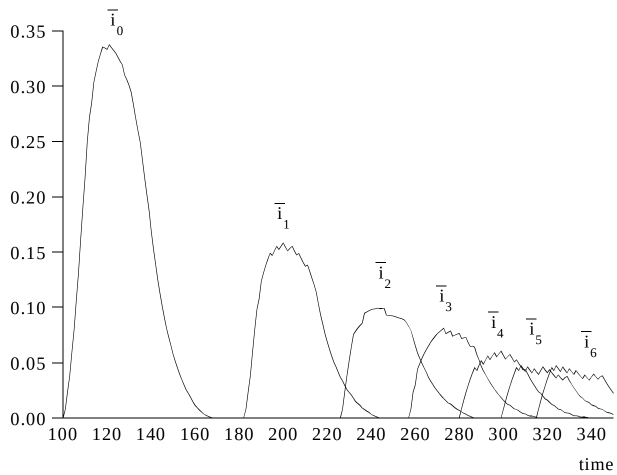

Figure 7A.1. The relative amount of production with each technology in the non-corrected model

288. The time interval which has to expire before two different firms will invest in the same technology is equal to: $t_2 - t_1 = \frac{1}{\rho - v}\left[\ln(f(\theta_2)) - \ln(f(\theta_1)\right]$ in which θ_1 and θ_2 denotes the planning period of firm 1 and 2 respectively. This implies that, given constant parameters and constant values of the planning period for both firms, the speed of diffusion should be the same for all technologies.

PART IV

SUMMARY AND CONCLUSIONS

8 Concluding Summary

The main aim of this thesis is to endogenize the transmission of technologies; it views technological change as being the result of economic choices of firms rather than as an exogenous factor. This subject is discussed in the light of one main theme: the productivity slowdown. The growth rate of labour productivity has been nearly constant in the developed countries during the post World War II period. Although there are some indications that the pace of growth decreased in the late sixties, the first oil crisis in 1973 is often seen as an end of this period. Both the growth of output and the growth of the labour productivity have slowed down to a large extent in the seventies and the eighties. The present study examines whether a model in which the transmission of technological change is endogenized is able to explain this productivity slowdown. The thesis consists of three parts. The first part gives a short overview of the literature on modelling technological change and presents some explanations of the productivity slowdown. It focuses on the new growth theory as well as on vintage models and on models on the adoption and diffusion of new technologies. The second part develops a macro-economic vintage-diffusion model in which a epidemic alike adoption pattern is incorporated in a putty-clay vintage framework. The speed of diffusion of a new technology depends on the expected profitability, relative to all alternative technologies, and on the available knowledge about that technology. The vintage-diffusion model is estimated using Dutch data on the enterprise sector. In order to obtain some insights into the importance of the diffusion component in our model, we also estimated a non-diffusion vintage model as a reference model. Part II ends with an investigation of the growth rate of labour productivity and decomposes aggregate labour productivity growth into several components in order to demonstrate the influence of the diffusion element in the model.

Firm behaviour is not elaborated in detail in the macro-economic model of part II. It is assumed that firms differ from each other regarding the tendency to innovate in new technologies. A possible explanation is that firms differ with respect to risk aversion and that less risk-averse firms innovate earlier in a new technology than more risk-averse firms. The model is non-stochastic, which implies that risk and risk aversion are concepts that are not incorporated in the model as such. Part III rectifies this omission, and develops a model in which the future is uncertain and in which firms differ from each other with respect to risk aversion. Chapter 5 shows that the length of the planning period employed by a firm to examine the profitability of an investment opportunity is a monotonic decreasing function of the level of risk aversion. Because firm behaviour cannot be traced analytically in the stochastic model, and because of the unique relation between risk aversion and the length of the planning period, part III continues with a non-stochastic vintage model in which the planning horizon is taken as an implicit measure of risk aversion. The choice of technologies, which is also described in Chapter 5, is incorporated into a vintage framework in Chapter 6, and results in a quasi-clay-clay vintage model. Chapter 6 contains a more advanced dynamic model as well as a non-myopic static version of the model. The static model proves to be a good approximation of its dynamic counterpart, and because the latter cannot be solved analytically, part III continues with the static version.

