Université de Montréal

ESSAIS SUR L'INTÉGRATION VERTICALE, LES EXTERNALITÉS DE RECHERCHE VERTICALES, LES CONSORTIUMS DE RECHERCHE ET LE PARTAGE D'INFORMATION

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Thèse présentée à la Faculté des études supérieures
en vue de l'obtention du grade de
Philosophiæ Doctor (Ph.D.)
en Sciences économiques

Juin 2000

0-612-56455-X

Université de Montréal

Faculté des études supérieures

Cette thèse intitulée:

Essais sur l'intégration verticale, les externalités de recherche verticales, les consortiums de recherche et le partage d'information

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Thèse acceptée le: 25/10/00

REMERCIEMENTS

Je tiens à remercier mon directeur de recherche, Marcel Boyer, et mon codirecteur de recherche, Gérard Gaudet, pour leur direction de cette thèse. Par leurs enseignements, conseils, suggestions et critiques, ils m'ont inculqué la méthodologie scientifique et le sens du perfectionnement continuel de la recherche.

J'aimerais remercier Stéfan Ambec, Caroline Boivin, Pierre Dubois, Léonard Dudley, Georg Erber, Keith Newton, Michel Patry, Michel Poitevin, Jacques Robert et Patrick Waelbroeck pour leurs commentaires sur différents aspects de la recherche.

Les essais constituant cette thèse ont été présentés dans le cadre de plusieurs congrès, notamment: les 46^{th} et 48^{th} International Atlantic Economic Conferences, le $33^{ème}$ Congrès annuel de l'Association canadienne d'économique, les $39^{ème}$ et $40^{ème}$ Congrès de la Société canadienne de science économique et les 17^{es} Journées de micro-économie appliquée. Ils ont été présentés aussi aux institutions suivantes: Université de Montréal, University of Toronto, Glendon College, C.R.D.E., École des Hautes Études Commerciales, Industrie Canada et Statistique Canada. Je remercie les participants et participantes à ces congrès et séminaires pour leurs commentaires et suggestions.

Je suis reconnaissant envers le C.R.D.E. et le CIRANO pour leur soutien financier. Une partie de cette thèse a été rédigée alors que j'étais à Industrie Canada, où j'ai bénéficié d'un environnement de travail stimulant et flexible.

Un merci tout particulier à ma femme Yasmine pour son soutien et pour la révision linguistique du texte.

À mes parents

SOMMAIRE

La thèse est constituée de trois essais sur l'analyse microéconomique du changement technologique. Le premier essai étudie l'effet du changement technologique sur les frontières de la firme en se basant sur la théorie des coûts de transaction et la théorie de l'agence. Dans le deuxième essai, on examine les externalités de recherche entre acheteurs et vendeurs, en incorporant différentes structures de marché, conditions d'appropriabilité et types de coopération. Le partage d'information et la stabilité de la coopération dans les consortiums de recherche sont le sujet du troisième essai.

Le premier essai analyse l'effet du changement technologique sur les frontières de la firme en se basant sur la théorie des coûts de transaction et la théorie de l'agence. Le modèle incorpore quatre types de coûts: coûts de production, de coordination, de management et de transaction. La firme bénéficie de coûts de coordination plus faibles que le marché, mais elle souffre de coûts de production plus élevés. L'analyse est effectuée dans un cadre principal-deux agents, avec sélection adverse et risque moral. Il est montré que les changements techniques affectant les coûts de production et les coûts de coordination ont des effets diamétralement opposés sur l'intégration verticale. En général, le changement technique affectant les coûts de production augmente le degré d'intégration, alors que le changement technique affectant les coûts de coordination induit davantage d'impartition. Alors que l'effet d'un changement technologique affectant les niveaux des coûts de production ou de coordination dépend du différentiel de coûts entre la firme et le marché et de l'importance relative des coûts de production et de coordination, l'effet d'un changement technique affectant la technologie de réduction des coûts est sans ambiguïté, et ne dépend pas de ces deux paramètres. Le changement technique peut réduire l'importance de certains types de coûts dans la décision d'intégration de la firme. Les effets statiques de la concurrence et de la supervision sur les frontières de la firme diffèrent de leurs effets dynamiques (à savoir, comment ils affectent l'impact du changement technologique sur les frontières de la firme). Cet essai constitue un mariage entre les explications contractuelles et les explications technologiques de l'existence et des frontières de la firme.

Le but du deuxième essai est d'analyser les externalités de recherche verticales entre des firmes en amont et des firmes en aval. On modélise deux industries verticalement reliées, avec des externalités horizontales au sein de chaque industrie et des externalités verticales entre les deux industries. Quatre types de coopération en R&D sont considérés: pas de coopération,

coopération horizontale, coopération verticale et coopération généralisée (horizontale et verticale). Les externalités verticales augmentent toujours la R&D et le bien-être, alors que les externalités horizontales peuvent les augmenter ou les diminuer. La comparaison entre les différentes structures de coopération en R&D révèle qu'aucun type de coopération ne domine uniformément les autres: les externalités horizontales, les externalités verticales et la structure de marché déterminent le classement des structures de coopération. Ce classement dépend des signes et magnitudes de trois externalités concurrentielles (verticale, horizontale et diagonale) qui captent l'effet de la R&D d'une firme sur les profits des autres firmes. Le type de coopération induisant les firmes à internaliser une somme positive plus grande d'externalités concurrentielles génère plus de R&D. Cette analyse démontre qu'un des résultats de base de cette littérature -que la coopération entre concurrents augmente (réduit) la R&D lorsque les externalités horizontales sont élevées (faibles)- peut être renversé lorsque les externalités verticales et la coopération verticale sont pris en considération. Une théorie liant l'innovation à la structure de marché est proposée. Cette relation dépend des externalités horizontales, des externalités verticales et des structures de coopération; elle peut être comprise en termes des externalités concurrentielles horizontale, verticale et diagonale. L'étude des incitations privées à la coopération révèle que les firmes en aval et les firmes en amont ont des préférences différentes quant au choix des structures de coopération, que les externalités augmentent la vraisemblance de l'émergence décentralisée de la coopération et que des problèmes de coordination sur l'adoption de structures de coopération profitables peuvent entraver la coopération technologique.

Le troisième essai endogénise le partage d'information entre des concurrents coopérant en R&D et étudie sa relation avec la taille et la stabilité du consortium de recherche (RJV). Dans un jeu à quatre étapes, les firmes décident sur leur participation à la RJV, le partage d'information, les dépenses de R&D et l'output. Une caractéristique importante du modèle est que le partage d'information volontaire entre des membres de la RJV augmente les fuites d'information vers les non membres. Il existe deux types d'externalités de recherche: une externalité générale, s'appliquant à toutes les firmes, et une externalité spécifique, s'appliquant au partage volontaire d'information entre les membres de la RJV. Il est montré que c'est l'externalité de recherche spécifique qui détermine si les membres de la RJV partagent de l'information, alors que c'est l'externalité générale qui détermine le niveau de partage d'information. Les RJVs représentant une plus grande part de l'industrie partagent l'information

plus souvent que les plus petites RJVs. Lorsque le partage d'information a un coût nul, les firmes ne choisissent jamais des niveaux intermédiaires de partage d'information: elles partagent toute l'information ou ne partagent aucune information. Donc, les niveaux intermédiaires de partage d'information seraient justifiés par des considérations technologiques ou d'opportunisme, mais non pas par des considérations concurrentielles. La taille de la RJV dépend de trois effets: un effet de coordination, un effet de partage d'information et un effet de concurrence. Selon les magnitudes relatives de ces effets, la taille de la RJV peut augmenter ou diminuer avec les externalités. Finalement, l'effet du partage d'information sur la profitabilité des firmes et sur le bien-être est étudié.

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LISTE DES SIGLES ET ABRÉVIATIONS

Production technology, information technology, and vertical integration under asymmetric information

c	Production cost
t_c, t_c^D, t_c^e	Technological parameters affecting production costs
i	Coordination cost
t_i, t_i^D, t_i^e	Technological parameters affecting coordination costs
$I(c), C(i)$	Decision functions
$e(.)$	Cost reduction effort (CRE)
$D(.)$	Disutility of cost reduction effort
$f(.)$, $F(.)$	Density and Distribution functions of c and i
P_s	Payment to the subcontractor
P_e	Payment to the employee
$\underline{P}_s$	Transaction costs
$\underline{P}_e$	Management costs
π	Profits
CRE	Cost reduction effort
IT	Information Technologies

Vertical R&D spillovers, cooperation, market structure, and innovation

a	Inverse demand intercept
w	Inverse demand slope
t	Price charged by suppliers
p	Final product price
π_i	Profits of firm i
W	Welfare
y_{bi}	Output of buyer i
y_{si}	Output of seller i
Y	Total output
bi	Buyer i
si	Seller i
m	Number of downstream firms
n	Number of upstream firms
c_i	Final marginal cost of production of firm i
r	Basic cost of production of a downstream firm
s	Basic cost of production of an upstream firm
u	Parameter of the R&D cost function
h	Horizontal R&D spillover
v	Vertical R&D spillover
V	Vertical competitive externality
H	Horizontal competitive externality
D	Diagonal competitive externality
X	Total R&D output
x_{bi}	R&D output of buyer i
x_{si}	R&D output of seller i

β	$\{x_{b1},\ldots,x_{bm},x_{s1},\ldots,x_{sn}\}$
TOC	Type(s) of cooperation
NCE	Non-cooperative equilibrium
GCE	Generalized cooperative equilibrium
HCE	Horizontal cooperative equilibrium
VCE	Vertical cooperative equilibrium
NC	No cooperation
GC	Generalized cooperation
HC	Horizontal cooperation
VC	Vertical cooperation

Information sharing and the stability of cooperation in research joint ventures

a	Inverse demand intercept
w	Inverse demand slope
p	Product price
π_i	Profits of firm i
W	Welfare
r	Basic cost of production
u	Parameter of the R&D cost function
y_i^m	Output of insider i
y_i^n	Output of outsider i
Y	Total output
T	Total number of firms
M	RJV size
M^*	Endogenously determined RJV size
M_w	Socially optimal RJV size
N	Number of outsiders
f	Basic R&D spillover
g	Voluntary information sharing
k	Leakage from the RJV to outsiders on voluntary information sharing
Γ_i	Total information received by firm i as a result of voluntary information sharing
x_i	R&D output of firm i
x_i^m	R&D output of insider i
x_i^n	R&D output of outsider i
X	Total R&D output
Q	Total effective cost reduction
RJV	Research Joint Venture

INTRODUCTION GÉNÉRALE

Cette thèse traite de deux thèmes en organisation industrielle. Le premier thème est l'effet du changement technologique sur les frontières de la firme. Le deuxième thème est l'investissement en R&D par les entreprises en présence d'externalités de recherche et de la possibilité de coopérer en R&D.

Durant les deux décennies précédentes les grandes firmes dans les pays industrialisés ont eu un recours croissant à l'impartition. Plusieurs facteurs sociaux, économiques, managériaux et technologiques contribuent à cette tendance. L'objectif du premier essai est d'analyser le rôle joué par le changement technologique dans la détermination des frontières de la firme. La technologie peut affecter les frontières de la firme de maintes façons. Les technologies de l'information (TI) peuvent réduire les coûts de recherche, de coordination et de supervision des agents. Cette réduction des coûts pouvant affecter à la fois les agents internes (employés) et les agents externes (fournisseurs), l'effet net dépendra desquels entre les coûts internes et les coûts externes sont réduits davantage. En ce qui concerne les technologies de production, les processus CAD/CAM facilitent la division des activités de production entre des agents internes et externes. De plus, les technologies flexibles peuvent réduire la spécificité des actifs, réduisant les problèmes de hold-up à l'externe.

Alors qu'il existe une littérature étendue discutant l'effet du changement technique sur l'intégration verticale, peu de travaux formels ont étudié cette problématique. Une exception importante est Lewis et Sappington (1991).[1] Lewis et Sappington (1991) (LS ci-après) analysent comment le choix d'une firme de faire ou faire-faire un input est affecté par plusieurs types de changement technologique affectant les coûts de production. La firme a un coût de production plus élevé que le fournisseur, mais ce dernier jouit d'une information privée sur ses coûts. La firme et le fournisseur peuvent réduire leurs coûts en investissant dans un effort de réduction des coûts. LS analysent trois types de changement technique: une baisse des niveaux des coûts, une réduction de la désutilité de l'effort de réduction des coûts et une augmentation de l'impact de l'effort de réduction des coûts. Ils trouvent que toutes ces formes de changement technologique poussent la firme à choisir l'intégration verticale plus souvent. Cela est la conséquence de deux effets induits par le changement technique: un effet d'efficience et un

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[1] Lewis, T.R., et Sappington, D.E.M., 1991, 'Technological Change and the Boundaries of the Firm', *AER*, 81(4):887-900.

effet de contrôle. L'effet d'efficience vient de l'impact différentiel du changement technique sur les coûts de la firme et ceux du fournisseur, vu qu'ils ont des coûts et des niveaux d'efforts différents. L'effet de contrôle vient de l'impact du changement technologique sur la rente informationnelle du fournisseur. L'effet d'efficience favorise l'intégration verticale, parce que la firme a des coûts plus élevés à l'origine, alors que l'effet de contrôle favorise l'impartition, parce qu'il n'y a pas de rentes informationnelles au sein de la firme. La conclusion principale du modèle de LS est que le progrès technologique augmente le degré d'intégration verticale. Une limite importante de cette analyse est que le modèle n'incorpore pas les TI, qui peuvent avoir des effets considérables sur l'impartition, en plus de ne pas prendre en considération la présence de comportements opportunistes au sein de la firme.

Le but du premier essai est d'analyser l'effet du changement technologique sur les frontières de la firme en tenant compte de trois facteurs. D'abord, l'information asymétrique et l'opportunisme existent au sein des hiérarchies comme sur le marché. Cela est en contraste avec l'approche classique plus étroite de la théorie des coûts de transaction, qui suppose que l'intégration verticale résout automatiquement les problèmes d'opportunisme. Ensuite, le modèle tient compte de la critique de Demsetz (1988),[2] Foss (1996),[3] Chandler (1992)[4] et Coase (1990),[5] que la théorie des coûts de transaction réduit les différences entre la firme et le marché à des différences dans les coûts de transaction, omettant les différences reliées à d'autres types de coûts. Pour cela, le modèle incorpore simultanément les coûts de production et de coordination, en plus des coûts d'opportunisme. Finalement, le modèle franchit une autre limite de la théorie des coûts de transaction, celle voulant que la technologie soit secondaire dans la détermination des frontières de la firme. En incorporant le changement technologique en présence de problèmes contractuels explicites, le modèle montre que la technologie joue un rôle déterminant dans la décision d'intégration verticale. Cet essai constitue donc un mariage des explications contractuelles et des explications technologiques de l'existence et des frontières de la firme.

Le modèle incorpore quatre types de coûts: coûts de production, de coordination, de

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[2]Demsetz, H., 1988, 'The Theory of the Firm Revisited', *Journal of Law, Economics, and Organization*, 4(1):141-61.

[3]Foss, N.J., 1996, 'Capabilities and the Theory of the Firm', *Revue d'Economie Industrielle*, 77:7-28.

[4]Chandler, A., 1992, 'Organizational Capabilities and the Economic History of the Industrial Enterprise', *Journal of Economic Perspectives*, 6(3):79-100.

[5]Coase, R.H., 1990, 'Accounting and the Theory of the Firm', *Journal of Accounting and Economics*, 12:3-13.

management et de transaction. La firme bénéficie de coûts de coordination plus faibles que le marché, mais elle souffre de coûts de production plus élevés. Les coûts de management représentent les coûts de l'information privée au sein de la firme, alors que les coûts de transaction représentent les coûts de l'information privée sur le marché. Le modèle tient compte du fait que certains coûts sont plus faciles à observer par la firme que d'autres.

L'analyse est effectuée dans un cadre principal-deux agents, avec sélection adverse et risque moral. La firme (l'acheteur) a besoin d'une unité d'un input qu'elle peut fabriquer à l'interne ou acheter chez un fournisseur indépendant. L'employé de la firme et le fournisseur ont chacun de l'information privée sur certains de leurs coûts, et peuvent investir un effort non observable afin de réduire les coûts. Pour les coûts qui sont observables, les agents choisissent les niveaux efficaces d'effort, tandis que pour les coûts non observables, les efforts des agents sont distortionnés afin de limiter leurs rentes. La firme demande à l'employé et au fournisseur de reporter chacun leur type, suite à quoi elle décide de fabriquer l'input par l'intermédiaire de l'employé ou de l'acheter chez le fournisseur. La firme adopte une règle de décision qui détermine le mode d'approvisionnement en fonction des rapports de coûts.

L'effet du changement technologique sur l'intégration verticale est étudié par le biais de son effet sur cette règle de décision. On simule trois types de changement technologique pour chaque type de coût (production et coordination): une baisse des coûts, une augmentation de l'impact de l'effort réduisant les coûts et une baisse de la désutilité de l'effort de réduction des coûts. Toute forme de changement technique induit deux effets, un effet d'efficience et un effet de contrôle. L'effet d'efficience vient de la différence dans les niveaux des coûts, ou dans les niveaux d'effort réduisant les coûts de la firme et du fournisseur, tandis que l'effet de contrôle vient du fait que le changement technique peut réduire les rentes de l'employé et du fournisseur. Lorsque l'effet d'efficience domine, le changement technologique favorise l'agent (i.e. induit le recourt à cet agent plus souvent) ayant les coûts les plus élevés, ou investissant plus dans l'effort de réduction des coûts. Lorsque l'effet de contrôle domine, le changement technologique favorise l'agent jouissant d'une rente, due à son information privée sur le coût affecté par le changement technologique. L'effet de la concurrence entre fournisseurs et de la supervision sur les résultats du modèle est discuté.

Le deuxième thème abordé dans cette thèse est l'investissement en R&D par les entreprises en présence d'externalités de recherche et de la possibilité de coopérer en R&D. Le nombre d'accords technologiques de coopération et d'échange d'information s'est accru durant les dernières années. Par exemple, Hagedoorn et al. (2000)[6] notent que le nombre de nouveaux accords de coopération technologiques chaque année est passé de 30-40 au début des années 70 à près de 600 durant les années 80 et 90. d'Aspremont et Jacquemin (1988) ont donné le coup d'envoi d'une littérature prolifique sur la coopération et la concurrence en R&D (connue comme la littérature sur l'investissement stratégique). La thèse fait deux contributions à cette littérature.

La première contribution est l'étude des externalités de recherche verticales, qui sont le sujet du deuxième essai. Presque toutes les études composant la littérature sur l'investissement stratégique traitent d'externalités de recherche entre concurrents. Les externalités entre des firmes en amont et des firmes en aval, que j'appelle externalités verticales, sont un type important d'externalité inter-industries. La différence principale entre les externalités horizontales et les externalités verticales est que les premières sont involontaires et (généralement) indésirables du point de vue de l'innovateur, alors que les dernières sont désirables (et plus souvent volontaires). Une autre différence est qu'alors que la coopération horizontale en R&D peut faciliter la collusion entre firmes, il est peu vraisemblable que la coopération verticale nuise à la concurrence. La coopération intra-industrie est généralement suffisante pour internaliser les externalités de recherche horizontales, mais l'internalisation des externalités de recherche verticales requiert la coopération inter-industries.

Tandis que la littérature empirique démontre que les flux technologiques verticaux sont importants, peu de travaux théoriques se sont penchées sur cette dimension de l'appropriabilité. Deux exceptions sont Peters (1995)[7] et Harhoff (1991).[8] Peters étudie un modèle de réseaux de firmes avec externalités verticales. Il trouve que les industries plus concentrées tendent à dépenser plus en R&D, que les externalités horizontales peuvent augmenter ou diminuer la R&D, et que les externalités verticales augmentent la R&D, les profits et le bien-être. Le modèle de Peters souffre de plusieurs hypothèses restrictives: les externalités sont dans une seule direction, des fournisseurs aux clients; les firmes en amont ne bénéficient pas de leur

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[6]Hagedoorn, J., Link, A.N., et Vonortas, N.S., 2000, 'Research partnerships', *Research Policy*, 29:567-86.

[7]Peters, J., 1995, *Inter-Industry R&D-Spillovers between Vertically Related Industries: Incentives, Strategic Aspects and Consequences*, Working Paper No. 139, Institut für Volkswirtschaftslehre, Universiät Augsburg.

[8]Harhoff, D., 1991, *R&D Incentives and Spillovers in a Two-Industry Model*, Zentrum für Europäische Wirtschaftsforschung GmbH, Industrial Economics and International Management Series, Discussion Paper No. 91-06.

propre R&D, tous les bénéfices allant aux firmes en aval; les firmes en amont ne peuvent pas ajuster leur output à leur investissement en R&D; et, finalement, la coopération en R&D n'est pas étudiée.

Harhoff (1991) étudie un modèle d'innovation produits avec des externalités de recherche verticales. Il trouve que la R&D en amont et la R&D en aval sont généralement des substituts: avec une structure de marché exogène et des externalités de recherche verticales parfaites (dans une seule direction), une seule des deux industries investit en R&D. Là aussi, le modèle souffre de plusieurs hypothèses restrictives. La présence d'un monopoleur en amont prenant ses décisions en Stackelberg rend les résultats applicables à des structures de marché très asymétriques. De plus, cette structure de marché rend impossible l'étude des externalités horizontales dans l'industrie en amont. Une autre hypothèse est que lorsque les externalités horizontales en aval sont incorporées, les prix en amont sont fixés de manière exogène. Aussi, les externalités de recherche sont parfaites et dans une seule direction. Finalement, la coopération en R&D n'est pas étudiée.

En vue d'étudier en profondeur l'impact des externalités verticales sur les investissements en R&D, le deuxième essai modélise ces externalités, en incorporant différents types de coopération en R&D, différents environnements d'appropriabilité et différentes structures de marché. La contribution de cet essai est triple. D'abord, il s'agit d'une première tentative de formaliser l'effet des externalités verticales dans un cadre relativement général. Ensuite, l'étude de la coopération va plus loin que les études existantes en modélisant différents types de coopération. Finalement, le modèle propose une théorie liant la structure de marché à l'innovation, tenant compte des externalités de recherche horizontales et verticales et des structures coopératives.

On modélise deux industries verticalement reliées, avec des externalités horizontales au sein de chaque industrie et des externalités verticales entre les deux industries. Le nombre de firmes dans chaque industrie est exogène mais n'est pas fixé à l'avance. Le jeu comprend trois étapes. Dans la première étape toutes les firmes déterminent leur investissement en R&D. Quatre environnements sont considérés pour cette étape: pas de coopération, coopération horizontale, coopération verticale et coopération généralisée (horizontale et verticale). Dans les deuxième et troisième étapes, les firmes en amont et en aval, respectivement, déterminent leur output de manière non coopérative. La concurrence en Cournot est résolue en se servant du cadre d'analyse des oligopoles successifs de Greenhut et Ohta (1979).[9]

On analyse d'abord l'effet des externalités de recherche sur la R&D et le bien-être, ainsi que les interactions entre les externalités horizontales et les externalités verticales. On compare ensuite les différents types de coopération en R&D. Le concept d'externalité concurrentielle -qui représente l'effet de la R&D d'une firme sur les profits des autres firmes- est introduit et utilisé dans la comparaison des structures coopératives. Le modèle fournit une théorie expliquant l'effet de la structure de marché sur l'innovation. Le modèle propose trois types de relations possibles entre la concurrence et l'innovation: a) une relation concurrentielle, où une augmentation de la concurrence augmente l'innovation; b) une relation Schumpeterienne, où une augmentation de la concurrence diminue l'innovation; et c) une relation asymétrique, où l'innovation est maximisée lorsqu'une industrie est très concurrentielle alors que l'autre est très concentrée. Le modèle montre comment le type de coopération et les niveaux des externalités horizontales et verticales déterminent laquelle de ces trois relations prévaut. Le concept d'externalité concurrentielle permet d'expliquer ces trois relations entre la concurrence et l'innovation. Finalement, les incitations privées à la coopération en R&D sont examinées.

La deuxième contribution à la littérature sur l'investissement stratégique est l'endogénisation du partage d'information dans les consortiums de recherche (RJVs), qui est le sujet du troisième essai. La coopération en R&D incorpore trois dimensions: la coordination des dépenses de R&D, le partage d'information et la stabilité de la coopération. La coordination des dépenses induit les firmes à internaliser l'effet de leurs innovations sur les autres firmes. Le partage d'information augmente les externalités de recherche entre les firmes. Finalement, la coopération peut être instable face aux déviations individuelles et coalitionnelles.

La plus grande partie de la littérature sur l'investissement stratégique s'est concentrée sur la coordination des dépenses de R&D, et peu d'attention a été portée vers la stabilité de la coopération, et encore moins vers le partage d'information. Généralement, le partage d'information et la formation des RJVs ont été étudiés séparément. Typiquement, le partage d'information est exogène et la coopération couvre toute l'industrie (qui n'est le plus souvent qu'un duopole). Toutefois, il existe des interactions importantes entre le partage d'information

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[9]Greenhut, M.L., and Ohta, H., 1979, 'Vertical Integration of Successive Oligopolists', *AER*, 69(1):267-77.

et la formation de la RJV. Le partage d'information affecte l'attrait de la RJV pour les non membres affecte la décision des membres d'accepter de nouveaux membres. L'étude des interactions entre le partage d'information et la formation des RJVs contribuerait à une meilleure compréhension des partenariats de recherche existants.