Finally, Chapter 7 investigates the properties of the model by means of some simulation experiments. The quasi-clay-clay vintage model is compared with a standard putty-clay vintage model. The first simulation experiment imitates the productivity slowdown and investigates the difference between both models. The quasi-clay-clay model is able to generate S-shaped diffusion patterns, independently of the distribution of firms with respect to risk aversion. The second experiment involves an analysis of such endogenous diffusion patterns. The third and last experiment examines the slope of the demand function of technologies. This result is used in the final section of part III: the supply of capital goods in which different technologies are embodied. Whereas this field is rather unexplored in the literature and although this subject is interesting and important enough to claim a thesis of its own, Chapter 7 only examines some possible extensions of the present analysis in the direction of endogenous growth models, where the generation as well as the transmission of new technologies are endogenized.

This chapter summarizes the thesis and reviews the main findings. The first three sections will summarize parts I, II and III, respectively. The last section presents some possible directions for further research in the field of vintage models and the diffusion of new technologies.

8.1 Theoretical Background

Chapter 2 reviews the literature on technological change and focuses on the question which model or which type of models is able to adequately describe the productivity slowdown. After a short description of the traditional growth theories of Harrod-Domar, Solow and Kaldor, the discussion concentrates first on the endogenous growth models and on the model of Scott. It is shown that these models are not able to explain the productivity slowdown without making some additional assumptions. Romer (1987) argues that a decrease in the wage rate, caused by a increase in the supply of labour, will decrease the labour productivity due to external effects of labour. His analysis is purely theoretical in nature and he is sceptical about the size of the external effects, hence it is doubtful whether the productivity slowdown can be explained by endogenous growth models. Scott (1990) reviews the productivity slowdown in a more empirical fashion and he investigates whether his model can explain the decreasing rate of productivity growth in the seventies and eighties. His analysis points into the direction of decreased investment opportunities in this period. However, he also examines some possible mismeasurements, such as the quality-adjusted amount of employment, the rate of capacity utilisation and a mismeasurement of the investment ratio. Correcting for these terms, he finds that his model can just explain a small part of the productivity slowdown.

Another explanation of the slowdown is given by David (1991) and Metcalfe and Gibbons (1991), whose analyses turn to the transmission of technological change. They argue that the turbulent movements of the economies in the early seventies have increased uncertainty and made firms more reluctant to buy new technologies. Finally, van Zon (1991) investigates whether there are mismeasurements of total factor productivity (TFP) due to the use of the aggregate production function. He shows that a vintage model which takes several effects such as the lifetime of equipment into account, results in different measures of the TFP and, consequently, of the productivity slowdown.

From this discussion, we concluded that a model is probably able to describe the productivity slowdown if it is based on a vintage model and if it incorporates the ideas of adoption and diffusion of new technologies. Section 2.2 describes the standard vintage models and shows that these models are not able to describe the productivity slowdown, given a constant rate of technological change. Moreover, it is assumed that all firms invest in the same ‘best-practice’ technology in standard vintage models. The literature on the adoption and diffusion of new technologies shows that this assumption contradicts reality. Section 2.3 investigates some models on the adoption and diffusion of new technologies and it is concluded that most of these models lack a broader framework, thus failing to give a good description of the amount of investment and the relation between scrapping and investment. Moreover, with respect to the productivity slowdown, the above-mentioned works of David and Metcalfe and Gibbons point at some possible explanations in the direction of a slowdown of the speed of diffusion. However, there is no empirical study which can provide some insights into the importance of this possible explanation.