Deux approches coexistent dans la littérature pour ce qui est du partage d'information. La première suppose que le partage d'information n'est pas affecté par la coopération, dans lequel cas la coopération se résume à la coordination des dépenses de R&D (De Bondt et al., 1992;[10] Kamien et al., 1992).[11] La deuxième approche est de supposer que la coopération implique le partage complet de l'information (Kamien et al., 1992; Poyago-Theotoky, 1995).[12] Les deux hypothèses sont arbitraires, en plus de manquer d'assises théoriques et empiriques. Il est raisonnable de penser que la coopération améliore le partage d'information, mais il n'existe aucun fondement pour l'hypothèse du partage complet de l'information.

Nombre d'études ont considéré le problème du partage d'information entre concurrents, sans toutefois étudier son interaction avec la stabilité de la coopération. d'Aspremont et al. (1996)[13] étudient le problème de la négociation quant à la divulgation de résultats de recherche dans une course pour une innovation brevetable entre deux firmes. Katsoulacos et Ulph (1998a, 1998b)[14] endogénisent les externalités de recherche en tenant compte de distinctions telles que les innovations produits versus les innovations processus, la substituabilité technique vs. la complémentarité technique et le partage d'information vs. la coordination de la recherche. Dans Poyago-Theotoky (1999),[15] deux firmes choisissent le niveau de partage d'information après avoir investi en R&D; elle trouve que les firmes coopérant (ne coopérant pas) en R&D choisissent un partage maximal (minimal) de l'information. Kamien et Zang (1998)[16]

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[10]De Bondt, R., Wu, C., et Lievens, D., 1992, *Stable Strategic R&D Cartels*, Onderzoeksrapport NR. 9204, Departement Toegepaste Economische Wetenschappen, Katholieke Universiteit Leuven.

[11]Kamien, M.I., Muller, E., et Zang, I., 1992, 'Research Joint Ventures and R&D Cartels', *AER*, 82(5):1293-1306.

[12]Poyago-Theotoky, J., 1995, 'Equilibrium and Optimal Size of a Research Joint Venture in an Oligopoly with Spillovers', *Journal of Industrial Economics*, 43(2):209-25.

[13]d'Aspremont, C., Bhattacharya, S., et Gérard-Varet, L.A., 1996, *Bargaining and Sharing Knowledge*, Discussion Paper No. TE/96/293, Suntory and Toyota International Centres for Economics and Related Disciplines, London School of Economics and Political Science.

[14]Katsoulacos, Y., et Ulph, D., 1998a, 'Endogenous Spillovers and the Performance of Research Joint Ventures', *Journal of Industrial Economics*, 46(3):333-57; Katsoulacos, Y., and Ulph, D., 1998b, 'Innovation Spillovers and Technology Policy', *Annales d'Economie et de Statistique*, 40-50:589-607.

[15]Poyago-Theotoky, J., 1999, 'A Note on Endogenous Spillovers in a Non-Tournament R&D Duopoly', *Review of Industrial Organization*, 15:253-62.

[16]Kamien, M.I., et Zang, I., 1998, *Meet Me Halfway: Research Joint Ventures and Absorptive Capacity*, Mimeo, Department of Managerial Economics and Decision Sciences, J.L. Kellogg Graduate School of Management, Northwester University.

permettent aux firmes de choisir une "approche de R&D" déterminant le degré auquel l'autre firme peut bénéficier de cette recherche. Combs (1993)[17] développe un modèle de R&D où la coopération augmente la probabilité d'innover par le biais du partage d'information concernant les stratégies et résultats de recherche. De Fraja (1990, 1993)[18] cherchent à déterminer si les firmes ont une incitation à divulguer les résultats de leurs recherches. Finalement, Bhattacharya et al. (1990)[19] développent un modèle où les chercheurs peuvent partager leurs dotations en connaissances productives dans la première étape et choisissent les efforts de R&D dans la deuxième étape.

Considérons ensuite la deuxième dimension de la coopération, la taille de la RJV. Les études ont typiquement supposé que tous les membres de l'industrie participent à la RJV. Parmi le peu d'études ayant endogénisé la décision de participation, on peut mentionner De Bondt et al. (1992), Poyago-Theotoky (1995), Kamien et Zang (1993),[20] Eaton et Eswaran (1997),[21] Kesteloot et Veugelers (1995)[22] et Yi (1998).[23] Toutefois, dans toutes ces études, le partage d'information est exogène.

Les deux seules études à avoir étudié conjointement la stabilité de la RJV et le partage d'information sont De Bondt et Wu (1997)[24] et Katz (1986).[25] De Bondt et Wu (1997) étudient la coopération en R&D avec une décision de participation endogène. Même s'ils étudient brièvement l'effet de différents niveaux de partage d'information sur la stabilité de la coopération, le partage d'information demeure exogène. Katz (1986) est la seule étude endogénisant simultanément le partage d'information et la formation de la RJV. Toutefois, son analyse se concentre sur le cas où il n'y pas d'externalités de recherche exogènes, et où le

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[17] Combs, K.L., 1993, 'The role of information sharing in cooperative research and development', *International Journal of Industrial Organization*, 11:535-51.

[18] De Fraja, G., 1990, *Strategic Disclosure of R&D Knowledge and Research Joint Ventures*, Discussion Paper No. 90/278, University of Bristol; De Fraja, G., 1993, 'Strategic spillovers in patent races', *International Journal of Industrial Organization*, 11:139-46.

[19] Bhattacharya, S., Glazer, J., et Sappington, D.E.M., 1990, 'Sharing Productive Knowledge in Internally Financed R&D Contests', *Journal of Industrial Economics*, 39(2):187-208.

[20] Kamien, M.I., et Zang, I., 1993, 'Competing Research Joint Ventures', *Journal of Economics and Management Strategy*, 2(1):23-40.

[21] Eaton, B.C., et Eswaran, M., 1997, 'Technology-trading coalitions in supergames', *RAND Journal of Economics*, 28(1):135-49.

[22] Kesteloot, K., et Veugelers, R., 1995, 'Stable R&D Cooperation with Spillovers', *Journal of Economics & Management Strategy*, 4(4):651-72.

[23] Yi, S.S., 1998, *Endogenous formation of joint ventures with efficiency gains*, Working paper, Dartmouth College.

[24] De Bondt, R., et Wu, C., 1997, 'Research Joint Venture Cartels and Welfare', in Poyago-Theotoky (ed.), *Competition, Cooperation, Research and Development*, MacMillan, London.

[25] Katz, M.L., 1986, 'An analysis of cooperative research and development', *RAND Journal of Economics*, 17(4):527-43.

choix est entre la coopération entre toutes les firmes et l'absence de coopération.

Pour étudier l'interaction entre le partage d'information et la stabilité de la coopération, on modélise une industrie de taille fixe où des firmes se concurrençant à la Cournot peuvent investir en R&D en vue de réduire leurs coûts. Il existe deux types d'externalités de recherche: une externalité générale, s'appliquant à toutes les firmes, et une externalité spécifique, s'appliquant au partage volontaire d'information entre les membres de la RJV. L'externalité spécifique constitue une fuite d'information de la RJV aux non membres. L'idée est que partager l'information augmente les chances qu'une partie de cette information soit transmise à d'autres firmes.

Le jeu comprend quatre étapes. À la première étape, la taille de la RJV est déterminée de manière endogène, en tenant compte de la stabilité interne, de la stabilité externe et de la capacité de la RJV à limiter sa taille. Lors de la deuxième étape, les membres de la RJV se mettent d'accord sur une quantité d'information à partager volontairement. Les firmes décident sur leurs investissements en R&D à la troisième étape. Cette décision est prise de manière coopérative par les membres de la RJV et de manière non coopérative par les non membres. En dernier lieu toutes les firmes se concurrencent à la Cournot. La complexité du modèle nous contraint à résoudre certaines étapes par le biais de simulations numériques.

On étudie d'abord le partage d'information par les membres de la RJV, pour une taille donnée de la RJV. Les déterminants de la décision de partager l'information et du niveau de partage sont étudiés. On analyse ensuite la taille et la stabilité de la RJV. Sa taille est déterminée par trois effets: un effet de coordination, qui est relié à la coordination des dépenses de R&D par les membres; un effet de partage d'information, qui est relié à la possibilité qu'ont les membres de partager l'information; et un effet concurrentiel, qui est relié au fait qu'accepter un membre additionnel dans la RJV en fait un concurrent plus féroce. La RJV est stable si aucun membre ne veut la quitter, que les membres n'ont pas intérêt à se débarrasser d'un membre et que l'une des deux conditions suivantes est satisfaite: soit qu'aucun non membre ne voudrait joindre la RJV, ou que les membres s'opposeraient à l'addition d'un membre. Sur la base des décisions des firmes à l'équilibre, on analyse la diffusion technologique, qui est décomposée en ses différentes composantes: effet propre, externalité générale, externalité spécifique et partage volontaire d'information. La variation des deux aspects fondamentaux de la RJV, qui sont la coordination des dépenses de R&D et le partage volontaire d'information, avec l'externalité générale est examinée. Finalement, les effets de la coopération et du partage d'information sur la profitabilité des firmes et sur le bien-être sont étudiés.

PRODUCTION TECHNOLOGY, INFORMATION TECHNOLOGY, AND VERTICAL INTEGRATION UNDER ASYMMETRIC INFORMATION

1. Introduction

During the last two decades large firms in industrialized countries turned toward outsourcing for an increasing portion of their inputs.[1] Many social, economic, managerial, and technological factors lie behind this change in procurement. The purpose of this paper is to analyse the role technological change plays in determining procurement practices. The paper constitutes a bridge between agency and contractual explanations on the one hand, and technological explanations on the other hand, of the existence and frontiers of the firm. Although there exists an extensive literature discussing the effect of technology on vertical integration, little formal work has dealt with this topic. Two important exceptions are Lewis and Sappington (1991) and Reddi (1994).

Reddi (1994) follows the decision-theoretic framework of Clemons, Reddi and Row (1993) to analyse the effects of information technologies (IT) on outsourcing. Three types of organization are possible: vertical integration, (long term) partnerships, and market (short term) suppliers. Quality and cost are variable across suppliers, who have a cost advantage over the buyer. The firm makes an investment in IT to coordinate operations with the supplying unit. Higher coordination costs reflect four characteristics of the component: higher complexity, difficulty of measurement, high demand uncertainty, and high lead time. The use of more IT reduces coordination costs. Given measurement difficulties, there is a moral hazard problem regarding quality. Reddi finds that as IT become cheaper the firm prefers to outsource rather than to produce in-house. When products are complex and uncertainty is high, partnerships are preferred to market suppliers. As the specificity of IT decreases, the buyer is more likely to outsource than to produce in-house. For complex (simple) products and high (low) uncertainty, this increase in outsourcing will favour partnerships (market suppliers). While the model incorporates production costs, technical progress on those costs is not considered.

Lewis and Sappington (1991) (LS hereafter) study how the choice by a firm between making and buying an input is affected by different types of technological progress on production costs. The firm has a higher cost than the supplier, but the supplier has private

1.A well known example is that of the American car industry, which is now outsourcing more than 50% of its inputs. The public sector is also increasingly turning toward outsourcing. McFetridge and Smith (1988) note that in most industrialised countries, service purchases by industries have increased significantly between 1961 and 1981, and the trend is stronger in fast growing industries. Between 1989 and 1994, IBM reduced its workforce from 100,000 to 60,000, increasing the number of suppliers during the same period from 1,000 to 20,000 (Rothery and Robertson, 1995). The median number of the Fortune 500 American firms was 16,000 in 1973, 13,000 in 1983, and 10,000 in 1993 (McMillan, 1994). For these same firms, during the last 50 years, the value of purchased materials and services rose from 20% to 50% of final product value.

information about her costs. The firm and the supplier can reduce their costs through a cost reducing effort. LS analyse how procurement is affected by three types of technical progress: a reduction in production costs, a reduction in the disutility of cost reducing efforts, and an increase in the effect of cost reducing effort. They find that any of these forms of technical progress leads the firm to choose vertical integration more often. This follows from two effects induced by technological progress: an efficiency effect and a control effect. The efficiency effect comes from the differential impact of technological change on the firm and the supplier, given that they have different costs and different effort levels. The control effect comes from the impact of technological change on the information rent appropriated by the supplier. The efficiency effect favours vertical integration, because the firm has higher initial costs, while the control effect favours the supplier, because there are no information rents when the input is produced internally. The main conclusion of the LS model is that technological progress induces the firm to make rather than buy the input more often. An important limitation of the model is that it does not incorporate IT, which represent the bulk of the effects of technology on outsourcing. Also, their model does not allow fór opportunism to arise within the firm.

The purpose of this paper is to analyse the effect of technological change on the frontiers of the firm while taking into account three factors related to the tradeoff between the firm and the market. First, asymmetric information and opportunism exist in firms as well as in markets. This is in contrast to the traditional transaction cost view that vertical integration automatically resolves opportunism problems. Second, the model takes into account the critiques of Demsetz (1988), Foss (1996), Chandler (1992), and Coase (1990) that transaction cost theory reduces the differences between the market and the firm to differences in transaction costs, omitting differences in other types of costs. For that, the model incorporates production and coordination costs, in addition to opportunism costs. Third, the model goes beyond another limit of transaction cost theory which asserts that technology plays but a secondary role in determining firms' frontiers. By incorporating technological change in the presence of explicit contractual problems, the model shows that technology plays a key role in determining firm's frontiers.

The paper builds on transaction cost theory and agency theory. The problem is studied in a principal-two agents model with adverse selection and moral hazard. The model is based on the framework of LS but enlarges the scope of the analysis by incorporating different types of costs and adopting a richer stochastic environment. Regarding costs, LS consider only production costs, whereas here both production and coordination costs are incorporated. Regarding the stochastic environment, in the LS model the disadvantage of the market was due only to private information. As for the firm, perfect knowledge of the production process was assumed, and no agency problems existed. Here, both governance structures (hierarchies and markets) have a mixture of deterministic and stochastic elements.

It is found that technological progress on production and coordination costs often has diametrically opposite effects on procurement. In general, technological progress on production costs leads to more vertical integration, whereas technological progress on coordination costs leads to more subcontracting. However, the opposite result obtains in many cases. When technological change concerns the level of costs, its effect on procurement depends on the cost differential between the firm and the market, and the relative importance of production and coordination costs; whereas, when technological change affects the effect or disutility of effort, its impact on procurement is unambiguous. Technical change can reduce the importance of some types of costs in the firm's procurement decision. The static effects of competition and monitoring on the frontiers of the firm, and their dynamic effects regarding how these frontiers are affected by technical change, are shown to differ.

In contrast to changes in the level of costs, the impact of which depends on the cost differential between the firm and the market, changes concerning the effect or disutility of cost reducing efforts have unambiguous impacts on procurement. The explanation lies in the dynamics of the efficiency and control effects. Technological change induces an efficiency effect (due to the cost differential between the firm and the market) which favours one type of procurement, and a control effect (due to the private information of agents) which favours the other type of procurement. When technical progress affects the level of costs, the efficiency effect dominates when the cost differential is important, whereas the control effect may dominate when the cost differential is negligible; henceforth the impact of technical change on procurement depends on the cost differential. When technical progress concerns the effect or the disutility of cost reducing efforts, the efficiency effect always dominates the control effect, therefore the impact of technical progress on procurement does not depend on the cost differential.

The paper is organized as follows. Section 2 analyses the effects of information and production technologies on the outsourcing decision. In section 3 the tradeoff between firms and markets is reviewed based on transaction cost theory and agency theory. Section 4 presents the model and the optimal contract. Section 5 discusses how different forms of technological progress affect procurement, and section 6 concludes.

2. Information and production technologies

Technological change can affect the boundaries of the firm in many ways. Hereafter these effects are classified according to whether the change concerns IT or production technology.[2]

2.1 Information technologies

IT can affect the tradeoff between markets and hierarchies in many ways. The main types of costs affected by IT are search costs, coordination costs, monitoring costs, and renegotiation hazards. Modern IT are different from older communication settings in two ways. The first difference is that it is cheaper and faster to transmit and verify information. This reduces the first three types of costs mentioned above: search, coordination (Malone et al., 1987), and monitoring (Clemons et al., 1993) costs. The second difference is that IT investments are less specific. This reduces the fourth type of cost: renegotiation cost. Each of these is discussed below.

The first type of costs IT can affect is search costs. By reducing search costs IT make external procurement relatively cheaper than before. At the same time, however, IT may reduce the cost of screening potential employees.

The second type of costs affected by IT is the cost of coordination. IT generally reduce coordination costs: "Since the essence of coordination involves communicating and processing information, the use of IT seems likely to decrease these costs." (Malone et al., 1987:486). The high costs of old IT systems made close coordination between the firm and its suppliers costly. This induced firms either to integrate the operation, or to outsource it while keeping coordination at a minimum level (Reddi, 1994). IT can improve coordination in many ways: -Shorter production runs -characteristic of CAD/CAM systems and of flexible production technologies- require more communication between units and a more frequent redesign. This intensifies communication, which is facilitated by modern IT. For instance, "the recent development of EDI ... in the automobile sector makes it possible for an assembler to

2.See Atallah and Boyer (1999) for a more detailed discussion of the effects of technology on procurement.

electronically coordinate with its supplier in most of the information and coordination intensive activities..." (Bensaou and Venkatraman, 1995:9).

-The costs of instantaneous transfer of information (e.g. order placement) between the firm and its suppliers are reduced, easing the delegation of more functions to external suppliers. For instance, flight reservations, which were largely controlled by firms, are increasingly outsourced (Gurbaxani and Whang, 1991).

-Coordination is improved through better integrated databases, easier data analysis and control, and superior query languages (Clemons et al., 1993). Ahmad et al. (1995) discuss how IT facilitate the redesign of organizational functions and processes (through effective use of communication, data accessibility and common systems designed to process data) to achieve better coordination between design and construction organizations in the construction industry.

-The networking of information eases instantaneous sharing of information between the firm and its suppliers. The access to the partner's database in order to coordinate operations is facilitated. *Just in time* inventory systems require such an instantaneous access to the buyer's inventories, for large inventories were one way of compensating for poor coordination.[3]

At the same time, however, IT improve coordination within the firm, and may in some cases encourage integration. Coase (1937) predicted that reductions in the cost of organizing spatially will increase the size of the firm. Bröchner (1990) notes that IT have the potential of improving coordination in the construction industry under both governance structures. Networking economies and informational scale economies ease the maintenance of large internal databases. In informationally intensive industries, some activities that were costly to manage internally are now being integrated. For instance, more hotel chains are centralising reservations management (Gurbaxani and Whang, 1991).

Monitoring costs are the third type of costs affected by IT. Monitoring requires access to specific information about the supplier's operations, and this access is facilitated by the greater availability of information and stronger treatment possibilities (Clemons et al., 1993). Some information may be too costly to collect manually, but can be collected with little extra cost as a byproduct of the information system. The customer can better observe the production process of the supplier, making monitoring and quality control easier. Moreover some variables that are typically difficult to observe, like customer support, become more easily verified.

3.Note however that this openness can make the buyer vulnerable to renegotiation from the supplier (Reddi, 1994).

Organizing and using information for the purpose of comparison -an essential component of monitoring- is improved by IT (Bröchner, 1990). At the same time, IT ease internal monitoring, which makes detection of opportunism within the firm easier.

The fourth dimension IT can affect is asset specificity. IT investments are less specific today, due to standardisation in software, in hardware, in telecommunications equipment, and in communication standards. Moreover, by making instantaneous communication easier, IT also reduce time specificity (e.g. perishable products) (Malone et al., 1987).

Many authors (e.g. Malone et al., 1987; Gurbaxani and Whang, 1991; Clemons et al., 1993; Brynjolfsson et al., 1994; Picot et al., 1996) have argued that by reducing transaction costs, IT induce firms to use more markets and less hierarchies. Empirical evidence supports an inverse relation between investments in IT and the level of integration of firms (Kambil, 1991; Komninos, 1994; Carlsson, 1988; Brynjolfsson et al., 1994; Shin, 1996). However, the causality could go either way. It may be the case that firms that outsource more invest more in IT to manage their outsourcing relations more effectively.

There is evidence that IT affect the nature -and not only the level- of outsourcing, by inducing a more cooperative and long term approach to supplier relationships (O'Neal, 1989; Malone et al., 1987; Clemons and Row, 1992; Picot et al., 1996). Bröchner (1990) notes that IT can affect the nature of the tendering process by encouraging product differentiation through the use of more detailed specifications, transforming a competitive auction into a more complex buyer-seller relation.

2.2 Production technology

Vertical integration has dominated in an era characterized by slow technical change and relatively standardised products. Today, product redesigns are more frequent and markets are more specialised (Powell, 1987). The question is: how have these changes affected the outsourcing decision?

CAD/CAM processes make outsourcing easier (Blois, 1986): design and production engineers can access and manipulate the requirements of external parties more easily (Clemons et al., 1993); different components of the systems need not be located within the same firm nor the same plant; suppliers have less independence and hence less margin for errors, given that they receive specific production instructions; and the systems are compatible with variable production scales, so that small suppliers are not disadvantaged. Moreover, flexible manufacturing technologies reduce asset specificity, facilitating outsourcing (Malone et al., 1987).

Modern technologies have increased product complexity. The empirical evidence on the relation between product complexity and outsourcing is mixed. European (SME Task Force, 1988) and Japanese (Ikeda and Lecler, 1984) firms seem to outsource more complex components. However, Masten (1984) and Walker and Weber (1984) find that firms make internally their most complex products. Masten et al. (1991) find a nonmonotonic effect of complexity on the probability of integration, decreasing and then increasing the probability of integration.

The nature of the input plays an important role in the outsourcing decision. Service inputs are outsourced more often than material inputs, given their technical and specialized character, and their increasing complexity (Daniels, 1985). Firms use more service inputs than before, such as design, quality control, and consulting. This increased use of service inputs should favour outsourcing.

Some technological developments can affect the efficiency of both governance structures. Alchian and Demsetz (1972) discuss how the development of efficient central sources of power led to the performance of weaving in proximity to power sources and to the engagement in team production. The former change reduced the cost of market transactions, but, because of the joint use of the equipment, vertical integration increased.

Many other interactions between production technology and outsourcing can arise. However, whereas the effect of IT seems, in general, to favour lower levels of integration, the effects of changes in production technology are less clear cut. Moreover, changes in IT are common to most sectors, while changes in production technology are more industry-specific.

3. Firms and markets

This section addresses the tradeoff between the firm and the market in terms of differences in cost levels and in cost observability, based on transaction cost theory and agency theory.[4] The first dimension of the tradeoff between the firm and the market relates to the relative levels of coordination and production costs under each governance mode. Consider

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4.Mahoney (1992) argues that measurement costs and transaction costs have to be considered jointly to predict organizational form. Lajili (1995) finds that combining the agency and transaction cost approaches yields useful insights for the understanding of vertical coordination in crop contracting in East Central Illinois.

first coordination costs. Coordination costs include "the costs of gathering information, negotiating contracts, and protecting against the risks of "opportunistic" bargaining." (Malone et al., 1987). Following transaction cost theory, markets have higher coordination costs than firms:[5] supplier search costs, monitoring costs, and renegotiation hazards (due to asset specificity, for instance) are the main transaction costs in a vertical relationship. Difficulties in the communication of the specifications of components to suppliers constitute a typical example of coordination costs (N. Foss, 1996).[6]

Assumption 1. *The market has higher coordination costs than the firm.*

Next, consider production costs. The transaction cost literature has tented to focus on the costs of opportunism, while neglecting potential differences in other types of costs.[7] The central claim of transaction cost theory, that in the absence of transaction costs the frontiers of the firm would be indeterminate, rules out the relevance of any type of cost not classified as a transaction cost. However, the decision to make or buy should not be merely based on the relative importance of transaction and management costs, but should also take into account other attributes of markets and firms. One such important attribute is production costs. As Demsetz notes:

> *in the ... context in which management, transaction, and production costs are all assumed to be positive, the correct decision is reached by assessing whether merger of independent production yields the lowest unit cost, taking all these costs into account (Demsetz, 1988:146)*
>
> *[in the transaction cost literature] the make-or-buy decision is not allowed to turn on differences in production cost (Demsetz, 1988:148)*
>
> *the transaction cost theory of the firm ignores differences between firms when these lie outside the control function and discourages a search for such differences. (Demsetz, 1988:148)*

In the same token, N. Foss (1996) explains that the contractual approach assumes that the only differences between institutions lies in control costs, not in production costs : "[the contractual

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5.Poppo (1995) argues that internal coordination costs may be higher than external coordination costs, because of the use of quasi-market incentives and decentralization in hierarchies.

6.From the study of the semiconductor industry, Monteverde (1995) finds that the integration decision in that industry is positively related to the intensity of unstructured technical dialogue required between engineers at the chip design and chip fabrication stages. While Monteverde interprets unstructured technical dialogue as specific human capital, it can also be viewed as a proxy for coordination costs between two stages of production. According to this interpretation, his results would indicate that coordination costs are lowered by integration.

7.Riordan and Williamson (1985) study a model where markets and hierarchies have different production and transaction costs; their analysis is centred around asset specificity.

approach assumes that] production costs do not vary over firms for the 'same' productive tasks - that is, what one firm can do, another firm can do equally efficient" (N. Foss, 1996:17). Chandler (1992) also adheres to the view that "the specific nature of the firm's facilities and skills becomes the most significant factor in determining what will be done in the firm and what by the market" (p.86). Finally, Coase (1990) notes that

> *... once most production is carried out within firms and most transactions are firm-firm transactions and not factor-factor transactions, the level of transaction costs will be greatly reduced and the dominant factor determining the institutional structure of production will in general no longer be transaction costs but the relative costs of different firms in organizing particular activities (p.11).*

These critiques of the excessive focus of the transaction cost approach on incentive costs point out that other types of costs play a role in procurement. In this paper the differences between firms and markets regarding production costs are modelled explicitly. Namely, markets have lower production costs than hierarchies, because of specialization and of economies of scale (Williamson, 1985), and of the competition between suppliers (Malone et ál., 1987).