By combining the vintage framework and the notion of diffusion of technologies, one can relax the stringent assumption of standard vintage models that all investment is in the same technology. Additionally, by integrating the models of adoption and diffusion into a more general framework, the relation between the choice of the technology and the amount of investment as well as the relation between scrapping and investment becomes more clear. Whereas standard diffusion models describe just the first part of the lifecycle of a new technology, a combined vintage-diffusion model is able to describe the whole lifecycle from investment until scrapping.

With respect to the productivity slowdown, a combined vintage-diffusion model endogenizes the transmission of technologies to a larger extent than standard vintage models. Moreover, it will provide some insight into the importance of changes in the speed of diffusion on the productivity growth if the resulting model can be tested empirically.

This leads to two different models. First, a model which has to provide some understanding of the empirical importance of diffusion at a macro-economic level. In order to keep the empirical model manageable, we decided to incorporate a fairly simple epidemic-based diffusion model into a vintage framework including the main properties of the diffusion models without making the resulting model unnecessarily complicated. This model is developed and estimated in part II of this thesis and will be summarized in the section 8.2.

The second model is more theoretical in nature. It is concerned with the question why some firms invest in new or advanced technologies, while others invest in old-fashioned equipment at the same point in time. This model, which is based on the probit-type models of David (1969) and Davies (1979), is discussed in part III and will be summarized in section 8.3.

8.2 Macro-Economic Analysis

Chapter 3 develops a non-diffusion as well as a diffusion version of a standard putty-clay vintage model. The non-diffusion model follows the Dutch vintage modelling tradition, and is a core version of the models of Kuipers and van Zon (1982), Gelauff, Wennekers and de Jong (1985), and of Muysken and van Zon (1987). The production structure is described by means of a CES production function and it is assumed that firms choose the initial labour intensity that maximizes expected rents over a certain planning period. Although the future wages and the interest rate are based on adaptive expectations, the expected lifetime, which is used as the planning period of the firm, is solved simultaneously with the initial labour intensity, which means that the expected lifetime is consistent with the expected date of scrapping. Because firms operate in a competitive output market by assumption, the scrapping rule is given by negative quasi-rents. Finally, the ex-post production structure allows for disembodied technological change and takes changes in working hours into account. Similar to Gelauff, Wennekers and de Jong and Muysken and van Zon, we allow for three reasons of scrapping: scrapping due to wear and tear, due to economic obsolescence (negative quasi-rent scrapping) and due to severe underutilisation of the production capacity. The final demand for labour includes labour-hoarding effects.

Whereas all firms invest in the same best-practice technology in a standard vintage model, the set of investment opportunities is not given by a single ex-ante production function in the vintage-diffusion model. It is assumed that each year, a new technology becomes available on the market for capital goods and that firms can choose from the set of available technologies in the vintage-diffusion model. The least advanced technology is determined by the negative expected rents condition. If the productivity of a technology is low to the extent that the expected profits are negative, no firm will invest in that technology and it is assumed that this technology will be withdrawn from the market for ever.

The ex-ante production function is given by a CES production function in which we allow for both embodied technological change of the best-practice technology and for ex-post improvements of existing technologies. This implies that we added an extra dimension to the standard vintage models: The capital stock is subdivided into different vintages and each vintage contains several different technologies.

Although the choice of the initial labour intensity is based on profit maximizing behaviour, the choice of the technologies is assumed to be the result of an underlying distribution of firms with respect to risk aversion. Without elaborating this is detail, it is assumed that the amount of investment in each technology, in terms of its relative output capacity, depends on the relative profitability of that technology and on its relative stock of (publicly available) knowledge. Because a technology invented at a later point in time is more productive, due to the exogenous shift of the ex-ante production function, there is an incentive to invest in that technology. But initially, little is known about that technology and only a few firms will invest in it. When time passes, the relative profitability of that technology declines due to the introduction of new alternatives, whereas the technology itself, or its characteristics, becomes better known. Since the stock of knowledge is assumed to be related to cumulative production with that technology, the knowledge increases rapidly once a technology is used. The relative profitability monotonically decreases because of the exogenous pace of technological change. This results in an increase of the amount of investment in a specific technology. Because the probability that a new piece of information will be generated decreases if the stock of knowledge increases, the amount of investment will decline at the end of the diffusion process. Although it is not certain, it is likely that the model is able to generate S-shaped diffusion patterns.

The rest of the model is comparable to the non-diffusion vintage model. There is only one point which needs some clarification. The data on investment are only available at an aggregate level, whereas the model is based on investment data for individual technologies. The data are aggregated by the statistical office by making use of Paasche price and Laspeyres quantity indices. We use the same methods to disintegrate the data, in which we have to specify a function relation of the prices of equipment. It is assumed that more advanced technologies, i.e., technologies which have been introduced more recently, are more expensive than less advanced technologies. This assumption enables us to derive data, prices as well as volumes, for individual technologies, conditional on the distribution of the amount of investment with respect to the incorporated technologies, which stems from the above-mentioned diffusion process.

The development of the labour productivity in the resulting vintage-diffusion model depends not only on the exogenous rate of technological change but also on the shape and skewness of the distribution of technologies. If the relative profitability of new technologies is large compared to older ones, more firms will invest in these new technologies and the labour productivity will grow rapidly. But if the profitability of new technologies declines relative to the profitability of older types of equipment, more firms will invest in older technologies. This reduces the impact of technological change on aggregate productivity. Whether such a relation is strong enough to explain the productivity slowdown is an empirical question which is answered in Chapter 4.

Another implication of the spread of technologies in the vintage model is that each vintage is no longer homogeneous. This implies that the rate of scrapping, which proves to have large discontinuities in standard vintage models, will be more smooth in the vintage-diffusion model. This relaxes some of the estimation problems which are due to these discontinuities in standard vintage models.

Chapter 4 presents the estimation results of both the diffusion and the non-diffusion vintage models. Both models are estimated for the period 1960-1988 using Dutch data for the enterprise sector. The estimation results of the vintage-diffusion model, in terms of the value of the objective function, are much better than the results of the non-diffusion model. In the vintage-diffusion model, we find almost no improvements of equipment once invented. This result suggests that one of the main criticism of Gold (1981) on epidemic models, i.e., that there is no room for ex-post improvements of technologies, is not that important from an empirical, macro-economic point of view.

With respect to the productivity slowdown, changes of the speed in diffusion are indeed able to explain the slowdown to a large extent. About 75% of the slowdown in structural labour productivity growth can be attributed to changes in the speed of diffusion. Compared to the results of Gelauff, Wennekers and de Jong (1985), we find that changes in the impact of new vintages and changes due to scrapping effects are much more important in the explanation of the productivity slowdown than changes in disembodied technological change. Yet, the latter factor is the main explanatory variable in the model of Gelauff, Wennekers and de Jong. Compared to the results of Romer (1987) and Scott (1989), we observe a large number of similarities. The decreasing growth rate of real wages decreases the incentive of firms to invest in new, more productive and labour-saving technologies. This is similar to the main argument of Romer. As in the analysis of Scott, the vintage-diffusion model includes lifetime effects and it takes into account changes in the rate of capacity utilisation as well as changes in the amount of labour hoarding. So, whereas Romer points in the direction of a relation between the development of wages and the growth rate of labour productivity, he is not able to give an empirical answer to the size of this relation. Scott's model is not able to explain the slowdown if he takes account of above-mentioned mismeasurements. In contrast to these models, our vintage-diffusion model is able to explain the slowdown and we concluded that the decline of the growth rate of real wages is responsible to a large extent for the labour productivity slowdown.