Assumption 2. *The firm has higher production costs than the market.*

We now turn to cost observability. Transaction cost theory acknowledges that measurement issues are important in the make-or-buy decision, but they have been relegated to a secondary position compared with asset specificity. Measurement difficulties play an important role in our model. How easy a cost is to observe depends on whether the activity is performed by an employee of the firm or by an outside agent, how easy the inputs and outputs of the activity are easy to identify ex ante and measure ex post, the possibility of collusion between agents, and whether there is a contract laying out the activities to be performed or not.

Given that production activities are generally well specified in advance, the cost of internal production -which is performed by the firm's employee- is relatively easy to observe. However, it is more difficult to monitor external production activities, which are performed by the subcontractor.[8] This is consistent with the views of agency theory and of the property rights theory that measurement problems are less important when the activity takes place in-house.

8.Poppo (1995) finds that product cost information disclosure is better with internal suppliers than with external suppliers.

In a property rights framework, if the right to audit is a residual rather than a contractible right, then cost observability is superior in-house (Grossman and Hart, 1986). While some firms may send their personnel to observe directly the production facilities of their subcontractors, in general it will be at least as easy for the firm to observe its internal production costs as to observe the production costs of its subcontractors. For the sake of simplicity, it will be assumed that a cost which is easy to observe is perfectly observable while a cost that is difficult to observe is not observable.

Assumption 3. *Internal production costs are observable by the firm, while external production costs are not.*

However, it is not true for all types of activities that measurement difficulties are greater in-house.[9] Contrarily to internal production costs, internal coordination costs are difficult to observe. First, coordination activities cannot be specified with the same degree of precision as production activities. A production process generally has clearly identifiable inputs and outputs, but the same cannot be said about coordination activities, which are more difficult to

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9.Although transaction cost theory focuses on informational asymmetries in markets, those problems do not disappear with vertical integration (Jensen and Meckling, 1976; Fama, 1980). Alchian and Demsetz (1972) discuss the difficulties arising from nonseparable team outputs, whether the transaction takes place inside or outside the firm. Melumad et al. (1992) show that centralization can induce costs due to restricted communication between the agents and the central authority. Poppo and Zenger (1998) estimate a model of the influence of transactions' characteristics on the performance of vertical integration versus subcontracting of information services; they find that management satisfaction with costs decreases with measurement difficulties both when the activity is outsourced and when it is performed in-house. Specifically, they find that measurement difficulties have a larger negative effect on cost performance in markets than in firms, but have a larger negative effect on quality and responsiveness in firms than in markets. Moreover, they find that measurement difficulties have no effect on whether firms outsource or not.

The bias of transaction cost theory toward the analysis of opportunism in markets has led it to overlook opportunism problems in the firm. However, opportunism is not the exclusivity of markets. There is a large literature on agency costs within the firm. Olsen (1996) shows that even though vertical integration can be preferable on efficiency grounds, agency costs within the firm, which arise from the possibility of contract renegotiation, can make the market transaction cheaper. Hennart (1993) discusses the costs of organization in both firms and markets: the internal organization costs of firms are mainly due to shirking, which arises because the firm relies mostly on hierarchy; while the external organization costs of markets are mainly due to cheating, which arises because the market relies mostly on prices. Eccles and White (1988) discuss the internal transaction costs associated with exchanges between profit centres in a multidivisional or multiprofit centre firm. Masten et al. (1991), from the study of a large naval construction project, find that, although the costs of the market rise with the potential for holdups, internal costs play a role in the integration decision. Milgrom and Roberts (1988) analyse the costs of influence activities in organizations. Demsetz argues that while the market has transaction costs, internal management is not costless: "The worldly roles of management ... [are] to explore uncertain possibilities and to control resources consciously, where owners of resources have a penchant for pursuing their own interests" (Demsetz, 1988:143). Finally, even though this has been overlooked by most of the transaction cost literature, Williamson (1975) notes that "the same transaction cost factors that increase the cost of market exchange may also serve to increase the cost of internal organization ... A symmetrical analysis of trading thus requires that we acknowledge the transactional limits of internal organization as well as the sources of market failure" (pp.8-9).

specify. Second, when many activities are being performed within the firm, it is difficult to separate the costs of coordinating different activities (this problem is less important for production costs).

On the other hand, the costs incurred by the employee while coordinating activities with the subcontractor are easy to observe (the subcontractor may well have some coordination costs of her own, but her high degree of specialization allows us to overlook those costs). First, a firm typically coordinates a large number of activities in-house, but only a few activities on the market. Therefore the problem of separating the coordination costs of different activities is less acute externally than internally. Second, external transactions are regulated through contracts, which specify to a certain extent the coordination activities of the employee of the firm. Internal coordination costs do not involve contracts, and henceforth are not described with the same degree of precision. Third, measuring internal coordination costs with accuracy can be complicated by collusion between supervisors and employees, which is made easier by the long term relationship between the two parties. The employees of the firm can act strategically and shift costs between activities (to hide inefficiencies, for example). This problem is less acute with external costs: it is more difficult for the employees to collude with external agents than to collude among themselves.

Assumption 4. *External coordination costs are observable by the firm, while internal coordination costs are not.*

The three sources of difficulty in measuring internal coordination costs -namely, cost separation, the absence of contracts, and collusion- are less acute with internal production costs. The relative ease of specifying the inputs and outputs of the production process leaves little scope for the manipulation of production cost information on the part of employees.

The following table summarizes the tradeoff between the firm and the market in terms of cost levels and observability. "High" and "low" in this table should be read vertically, meaning that no assumption is made on the level of production costs relative to the level of coordination costs.

Table 1 - Cost levels and observability

	Production costs	Coordination costs
Internal	High - Observable	Low - Not observable
External	Low - Not observable	High - Observable

4. The model

The effects of technological change on firm boundaries are addressed in a principal-two agents model, with moral hazard and adverse selection. The model is based on LS. There are two organisations, a firm (the buyer) and a supplier. The firm needs one unit of an input. It may make the input internally or buy it from the supplier. There are two types of costs: production costs, and coordination costs (examples of coordination activities are planning, communicating, analysing data, and controlling). The firm incurs both types of costs (possibly in addition to other effort costs or information rents) whether it makes or buys the input. Following assumptions 1 through 4, it is assumed that the firm has lower coordination costs but higher production costs than the subcontractor, and that internal production costs and external coordination costs are observable, while internal coordination costs and external production costs are not. Differences between agents are due to institutional characteristics, and not to the fact that an agent is not using the most efficient technology.

The production cost of the supplier is $t_c c$, and the production cost of the firm is $t_c \bar{c}$. The external coordination cost (between the two firms) is $t_i \bar{i}$, and the internal coordination cost (within the buying firm) is $t_i i$. The stochastically independent random variables c and i are such that $c,i \sim f(c,i)$, $c \in [\underline{c}, \bar{c}]$, $i \in [\underline{i}, \bar{i}]$. The joint distribution function associated with $f(c,i)$ is $F(c,i)$. It is assumed that $F(c,i)/f(c,i)$ is nondecreasing in c and i.

Both the buyer and the supplier can invest in a cost reduction effort (CRE) of either or both types of costs. For production costs, investing e_c units of effort reduces costs by $t_c^e e_c$, and induces a disutility $t_c^D D(e_c)$. For coordination costs, investing e_i units of effort reduces costs by $t_i^e e_i$, and induces a disutility $t_i^D D(e_i)$. The disutility of cost reduction function, $D(.)$, is the same for production and coordination costs, for simplicity's sake. It is assumed that $D'(.)>0$, $D''(.)>0$, and $D'''(.)\geq 0$.[10]

When the firm buys the input from the supplier, it can observe the coordination cost $t_i \bar{i}$;

10.Contrarily to the more realistic assumption that, when an agent performs more than one task, effort disutility should depend on total effort devoted to all tasks performed by that agent (Holmstrom and Milgrom, 1991), it is assumed that the total disutility of the employee is additively separable in production CRE and coordination CRE.

as for production costs, the firm can observe their total level, but cannot observe which part is due to the realization of c (the part $t_c c$) and which part is due to the CRE of the subcontractor (the part $t_c^e e_c$). When the firm makes the input internally, it can observe the production cost, $t_c \bar{c}$; as for coordination costs, the firm can observe their total level, but cannot observe which part is due to the realization of i (the part $t_i i$) and which part is due to the CRE of the employee (the part $t_i^e e_i$). The firm knows $f(c,i)$ and $F(c,i)$, however.

The firm cannot observe the CRE invested by agents, internal e_c and e_i, and external e_c and e_i. It can only observe final production costs and final coordination costs for each agent. For internal production costs and external coordination costs, which are non random and observable, this nonobservability of efforts is not a problem. For those costs agents choose the optimal amounts of effort, which are given by

$$e_c^* = argmax_{e_c} \quad t_c^e e_c - t_c^D D(e_c) \tag{1}$$

$$e_i^* = argmax_{e_i} \quad t_i^e e_i - t_i^D D(e_i) \tag{2}$$

Although with internal provision the employee performs two tasks, the observability of internal production costs implies that the firm can set production CRE at any desired level costlessly (Holmstrom and Milgrom, 1991). However, the unobservability of CRE for internal coordination costs and external production costs implies that the firm has to induce special provisions in the contract in order to mitigate agents' incentives to inflate their costs.

When the employee gets the contract, the firm incurs production costs, minus the effect of production CRE, and compensates the employee for the disutility of production CRE. As for coordination costs, only the total of which is observable, the firm incurs the observed total cost, plus a payment to be specified in the contract. When the subcontractor gets the contract, the firm incurs coordination costs (even when the input is bought, it is the employee who coordinates operations between the firm and the subcontractor), minus the effect of coordination CRE, and compensates the employee for the disutility of coordination CRE. As for production costs, only the total of which is observable, the firm incurs the observed total cost, plus a payment to be specified in the contract. Collusion or side payments between the employee and the subcontractor are not possible.

Letting c_T represent the final observable production costs of the subcontractor (which are the difference between her innate production cost and her production CRE), and letting P_s

represent the payment she receives, her profit from reporting $c°$ when her true type is c is

$$\pi_s(c°\,|\,c) = P_s(c°,.) - t_c^D\, D\,((t_c^e)^{-1}[t_c c - c_T(c°)])$$

where the argument of D represents the effort level required to achieve a total cost $c_T(c°)$ when the subcontractor's true production cost is c.

Similarly, letting i_T represent the final observable coordination costs of the employee (which are the difference between her innate coordination cost and her coordination CRE), and letting P_e represent the payment she receives, her profit from reporting $i°$ when her true type is i is

$$\pi_e(i°\,|\,i) = P_e(i°,.) - t_i^D\, D\,((t_i^e)^{-1}[t_i i - i_T(i°)])$$

where the argument of D represents the effort level required to achieve a total cost $i_T(i°)$ when the employee's true coordination cost is i.

The sequence of decisions is as follows. First, the employee learns the realization of i, and the subcontractor learns the realization of c. Next, the firm announces, simultaneously: *a)* a menu of payments and observed coordination costs to the employee[11] $\{P_e(.),i_T(.)\}$ and a menu of payments and observed production costs to the subcontractor $\{P_s(.),c_T(.)\}$ and *b)* the combinations of reports *($i°,c°$)* such that self provision will be chosen, and the combinations *($i°,c°$)* such that outsourcing will be chosen. The firm can commit to this contract. Next, the employee makes a (public) report $i°$, and the subcontractor makes a (public) report $c°$, simultaneously. Finally, the firm chooses the procurement method, and efforts, production, and payments takes place.

Figure 1 - Decision sequence

-employee learns realization of i; -subcontractor learns realization of c;	-firm announces: $\{P_e(.),i_T(.)\}$ $\{P_s(.),c_T(.)\}$ S,S^-	-employee reports $i°$ -subcont. reports $c°$	-firm chooses procurement mode	-efforts, production, and payments take place

The firm aims at minimizing the sum of production and coordination costs (and information rents) by solving the following problem:

11.Employees don't typically face menus of contracts (although there are some exceptions. For instance, IBM uses menus of contracts in compensating the sales force; see Milgrom and Roberts, 1992, ch.12). However, the employee can be thought of as a division constituting a profit centre. It is not uncommon for firms to put internal divisions in competition with outside contractors.

$$max_{P_e,P_s,e_i,e_c,S,S^-} \quad \pi_f = \iint_S [V-(t_c c - t_c^e e_c(c) + P_s + t_i \bar{i} - t_i^e e_i^* + t_i^D D(e_i^*))] f(c,i)\, dS + \iint_{S^-} [V-(t_c \bar{c} - t_c^e e_c^* + t_c^D D(e_c^*) + t_i i - t_i^e e_i(i) + P_e)] f(c,i)\, dS^-$$

$$\begin{array}{lll} s.t. & \pi_s(c|c) \geq \overline{\pi_s} & \forall\ c\in S \\ & \pi_s(c|c) \geq \pi_s(c^\circ|c) & \forall\ c,c^\circ \in S \\ & \overline{\pi_s} \geq \pi_s(c^\circ|c) & \forall\ c\in S^-,\ c^\circ\in S \\ & \pi_e(i|i) \geq \overline{\pi_e} & \forall\ i\in S^- \\ & \pi_e(i|i) \geq \pi_e(i^\circ|i) & \forall\ i,i^\circ\in S^- \\ & \overline{\pi_e} \geq \pi_e(i^\circ|i) & \forall\ i\in S,\ i^\circ\in S^- \end{array} \qquad (3)$$

where S represents the set such that subcontracting is chosen, and S^- represents the set such that self provision is chosen. $\overline{\pi_s}$ and $\overline{\pi_e}$ represent the reservation profits of the subcontractor and the employee, respectively. Without loss of generality it is assumed that $\overline{\pi_s}=\overline{\pi_e}=0$.[12]

For each agent there are three constraints: one individual rationality constraint, and two incentive compatibility constraints. By the revelation principle we can restrict our attention to direct mechanisms. By using a Vickrey auction, truthful revelation is a dominant strategy.