8.3 Firm Behaviour

The macro-economic model shows the importance of diffusion in the explanation of the productivity slowdown. The distribution of the technologies depends on the profitability and on the stock of knowledge and is not derived explicitly from firm behaviour. Part III is more theoretical in nature and develops some (possible) underlying economic mechanisms to explain diffusion patterns from differences in firm behaviour. The main assumption is that firms differ from each other with respect to risk aversion whereas each firm maximizes expected profits. Chapter 5 is addresses the choice of technologies without determining the amount of investment or the influence of this choice on economic scrapping. Chapter 6 incorporates the choice of technologies into a more general vintage framework. Finally, Chapter 7 investigates the properties of the model by means of some simulation experiments.

8.3.1 The Choice of Technologies

In contrast to part II, Chapter 5 assumes that there is an infinite range of different technologies available at any moment in time. The technologies differ from each other with respect to the embodied labour productivity and with respect to their price. The capital productivity is assumed to be constant and identical for all technologies, which implies that each technology can be characterized by a clay-clay, or Leontief, production function. The model comes in two versions: a stochastic and a deterministic version.

The stochastic version assumes that future prices of output are uncertain and a longer planning period — the period used to determine expected profits — involves more risk. The investment expenditures are assumed to be sunk costs, in other words, there exists a trade-off between the amount of risk involved with an investment project and the present value of expected profits. It is assumed that firms are utility maximizers and we adopted the constant absolute risk aversion utility function which leads to the mean-variance approach.

The model is a continuous version of the probit model developed by David (1969) and Davies (1979). As soon as the risk-adjusted expected profits of a new technology exceed those of an older, less productive, technology, a firm will buy that new technology. Because we assume a continuous range of different technologies, each firm will invest in a different technology at each moment in time.[289]

Although the choice of the technology cannot be determined explicitly as a function of the level of risk aversion, Chapter 5 shows that there is a unique relation between the level of risk aversion and the length of the planning period, and between the length of the planning period and the choice of technologies. Therefore, there exists an implicit relation between risk aversion and the choice of technologies. Because of this relation, and because the stochastic model involves some analytical problems, part III continues with the non-stochastic version of the model, in which it is assumed that firms differ from one another with respect to the length of the planning period. It is shown that firms with a longer planning period tend to invest in more productive, but also more expensive technologies.

Assuming a bell-shaped distribution of the number of firms with respect to the length of the planning period, this model is able to generate S-shaped diffusion patterns. Moreover, it is shown that a decline in the growth rate of wages will delay the adoption of new technologies and will increase the period from first adoption until the end of the diffusion process, i.e., the speed of diffusion decreases. This result resembles the importance of the growth rate of wages and the development of the labour productivity. At each moment in time, firms will invest in new technologies if there are no ex-post changes in the labour productivity. This implies that the model is able to generate inter-firm diffusion patterns but no intra-firm patterns as each firm invests in a specific technology only once. Although the macro-economic model allows for disembodied technological change, this ex-post development is assumed to be constant and independent of the age of the vintage. This assumption contradicts the literature on ‘learning by doing’ of among which Arrow (1962) is the most well known.

To overcome this shortcoming, Chapter 5 also develops a variant of the model in which firms can increase the productivity of existing equipment by means of learning by doing. Producing more output with the same technology generates more experience so that the productivity will increase. In line with Stiglitz (1987) and in contrast to Arrow, it is assumed that there are decreasing productivity returns to learning: if time progresses and production continues, everything which can be learned about a specific technology *will* be learned.

With respect to the choice of technologies this implies that firms must decide whether they will switch to a new technology, which makes present knowledge

289. With one exception: If the growth rate of wages is equal to the growth rate of the price of equipment for each specific technology, each firm will invest in the same technology at all points in time.

about other technologies obsolete as far at it concerns production with the new technology, or invest in a technology in which it invested before in order to benefit from previously generated knowledge. Chapter 5 shows that all firms will invest in a specific technology for a while until the influence of learning on productivity gains declines, so that it is worthwhile to invest in a new technology. Thus, the learning-by-doing approach gives some motivations for intra-firm diffusion.