From the above representation of internal and external costs we know that a higher i increases internal coordination costs, and has no effect on external costs. Therefore, for a given c, a higher i increases the likelihood of outsourcing. Conversely, for a given i, a higher c increases external production costs, with no effect on internal costs. Therefore, for a given i, a higher c increases the likelihood of vertical integration. In sum, the firm will subcontract if, for a given c, i is higher than a certain threshold (or, alternatively, if, for a given i, c is lower than a certain threshold). Let $(c,I(c))$ with $i=I(c)$ represent the couples (c,i) such that, for a given c, when $i<I(c)$ the firm chooses vertical integration, and when $i>I(c)$ the firm chooses subcontracting, with $I(c)\in[\underline{i},\bar{i}]$. Figure 2 illustrates the simplest possible shape of $I(c)$ (other possible shapes will be discussed shortly). To the right (left) of $I(c)$, the firm chooses vertical integration (outsourcing). For any $c\in[\underline{c},\bar{c}]$, the solution is said to be interior when $I(c)\in(\underline{i},\bar{i})$, and is said to be a boundary solution when $I(c)\in\{\underline{i},\bar{i}\}$. Most cases are such that $I(c)$ has both interior and boundary parts. I consider cases where at least part of the solution is interior, i.e. configurations such that there exists $c\in[\underline{c},\bar{c}]$ such that $I(c)\in(\underline{i},\bar{i})$.

The decision criterion was characterized above as a critical level of i that, for a given c, separates the two procurement modes. In what follows it will sometimes be useful to study

12.All what matters is that they be equal.

the solution in the inverse form, that is, to find the critical level of c for a given i. However, the function $I(c)$ is not monotonically increasing, hence the inverse function $I^{-1}(i)$ does not always exist. Because $I'(c)>0$ over all c such that $I(c)\in(I(\underline{c}),I(\bar{c}))$, it follows that $I^{-1}(i)$ exists for all i such that $i\in(I(\underline{c}),I(\bar{c}))$. However $I^{-1}(i)$ does not exist at boundary solutions.

With this caution in mind we now characterize the inverse decision problem. Let $c=C(i)$ represent, for a given i, the critical threshold of c separating the two procurement modes. Then it is easily seen that $C(i)$ can be characterized as follows:

a) $C(i \mid i\leq I(\underline{c})) = max\ \{c \mid \nexists\ c^{+}\in[\underline{c},\bar{c}] \mid I(c^{+})<I(c)\}$,

b) $C(i \mid i\geq I(\bar{c})) = min\ \{c \mid \nexists\ c^{+}\in[\underline{c},\bar{c}] \mid I(c^{+})>I(c)\}$,

c) $C(i \mid i\in(I(\underline{c}),I(\bar{c}))) = I^{-1}(i)$, where $I^{-1}(i)$ is the local inverse of $I(c)$ over $I(c)\in(\underline{i},\bar{i})$.

Parts a and b of the definition account for the fact that some parts of $I(c)$ may be boundary solutions. Part c uses the fact that $I(c)$ is monotonically increasing over its interior part.

Payments to the agents are derived in the appendix, and are shown to be as follows:

$$P_s(c,i) = t_c^D D(e_c(c)) + \frac{t_c t_c^D}{t_c^e}\int_c^{C(i)} D'(e_c(\alpha))d\alpha \tag{4}$$

$$P_e(c,i) = t_i^D D(e_i(i)) + \frac{t_i t_i^D}{t_i^e}\int_i^{I(c)} D'(e_i(\gamma))d\gamma \tag{5}$$

Each agent, when she performs a task on which rent extraction is possible (i.e. for which the type of the agent is unobservable), gets reimbursed for the disutility of CRE, plus a rent. The information rent of the subcontractor depends on her production costs, but not on external coordination costs, since the latter are known. Conversely, the information rent of the employee depends on her coordination costs, and not on her production costs, since the latter are known.

Due to competition between the employee and the subcontractor, the rent of the agent who gets the contract is truncated according to the efficiency of the agent who does not get the contract (following Laffont and Tirole, 1987). This explains why the payment to each agent, and not only the choice of procurement, depends on the cost realizations of both agents. The particularity of the mechanism used here is that each agent's type is defined over a different dimension.

Figure 3 illustrates rent extraction. On figure 3a, because $i>I(c)$, the subcontractor obtains the contract. The rents of the subcontractor are truncated from above at $\hat{c}$, where

$\hat{c}=C(i)$, because of the competition of the employee. For any $i>I(c)$, the rent of a subcontractor with a given c is higher the more inefficient the employee is (the higher i). A similar analysis applies to the rent of employee on figure 3b.[13] In this model it is possible that the most efficient agent (the employee of type $\underline{i}$, or the subcontractor of type $\underline{c}$) obtains the contract but extracts no rent.

Although technically speaking the model has two types of costs, c and i, from an economic point of view it incorporates four types of costs: production, coordination, management, and transaction costs.[14] Production costs are the direct -internal or external- costs of producing the input. Coordination costs are the direct -internal or external- coordination costs. Transaction costs arise because of the private information of the subcontractor. In the appendix it is shown that transaction costs are

$$\frac{t_c t_c^D}{t_c^e} D'(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} \tag{6}$$

Management costs arise because of the private information of the employee. In the appendix it is shown that management costs are

$$\frac{t_i t_i^D}{t_i^e} D'(e_i(i)) \frac{F(\bar{c},i)}{f_i(i)} \tag{7}$$

Table 2 shows the decomposition of costs under each procurement mode.

Table 2 - Decomposition of costs under different procurement modes

	Vertical integration	Subcontracting
Production costs	$t_c\bar{c}-t_c^e e_c^*+t_c^D D(e_c^*)$	$t_c c-t_c^e e_c(c)+t_c^D D(e_c)$
Coordination costs	$t_i i-t_i^e e_i(i)+t_i^D D(e_i)$	$t_i \bar{i}-t_i^e e_i^*+t_i^D D(e_i^*)$
Information rents	$(t_i t_i^D/t_i^e)D'(e_i)(F(\bar{c},i)/f_i(i))$	$(t_c t_c^D/t_c^e)D'(e_c)(F(c,\bar{i})/f_c(c))$

From (25) in the appendix the problem of the firm can be rewritten as

13.There is evidence that putting the employees of the public sector in competition with private contractors reduces costs within the public sector (Szymanski and Wilkins, 1993; Szymanski, 1996).

14.We use the term transaction cost to denote the cost of opportunism in market relations. Following Demsetz (1988) we use the term management cost to represent the cost of opportunism within the firm (actually, Demsetz uses the term management cost to represent the cost of organising resources within firms).

$$max_{e_i,e_c,I(c)} \quad \pi_f = \int_{\underline{c}}^{\bar{c}}\int_{I(c)}^{\bar{i}} [V-(t_c c - t_c^e e_c + t_c^D D(e_c(c)) + \frac{t_c t_c^D}{t_c^e} D'(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} + t_i \bar{i} - t_i^e e_i^* + t_i^D D(e_i^*))] f(c,i)\ di\ dc$$

$$+\int_{\underline{c}}^{\bar{c}}\int_{\underline{i}}^{I(c)} [V-(t_c \bar{c} - t_c^e e_c^* + t_c^D D(e_c^*) + t_i i - t_i^e e_i(i) + t_i^D D(e_i(i)) + \frac{t_i t_i^D}{t_i^e} D'(e_i(i)) \frac{F(\bar{c},i)}{f_i(i)})] f(c,i)\ di\ dc \qquad \textbf{(8)}$$

The nonobservability of effort levels forces the firm to design contracts inducing agents to choose effort levels maximizing the expected profit of the firm. The effort level that the firm induces an agent to choose is independent of the number of agents (Laffont and Tirole, 1987). The choice of e_i by the employee must satisfy

$$-t_i^e + t_i^D D'(e_i(i)) + \frac{t_i t_i^D}{t_i^e} D''(e_i(i)) \frac{F(\bar{c},i)}{f_i(i)} = 0 \qquad \textbf{(9)}$$

Comparing this choice with the optimal level of coordination CRE, chosen by the employee when the subcontractor is given the contract, and given by (1), shows that $e_i < e_i^*$. When the input is made internally, the employee is induced to invest less than the optimal amount in coordination cost reduction in order to limit her rents. From (5) it is clear that the rents of the employee increase with its coordination CRE. Whereas with internal provision the employee invests the optimal amount, because she enjoys no rents on coordination costs.

The choice of e_c by the subcontractor must satisfy

$$-t_c^e + t_c^D D'(e_c(c)) + \frac{t_c t_c^D}{t_c^e} D''(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} = 0 \qquad \textbf{(10)}$$

Comparing this choice with the optimal level of production costs reduction efforts, chosen by the employee and given by (2), shows that $e_c < e_c^*$. The subcontractor is induced to invest less than the optimal amount in production cost reduction[15] in order to limit her rents. From (4) it is clear that the rents of the subcontractor increase with its production CRE. Whereas the employee invests the optimal amount, because she enjoys no rents on production costs.

Regarding production costs, the subcontractor spends too little on cost reduction, while the employee spends the optimal amount on cost reduction. Regarding coordination costs, the employee spends the optimal amount on cost reduction when the input is bought, while she spends too little on coordination cost reduction when the input is made internally. These

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15.Helper (1991) finds that in the Auto industry, the unwillingness of suppliers to provide buyers with detailed cost information makes the implementation of cost reduction practices difficult.

distortions will be important in the analysis of changes in the technology of CRE.

Note that π_f is concave in $I(c)$:

$$\frac{\partial^2 \pi_f}{\partial I(c)^2} = -t_i - \frac{t_i t_i^D}{t_i^e} D'(e_i(I(c))) \frac{d}{dI} \frac{F(\bar{c},I(c))}{f_i(I(c))} < 0 \tag{11}$$

Therefore for $I(c)$ to be optimally chosen, the following must be true at an interior solution:

$$\begin{aligned} & t_c c - t_c^e e_c(c) + t_c^D D(e_c(c)) + \frac{t_c t_c^D}{t_c^e} D'(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} + t_i \bar{i} - t_i^e e_i^* + t_i^D D(e_i^*) \\ & -t_c \bar{c} + t_c^e e_c^* - t_c^D D(e_c^*) - t_i I(c) + t_i^e e_i(I(c)) - t_i^D D(e_i(I(c))) - \frac{t_i t_i^D}{t_i^e} D'(e_i(I(c))) \frac{F(\bar{c},I(c))}{f_i(I(c))} = 0 \end{aligned} \tag{12}$$

(12) implies that on the interior parts of $I(c)$ the firm equates the total costs of internal and external provision. Figures 4a through 4d illustrate different possible shapes of $I(c)$. $I(c)$ need not necessarily pass through the coordinates $(\underline{c},\underline{i})$ or $(\bar{c},\bar{i})$. Moreover, $I(c)$ need not be (and is generally not) linear; however, for simplicity, all graphical representations of $I(c)$ will be linear. When $i=I(c)\in(\underline{i},\bar{i})$, the firm chooses randomly between subcontracting and self-provision. When $i=I(c)=\underline{i}$, the firm chooses subcontracting. When $i=I(c)=\bar{i}$, the firm chooses vertical integration.

At an interior solution of $I(c)$, $\partial\pi_f/\partial I(c)=0$: the (virtual) costs of internal provision and the (virtual) costs of subcontracting are equalized. Boundary solutions obtain when one agent is so favoured (by technological parameters, for instance) that, for some (but not all) of its cost realizations,[16] she obtains the contract, irrespective of the cost realization of the other agent. At $I(c)=\underline{i}$, $\partial\pi_f/\partial I(c)<0$: the costs of vertical integration are strictly higher than the costs of subcontracting. Therefore the firm sets $I(c)$ as low as possible. In this case the subcontractor is so attractive that even very low internal coordination costs cannot induce vertical integration. At $I(c)=\bar{i}$, $\partial\pi_f/\partial I(c)>0$: the costs of vertical integration are strictly lower than the costs of subcontracting. Therefore the firm sets $I(c)$ as high as possible. In this case the employee is so attractive that no matter how low the production costs of the subcontractor turn out to be, the subcontractor cannot get the contract.