Chapter 5 ends with a comparison between the choice of technologies and the choice of the optimal labour intensity in the macro-economic putty-clay vintage-diffusion model. It is shown that the choice of technologies can be interpreted as substitution along a Cobb-Douglas production function if capital is indexed to account for differences with respect to the price. Notwithstanding the fact that each technology is characterized by a clay-clay production function, the possibility of choosing between different technologies gives the model an ex-ante putty character, and therefore we called it a quasi-clay-clay vintage model. Moreover, it is shown that the choice of the initial labour intensity is comparable to the choice of the initial labour intensity in the putty-clay model. The relation between the relative productivity differences and the relative price differences between technologies in the quasi-clay-clay model can be interpreted as the elasticity of substitution in the putty-clay model.

8.3.2 A Quasi-Clay-Clay Vintage Model

Chapter 6 integrates the non-stochastic and non-learning version of the model into a vintage framework. Both the macro-economic model and the model in Chapter 5 assume that the output market is competitive, and thus, that the prices are given to each firm. This rather unrealistic assumption is replaced in Chapter 6 by monopolistic competition, where firms act as price setters and as quantity takers. This enables us to investigate the relation between the speed of diffusion and the market structure. Moreover, the scrapping condition is affected by this assumption, causing a relation between the choice of new technologies and the amount of scrapping of old equipment. Before we turn to these subjects, we will discuss the implementation of the choice of technologies in a vintage framework. Again, the model comes in two versions: a dynamic and a static, but non-myopic, version.

Similar to the stochastic version of the choice of technologies, the dynamic version of the model is preferable from a theoretical point of view. The non-competitiveness assumption implies that the Malcomson scrapping condition is no longer equal to the negative quasi-rent scrapping rule. Since maximizing the expected profits of the newest vintage — which is employed in part II — is not equal here to maximizing the expected profits of all vintages taken together, we have to reconsider the objective function of firms.

Another implication of the non-competitiveness assumption is that scrapping of equipment depends on the total of variable costs of the newest vintage. This implies that the expected date of scrapping, which is needed to evaluate the integral rents, depends on the marginal costs of the vintage that replaces the vintage in consideration. However, because the marginal costs of that future vintage depends on its expected lifetime, the expected lifetime of the present vintage depends on all future investment decisions. To be consistent, this implies that we have to consider investment decisions in a dynamic model.

A complicating factor of the present model is that, in addition, the maximum length of the planning period is treated as a measure of risk aversion. It is obvious that if the expected lifetime exceeds the maximum length of the planning period, a firm will apply the latter so that the influence of the market structure on the expected lifetime disappears. If the expected lifetime is shorter than the maximum planning period, Chapter 5 shows that each firm will apply the expected lifetime as a planning period because it would otherwise increase risk and decrease expected profits. In order to investigate the importance of the expected lifetime, and because the dynamic model will give some insight into the relation between investment and expectations with respect to future technologies, Chapter 6 develops such a dynamic model. There, the analysis is restricted to the first order conditions because of the analytically unsolvable relation between the present investment decisions and the future. The end point conditions as well as the optimal paths are not examined in that Chapter.

The choice of technologies is about the same in the dynamic version of the quasi-clay-clay model as that found in Chapter 5. The only difference is the length of the planning period which, as discussed previously, is the same if the expected lifetime exceeds the maximum length of the planning period. An interesting result of the dynamic model is that the marginal costs of the newest vintage include opportunity costs which arise due to future (expected) improvements of technologies. If a firm expects future technologies to be more productive, the marginal costs of the present vintage will increase and lead to a decrease in the amount of scrapping, and consequently, the amount of replacement investment.

Apart from the dynamic version, Chapter 6 develops an analytically more manageable static version of the quasi-clay-clay vintage model in which the amount of scrapping is determined by the Malcomson scrapping condition, but in which the expected lifetime is based on negative quasi-rent scrapping. Although the choice of technologies appears to be the same as in the dynamic model, the marginal costs of the newest vintage are independent of technological expectations.

One of the main goals of the integration of the choice of technologies into a vintage framework is to determine the relation between the amount of investment and the choice of technologies. Chapter 6 shows that such a relation can be derived analytically in a steady state situation, whereas non-steady state results should be investigated by simulation experiments. We investigated the relation between the amount of investment and the choice of technologies by assuming a deviation of the price of capital goods from its steady state value. This leads to three different effects: (i) firms will choose other technologies, (ii) the marginal costs of the newest vintage will change, and, consequently, the amount of scrapping will be altered, and (iii) different marginal costs will lead to different output prices, and, thus, a final demand effect which alters the amount of investment. The first effect is described by the choice of technologies, which says that increasing capital costs will increase the labour intensity, causing firms to buy less labour productive equipment. The second and third effects lead to a negative sloping demand curve for equipment. If the price of equipment increases, the marginal costs of the newest vintage will increase, less capital will be scrapped and there is a smaller need for replacement investment. The effect through final demand depends on the question whether total final demand is exogenously given or whether it depends on the aggregate price index.[290] This thesis assumes exogenous final demand, so that the aggregate amount of demand is not altered by changes in the price of equipment. If each individual firm assumes that the aggregate price level is constant, i.e., if they expect all other firms not to change their price and if the effect of their own price on the aggregate price level can be neglected, each individual firm will decrease investment because of the increased marginal costs, and consequently the decreased market share. Because the amount of investment will now decline, the negative sloping demand curve for equipment is pronounced through the final demand effect. Of course, if each firm knows, or expects, that all other firms face the same increase in the price of equipment, it will expect its market share not to change, which means that the negative slope of the demand curve for equipment is determined solely by the lifetime effect.

With respect to the resulting diffusion patterns, Chapter 6 considers two different cases: One in which the growth rate of real wages is nearly zero and the maximum length of the planning period of the least risk-averse firms is relatively small, and one which is characterized by a relatively large growth rate of real wages and relatively long planning periods.

The first case generates S-shaped diffusion patterns if the distribution of the number of firms with respect to the length of the planning period is bell-shaped. An appealing result is that the speed of diffusion depends on the market structure of final output. The speed of diffusion increases if the market is more competitive.

The second case generates S-shaped diffusion patterns which are *independent* of the distribution of the number of firms with respect to the planning period. This result is obtained by assuming that all firms with the same planning period produce the same consumption goods and that there are no further differences between firms. The S-shaped diffusion pattern is obtained through a bell-shaped distribution of market shares with respect to the length of the planning period of firms. Next to a relatively high growth rate of real wages and a relatively long

290. In which case we should have included a utility function for consumers which contains real money balances, for instance, as an alternative ‘consumption’ opportunity.

planning period, a nearly monopolistic market is needed to generate such bell-shaped distribution and, consequently, an S-shaped diffusion pattern.

8.3.3 Simulation Results of the Quasi-Clay-Clay Vintage Model

Part III concludes with some simulation results and a short impression of the supply of new technologies. The first simulation experiment imitates the productivity slowdown by decreasing the growth rate of wages and it is shown that the quasi-clay-clay model is able to describe the fall of the growth rate of labour productivity to a much larger extent than a standard putty-clay vintage model. This result can be attributed to the difference between the exogenous rate of technological change in the putty-clay model and the endogenously determined choice of technologies in the quasi-clay-clay model.

As in the case of the macro-economic vintage-diffusion model, firms will delay the adoption of new technologies in order to increase the amount of investment in relatively old technologies. An interesting difference between the quasi-clay-clay model and the putty-clay model is that the former incorporates larger path dependencies through the endogenous investment decisions. Thus, the labour productivity continues to be below the labour productivity in the putty-clay model, even if the growth rate of wages is restored to its original value.