The private information of agents causes the firm's decision criterion to differ from

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16.The case where an agent obtains the contract irrespective of all cost realizations, which would yield a solution entirely on the boundaries of the parameter space, is without interest, and is therefore not considered here.

what would prevail in a world with symmetric information. The private information of the employee on internal coordination costs induces the firm to use internal procurement less often (by setting $I(c)$ lower), and to distort the coordination CRE of the employee downward. Similarly, the private information of the subcontractor on production costs leads the firm to use subcontracting less often (by setting $I(c)$ higher), and to distort the production CRE of the subcontractor downward.

The following lemmas characterise the decision of the firm when there is only one cost dimension. They will be useful in the analysis of comparative statics.

Lemma 1.[17] *When there are no production costs ($t_c=t_c^e=t_c^D=0$), the firm subcontracts if $i>i'$ and makes the input itself if $i<i'$, $i'[\underline{i},\bar{i}]$.*

Lemma 2. *When there are no coordination costs ($t_i=t_i^e=t_i^D=0$), the firm subcontracts if $c<c'$ and makes the input itself if $c>c'$, $c'[\underline{c},\bar{c}]$.*

(The decision rule described in lemma 2 is the same as the decision rule of the LS model.)

From (12) let

$$\begin{aligned} a(c) &= t_c c - t_c^e e_c(c) + t_c^D D(e_c(c)) + \frac{t_c t_c^D}{t_c^e} D'(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} - t_c\bar{c} + t_c^e e_c^* - t_c^D D(e_c^*) \\ b(I(c)) &= t_i\bar{i} - t_i^e e_i^* + t_i^D D(e_i^*) - t_i I(c) + t_i^e e_i(I(c)) - t_i^D D(e_i(I(c))) - \frac{t_i t_i^D}{t_i^e} D'(e_i(I(c))) \frac{F(\bar{c},I(c))}{f_i(I(c))} \end{aligned} \quad \textbf{(13)}$$

We have that $a(c')=0$: at c' internal and external production costs are equalized. Similarly, $b(i')=0$: at i' internal and external coordination costs are equalized. We wish to see how $I(c)$ is related to i' and c'. We know that $a(c')=0$ and $b(i')=0$. Now, (12)$\Rightarrow a(c)+b(I(c))=0$ $\Rightarrow a(c')+b(I(c'))=0 \Rightarrow I(c')=i'$. Moreover, $a'(c)>0$ and $b'(i)<0$, implying that $I(c>c')>i'$ and $I(c<c')<i'$. Figure 5 illustrates these features. This figure shows that $I(c)$ has to pass through the coordinate (c',i'). Moreover, $I(c)$ cannot be found in the southeast or northwest rectangles on that figure, because in those areas one agent has an advantage in the total cost of both production and coordination activities over the other agent.

17.All proofs are in the appendix.

5. Comparative statics

We now wish to assert the effect of technological progress on the decision of the firm, which is characterised by $I(c)$. There are six types of technical progress: a reduction in production costs (decline in t_c), a reduction in coordination costs (decline in t_i), an increase in the impact of production CRE (increase in t_c^e), an increase in the impact of coordination CRE (increase in t_i^e), a decline in the disutility of production CRE (decline in t_c^D), and a decline in the disutility of coordination CRE (decline in t_i^D).[18]

One characteristic of technical progress on either production or coordination costs is that it often affects both the market and the firm (see section 2). The question is: which effect is more important, and how is the procurement decision affected? To answer that question we focus the analysis on symmetric technical change, which affects the firm and the subcontractor proportionally. The effects of non symmetric technical change may differ.

All comparative statics are evaluated at the interior parts of $I(c)$. However, the shift of the interior portion of $I(c)$ provides unambiguous inferences about the shift of its boundary parts (if any). Table 3 shows how different types of costs are affected by changes in the parameters. Realizations of i and c are random. Changes in the technological parameters t_x denote technical progress. Changes in $\bar{c}$ and $\bar{i}$ represent changes in the production and coordination intensity of the technology.

Table 3 - Effect of an increase in parameters on costs

	External costs			Internal costs		
	Production	Coordination	Transaction	Production	Coordination	Management
i	0	0	0	0	+	+
$\bar{i}$	0	+	0	0	0	?
c	+	0	+	0	0	0
$\bar{c}$	0	0	?	+	0	0
$-t_c$, $-t_c^D$, or t_c^e	-	0	-	-	0	0
$-t_i$, $-t_i^D$, or t_i^e	0	-	0	0	-	-

From (11) and (12) we have that

$$sign(\frac{dI(c)}{d\alpha}) = sign(\frac{\partial^2\pi_f}{\partial I(c)\partial\alpha}) \quad \textbf{(14)}$$

18.Hubbard (1998) distinguishes between the incentive and coordination benefits of IT. Here technological progress on IT (changes in t_i, t_i^e, or t_i^D) represents coordination benefits, but has an indirect effect on incentives.

where α stands for any parameter of the model. This equality will be used throughout the paper.

5.1 Decline in production and coordination costs

Consider first the decline in production costs.

Proposition 1. *Let the unique* $c^* \in (c', \bar{c}]$ *be characterized by the implicit function*

$$\bar{c} - c^* - \frac{t_c^D}{t_c^e} D'(e_c(c^*)) \frac{F(c^*, \bar{i})}{f_c(c^*)} = 0 \tag{15}$$

Then

a) if $I(c^*) < \bar{i}$*, so that very inefficient subcontractors can obtain the contract, then* $dI(c)/dt_c \lessgtr 0$*: a decline in production costs induces more vertical integration in the interval* $c \in [\underline{c}, c^*)$*, and more subcontracting in the interval* $c \in (c^*, \bar{c}]$*;*

b) if $I(c^*) = \bar{i}$*, so that very inefficient subcontractors cannot obtain the contract, then* $dI(c)/dt_c < 0$*: a decline in production costs induces more vertical integration.*

The impact of a decline in t_c can be decomposed into the production efficiency effect and the production control effect.[19] The production efficiency effect comes from the fact that the reduction in t_c reduces the costs of the firm more than the costs of the subcontractor, because the firm's production costs are initially higher. The production control effect is due to the fact that the reduction in t_c reduces the information rent of the subcontractor, because an initial difference in costs becomes less important with the decline in t_c. The production efficiency effect induces more internal provision, whereas the production control effect induces more subcontracting. The net impact depends on which effect dominates.

Figure 6 shows the possible shifts in $I(c)$ following a decline in t_c, depending on the initial position of $I(c)$. Before technical progress the decision function was the old $I(c)$. Figure 6a illustrates the case where the decline in t_c shifts the decision function to the left (more vertical integration, because the efficiency effect dominates) for $c<c^*$, and to the right (more outsourcing, because the control effect dominates) for $c>c^*$. The critical c^* is where the old

19.Whereas in the LS model technological change induced two effects, an efficiency effect and a control effect, here we need to distinguish between two types of efficiency effects: production efficiency effects and coordination efficiency effects, and two types of control effects: production control effects and coordination control effects.

and new $I(c)$ functions cross (when they do), i.e. where the efficiency and control effects cancel out. Figure 6b illustrates the case where the decline in t_c shifts the decision function to the left (more vertical integration). In all cases the new function passes through the new coordinate (c'',i').

When $c<c^*$, the production cost differential between the firm and the market is substantial, therefore the firm benefits substantially more from the decline in t_c, implying that the efficiency effect -which induces more vertical integration- is important. Also, for that level of cost the control effect is negligible, because there are relatively few subcontractors more efficient than that subcontractor, hence the reduction in rents is secondary. Therefore the production efficiency effect dominates and the decline in t_c leads to more vertical integration. This result obtains on both figures 6a and 6b.

For $c>c^*$, the production cost differential between the firm and the market is negligible, therefore the efficiency effect is small. At the same time, the control effect is important, because there is a large number of subcontractors below that subcontractor. Therefore the control effect dominates, and the decline in t_c leads to more subcontracting. This effect obtains on figure 6a, but does not obtain on figure 6b.

The difference between figures 6a and 6b is that on figure 6a, $I(\bar{c}-\varepsilon)<\bar{i}$, meaning that all subcontractors can obtain the contract, whereas on figure 6b, $I(\bar{c}-\varepsilon)=\bar{i}$, meaning that some subcontractors never obtain the contract. When very inefficient subcontractors cannot get the contract, the efficiency effect may never become small enough, and the control effect may never become large enough, for the control effect to dominate, and for more subcontracting to be induced. Part *b* of proposition 1 (which corresponds to the case depicted in figure 6b) indicates that a sufficient condition for the efficiency effect to dominate everywhere (and therefore for more vertical integration to be induced everywhere) is that $I(c^*)=\bar{i}$: the decision function is such that the subcontractor for which the efficiency and control effects would have cancelled out never obtains the contract.

The result of proposition 1b is more likely to hold than the result of proposition 1a in one important case: when production costs are significantly quantitatively more important than coordination costs. In that case there exists $c^+<\bar{c}$ such that $I(c^+)=\bar{i}$: very inefficient employees can get the contract, but very inefficient subcontractors cannot. In other words, the firm accepts very high coordination costs in order to avoid high production costs, because of the quantitative importance of production costs. From proposition 1 we see that this asymmetry corresponds to the case b, where very inefficient subcontractors cannot get the contract. Therefore when the asymmetry between production and coordination costs is sufficiently pronounced, the decline in production costs induces more vertical integration everywhere.

In the LS model the production efficiency effect always dominates, and a decline in t_c induces more vertical integration unambiguously. The possible dominance of the production control effect in this model is due to the change in the decision criterion, which in turn is due to the presence of coordination costs. While for a given c, coordination costs do not affect the relative importance of the production efficiency effect and the production control effect, they determine at which levels of c those effects are evaluated, and therefore they affect the impact of a decline in t_c. In the LS model (described by lemma 2), the subcontractor cannot get the contract if $c>c'$. Here, this is possible, because a high i increases internal costs, and encourages subcontracting. As c increases, the production efficiency effect diminishes (this is clear from (27)). When the production cost advantage of the subcontractor is sufficiently small, the production efficiency effect -which induces vertical integration- may be dominated by the production control effect -which induces subcontracting. The presence of coordination costs affects the impact of technical progress regarding production costs.

At c' the efficiency effect dominates because of distortions in the subcontractor's production CRE compared to the employee's (LS). At c', internal and external production costs are equal. Because the cost of production CRE is higher under subcontracting, the difference between total production costs and production CRE costs is larger under vertical integration. Therefore the firm's production costs are reduced by more than those of the subcontractor (LS). However, when $c>c'$, external production costs are higher than internal production costs, therefore the distortion in the subcontractor's e_c does not imply that the difference between total production costs and production CRE costs is larger under vertical integration.

Consider now the impact of a technical progress reducing coordination costs. Such progress can be due to the adoption of systems with better compatibility, or a more open/flexible technology.

Proposition 2. *Let the unique $i^*\in(i',\bar{i}]$ be characterized by the implicit function*

$$\bar{i}-i^*-\frac{t_i^D}{t_i^e}D'(e_i(i^*))\frac{F(\bar{c},i^*)}{f_i(i^*)} = 0 \tag{16}$$

Then

a) if $I^{-1}(i^*)<\bar{c}$, so that very inefficient employees can obtain the contract, then $dI(c)/dt_i \lessgtr 0$: a decline in coordination costs induces more subcontracting in the interval $i \in [\underline{i}, i^*)$, and more vertical integration in the interval $i \in (i^*, \bar{i}]$;

b) if $I^{-1}(i^*)=\bar{c}$, so that very inefficient employees cannot obtain the contract, then $dI(c)/dt_i > 0$: a decline in coordination costs induces more subcontracting.

The impact of a decline in t_i can be decomposed into the coordination efficiency effect and the coordination control effect. The coordination efficiency effect comes from the fact that the reduction in t_i reduces the costs of the subcontractor more than the costs of the firm, because the subcontractor's coordination costs are initially higher. The coordination control effect comes from the fact that the reduction in t_i reduces the information rent of the employee, because an initial difference in costs becomes less important with the decline in t_i. The coordination efficiency effect induces more subcontracting, whereas the coordination control effect induces more vertical integration. The net impact depends on which effect dominates.

Figure 7 shows the possible shifts in $I(c)$ following a decline in t_i, depending on the initial position of $I(c)$. Before technical progress the decision function was the old $I(c)$. Figure 7a illustrates the case where the decline in t_i shifts the decision function to the right (more subcontracting, because the efficiency effect dominates) for $i<i^*$, and to the left (more vertical integration, because the control effect dominates) for $i>i^*$. The critical i^* is where the old and new $I(c)$ functions cross (when they do), i.e. where the efficiency and control effects cancel out. Figure 7b illustrates the case where the decline in t_i shifts the decision function to the right (more subcontracting). In all cases the new function passes through the new coordinate (c', i'').