The second simulation involves an examination of endogenous S-shaped diffusion patterns and is mainly concerned with the relation between the market shares and the length of the planning period and with that between expected profits and the length of the planning period. It is shown that the adoption patterns are bell-shaped and that the expected profits are an increasing function of the length of the planning period. Moreover, the length of the planning period is not unreasonably large to obtain S-shaped diffusion patterns.

Finally, the last simulation experiment shows that the demand for a capital good increases dramatically if the supplier of that technology lowers its price by 10%. This implies that the demand curve of equipment is rather flat, which points to a rather competitive market for capital goods. This result is used in the last section of Chapter 7: the supply of new technologies.

In that section, we find some connections between our own quasi-clay-clay model and the endogenous growth model of Romer (1990). By using the Romer production function of new designs, which are needed to develop new process technologies, this section shows that the relative costs of inventing a new technology are constant. Moreover, it shows that the development of the prices of capital goods will be below the growth rate of real wages. This result is needed to generate positive technological change in our model. The supply side is one of the possible extensions for research described in the next section.

8.4 Possible Directions for Further Research

Chapter 7 ends with a short discussion of possible further research by introducing of the supply of new technologies in the present model. The Romer (1990) model on endogenous growth seems to be a good candidate for such an extension. This may relax Romer's stringent assumption that all equipment is equally productive. Furthermore, the inclusion of an R&D sector which develops designs for new production processes in the present quasi-clay-clay model leads to endogenous generation as well as endogenous transmission of technologies change, so that the whole Schumpeterian trajectory from invention to final use can be described by one model.

However, such an approach is not without its problems. To mention one, it is far from easy to derive a final aggregate supply function, which means that the relation between consumption and production is not very clear in advance. However, such a relation is needed to maximize consumer utility and to determine the supply of labour. This section will be limited to two other main topics which give directions for possible future research: (i) economic policy, and (ii) aggregation of production units.

The present model only describes the production structure of an economy, which implies that it is of limited use to study effects of economic policy. However, the endogenous transmission of technological change provides some handles to investigate the relation between wage rates, or income tax policies, technological change and employment. The present model shows that the growth rate of labour productivity declines to a large extent if the growth rate of wages is reduced. Because such a reduction of the labour productivity growth will have a downward pressure on wages, a revival of the growth rate of wages becomes unlikely. In the short run, this will generate more employment, but the longer-term consequences are less optimistic. A (permanent) reduction of the labour productivity will decrease international competitiveness, and may thus lead to negative long-term effects. A decrease of wages will decrease total expenditures and will have a negative impact on final demand. Moreover, a decrease of the growth rate of labour productivity will have a negative impact on welfare, increasing social unrest and increasing fluctuations of wages or prices. This will increase uncertainty which again has a negative impact on the incentive to innovate. Altogether, this implies that a moderate growth of real wages in a stable environment leads to a higher rate of innovative activities.

Before we can give a decisive answer to such a question, the model must be extended by at least the labour market, a macro-economic part which determines consumption and saving, and a international part to describe imports, exports and the exchange rate. Together with a development of the supply of new technologies, this will lead to a model which can answer the relation between the generation and the adoption of new technologies and total output and employment.

The final extension suggested is more theoretical in nature. The present model decomposes the capital stock and consequently the distribution of production units even more than a standard vintage model. Although this will imply several simplifications of the present model, a distribution approach to the aggregation of several production functions within each vintage and a similar approach to the aggregation of all ‘vintages’ would lead to such an aggregate production function as derived by Johansen (1972), Sato (1975) and Muysken (1979, 1983) for a standard putty-clay model. This would lead to a full-capacity production function, a short-run aggregate production function, and by combining these two, a long-run production function of the industry. Moreover, such an approach would also be helpful in the derivation of the final supply function needed to integrate the present model into a more general endogenous growth model as suggested previously.

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