When $i<i^*$, the coordination cost differential between the firm and the market is substantial, therefore the market benefits substantially more from the decline in t_i, implying that the efficiency effect -which induces more subcontracting- is important. Also, for that level of cost the control effect is negligible, because there are relatively few employees more efficient than that employee, therefore the reduction in rents is secondary. Therefore the coordination efficiency effect dominates and the decline in t_i leads to more subcontracting. This result obtains on both figures 7a and 7b.

For $i>i^*$, the coordination cost differential between the firm and the market is negligible, therefore the efficiency effect is small. At the same time, the control effect is important, because there is a large number of employees below that employee. Therefore the control effect dominates, and the decline in t_i leads to more vertical integration. This effect obtains on figure 7a, but does not obtain on figure 7b.

The difference between figures 7a and 7b is that on figure 7a, $I(\bar{c})=\bar{i}$, meaning that all employees can obtain the contract, whereas on figure 7b, $I(\bar{c})<\bar{i}$, meaning that some employees never obtain the contract. When very inefficient employees cannot get the contract, the efficiency effect may never become small enough, and the control effect may never become large enough, for the control effect to dominate, and for more vertical integration to be induced. Part *b* of proposition 2 (which corresponds to the case depicted in figure 7b) indicates that a sufficient condition for the efficiency effect to dominate everywhere (and therefore for more subcontracting to be induced everywhere) is that $I^{-1}(i^*)=\bar{c}$: the decision function is such that the employee for which the efficiency and control effects would have cancelled out never obtains the contract.

Consider the implication of the asymmetry between production and coordination costs mentioned above for the impact of a decline in t_i. From proposition 2 we see that this asymmetry implies that case *a* is more likely, and therefore the decline in t_i is more likely to induce a rotation of $I(c)$ than a parallel shift: less vertical integration for efficient employees, and more vertical integration for inefficient employees.

Note the asymmetry between the impact of a decline in t_c and the impact of a decline in t_i when production costs are quantitatively more important than coordination costs: when production costs decline, more vertical integration is induced everywhere; when coordination costs decline, the impact depends on the coordination cost differential between the firm and the market.

The impact of progress on the level of coordination costs can be understood in light of the analysis of Malone et al. (1987), who argue that even if progress on IT benefits the firm and the market, it will favour the market, because it is on this dimension (coordination costs) that the market is weak. In terms of the model, Malone et al. consider the coordination efficiency effect. However, as the model shows, the coordination efficiency effect is only part of the story, because of the private information of agents (the coordination control effect), and because of the presence of other types of costs.

5.2 Improvements in the technology of cost reduction

Consider now the impacts of technological progress that improves the technology of cost reduction. This can take the form of either an improvement in the effect of, or a decline in the disutility of CRE. It turns out that these two types of technical progress have the same (qualitative) effect. Consider first the impact of an improvement in the technology of production CRE.

Proposition 3. *($dI(c)/dt_c^D<0$; $dI(c)/dt_c^e>0$). For D''' sufficiently small, a decline in the disutility of production cost reduction efforts, or an increase in the impact of production cost reduction efforts induces more vertical integration.*

The decline in t_c^D represents a decline in the disutility of production costs reduction. Because the firm invests more in production cost reduction than the subcontractor, the firm benefits more from this decrease. This is the production efficiency effect, which induces more vertical integration. However, the information rent of the subcontractor decreases when t_c^D decreases, because the initial cost disadvantage of the firm is more easily compensated for by the firm investing more in production cost reduction. This is the production control effect, which favours outsourcing. The production efficiency effect dominates, inducing more vertical integration.

An increase in t_c^e represents an increase in the impact of CRE. The increase in t_c^e benefits the firm more, because it invests more in production cost reduction. This is the production efficiency effect, which favours vertical integration. At the same time, the increase in t_c^e reduces the information rent of the supplier, because it becomes easier for the firm to compensate for its initial cost disadvantage. This is the production control effect, which favours outsourcing. The production efficiency effect dominates, inducing more vertical integration.

Figure 8 illustrates the shift in $I(c)$ following a decline in t_c^D or an increase in t_c^e.[20] The shift in $I(c)$ is stronger when c is high, because the distortion in the subcontractor's efforts increases with c.

20.Without loss of generality, the graphical representation of comparative statics results starts from a case where $I(c)$ passes through the coordinates $(\underline{c},\underline{I})$ and $(\bar{c},\bar{I})$. However, this presentation is used only for convenience, and is in no way implied by the analytical results.

Consider next the impact of an improvement in the technology of coordination CRE.

Proposition 4. *($dI(c)/dt_i^D>0$; $dI(c)/dt_i^e<0$). For D''' sufficiently small, a decline in the disutility of coordination cost reduction efforts, or an increase in the impact of coordination cost reduction efforts induces more outsourcing.*

The decline in t_i^D represents a decline in the disutility of coordination costs reduction. Because coordination CRE are higher under external provision, the subcontractor benefits more from this decrease. This is the coordination efficiency effect, which induces more outsourcing. However, the information rent of the employee decreases when t_i^D decreases, because the initial cost disadvantage of the subcontractor is more easily compensated for by the subcontractor investing more in cost reduction. This is the coordination control effect, which favours vertical integration. The coordination efficiency effect dominates, inducing more outsourcing.

An increase in t_i^e represents an increase in the impact of CRE. The increase in t_i^e benefits the subcontractor more, because coordination CRE are higher under subcontracting. This is the coordination efficiency effect, which favours subcontracting. At the same time, the increase in t_i^e reduces the information rent of the employee, because it becomes easier for the subcontractor to compensate for its initial cost disadvantage. This is the coordination control effect, which favours vertical integration. The coordination efficiency effect dominates, inducing more outsourcing.

Figure 9 illustrates the shift in *I(c)* following a decline in t_i^D or an increase in t_i^e. The shift in *I(c)* is stronger when *i* is high, because the distortion in the employee's efforts increases with *i*.

In contrast to changes in t_c or t_i, which have mixed effects on procurement, changes in t_c^e, t_c^D, t_i^e, or t_i^D have unambiguous effects. Consider the case where technical progress affects the level of costs (t_c or t_i). When the cost differential between the firm and the market is at its maximum, there is no control effect (because in that case there are no agents more efficient than that agent), there is only an efficiency effect. When the cost differential is nil, there is no efficiency effect, there is only a control effect. Therefore the impact of technical progress on procurement depends on the cost differential.

Consider now the case where technical progress concerns the effect or the disutility of

CRE (t_c^e, t_c^D, t_i^e, or t_i^D). In that case, when the cost differential is at its maximum, there is no efficiency effect (because the privately informed agent with a low cost invests the optimal amount of CRE), and there is no control effect. When the cost differential is nil, or that it is positive but not at its maximum, there is an efficiency effect (because in that case the privately informed agent invests a suboptimal amount of CRE), and there is a control effect (because technical progress reduces the rents of all agents who might be more efficient than that agent); in that case the efficiency effect always dominates. Therefore the impact of technical progress does not depend on the cost differential between the firm and the market.

5.3 Simultaneous change in more than one technological parameter

In many situations technical change affects many aspects of the technology simultaneously. Consider the case where all technological parameters concerning a given type of cost change simultaneously. Consider first production costs. Let the technological parameters regarding production costs be as follows: $T_c t_c$,$T_c t_c^e$,$T_c t_c^D$, with T_c >0. What would be the impact of a simultaneous and equi-proportional change in all these parameters? This would correspond to a case where innate costs decline (t_c declines), and there is a new cost reduction technology that is less costly (t_c^D declines) but also less effective (t_c^e declines).

Proposition 5. *($dI(c)/dT_c \lesseqgtr 0$). A decline in production costs, parallelled by the adoption of a production cost reduction technology that is less costly, but also less effective, induce more vertical integration when the production cost differential is large (c<c'), and induce more outsourcing when the production cost differential is small (c>c').*

Figure 10 illustrates the shift in *I(c)* resulting from a decline in T_c. For this type of technological change there is no control effect, there is only an efficiency effect, therefore technological change favours the procurement mode with higher total production costs. Consider the portion of *I(c)* that shifts to the left, with *c<c'*. At this level of cost the total production costs of the subcontractor are lower than the firm's, implying that the reduction in production costs is more important for the firm, inducing more vertical integration. Consider now the portion of *I(c)* that shifts to the right, with *c>c'*. At this level of cost the total production costs of the subcontractor are higher than the firm's, implying that the reduction in production costs is more important for the subcontractor, inducing more outsourcing. At *c'* internal and external production costs are equal, therefore there is no change in the decision criterion: the new $I(c)$ passes through (c',i').

Moreover the decline in T_c reduces the importance of production costs in explaining firm boundaries. Figure 10 shows that the decline in T_c reduces $I'(c)$. As $I'(c)$ decreases, c becomes less important, and i more important, in the procurement decision. In the limit case where $I'(c) \to 0$ (because $T_c \to 0$), procurement depends only on i, and is independent of c. For instance, more vertical integration is induced when $c<c'$;[21] because $I(c<c')<i'$, in that case the low coordination costs of the employee encourage vertical integration. Similarly, more outsourcing is induced when $c>c'$; because $I(c>c')>i'$, in that case the high coordination costs of the employee also encourage outsourcing. When technology changes, it may be factors for which technology is not changing, rather than factors for which technology is changing, which explain better the change in firms' boundaries.

In the same fashion the impact of a simultaneous and equi-proportional change in all technological parameters concerning coordination costs is determined. Let the technological parameters regarding coordination costs be as follows: $T_i t_i$, $T_i t^e_i$, $T_i t^p_i$, with $T_i>0$. What would be the impact of a simultaneous and equi-proportional change in all these parameters?

Proposition 6. *$(dI(c)/dT_i \lesseqgtr 0)$. A decline in coordination costs, parallelled by the adoption of a coordination cost reduction technology that is less costly, but also less effective, induce more outsourcing for $i<i'$, induce more vertical integration for $i>i'$, and have no effect for $i=i'$.*

Figure 11 illustrates the shift in $I(c)$ following a decline in T_i. Consider the portion of $I(c)$ that shifts to the right, with $i<i'$. At this level of cost the total coordination costs of the firm are lower than the subcontractor's, implying that the reduction in coordination costs is more important for the subcontractor, inducing more outsourcing. Consider now the portion of $I(c)$ that shifts to the left, with $i>i'$. At this level of cost the total coordination costs of the firm are higher than the subcontractor's, implying that the reduction in coordination costs is more important for the firm, thus inducing more vertical integration. For this type of technological change there is no control effect, there is only an efficiency effect, therefore technological change favours the procurement mode with higher total coordination costs.

21.A similar result obtains when t_c declines (see figure 6).

Moreover the decline in T_i reduces the importance of coordination costs in explaining firm boundaries. Figure 11 shows that the decline in T_i increases $I'(c)$. As $I'(c)$ increases, i becomes less important, and c more important, in the procurement decision. In the limit case where $I'(c) \to \infty$ (because $T_i \to 0$), procurement depends only on c, and is independent of i. For instance, more outsourcing is induced when $i<i'$;[22] because $C(i<i')<c'$, in that case the low production costs of the subcontractor encourage outsourcing. Similarly, more vertical integration is induced when $i>i'$; because $C(i>i')>c'$, in that case the high production costs of the subcontractor also encourage vertical integration.

It is important to distinguish between, on the one hand, the impact of a decline in costs on the extent of use of one type of procurement, which depends on the shift in the decision function, and, on the other hand, the impact of a decline in costs on the importance of that type of cost in the procurement decision, which is determined by the slope of the decision function. For instance, a decline in T_i reduces the importance of coordination costs in the procurement decision (by increasing the slope of the decision function in the space (c,i)), but we cannot say whether it leads to more subcontracting or more internal provision (see proposition 6). Similarly, a decline in T_c reduces the importance of production costs in the procurement decision (by decreasing the slope of the decision function in the space (c,i)), but we cannot say whether it leads to more subcontracting or more internal provision (see proposition 5).

In light of this analysis, Coase (1990) is right when he points out that once transaction costs are minimized, they become less important in the procurement decision. The model shows that technological progress can have an impact similar to that pointed out by Coase. However, Malone et al. (1987) are only partly right when they argue that, because the reduction in coordination costs reduces the importance of the coordination cost dimension, and that markets are weak on this dimension, this should lead to more subcontracting. Our analysis shows that this is true when the coordination cost advantage of the firm is important, so that the efficiency effect dominates the control effect. However, when the coordination cost advantage of the firm is negligible, the control effect may dominate, and the decline in coordination costs can lead to more vertical integration.

Consider now a simultaneous change in all technological parameters. Let the technological parameters be Tt_c, Tt_c^e, Tt_c^D, Tt_i, Tt_i^e, Tt_i^D, with $T>0$.

22.A similar result obtains when t_i declines (see figure 7).

Proposition 7. *($dI(c)/dT=0$). A simultaneous and equi-proportional change in all technological parameters has no effect on procurement.*

In the LS model a proportional technical change in all technological parameters (which concerned only production costs) had no effect on procurement. Here, however, the neutrality of this form of technical change does not obtain. When either technological parameters of production costs, or technological parameters of coordination costs change, procurement is affected. The no effect case obtains only when all technological parameters, for both production and coordination costs, change simultaneously. Given that technological change affecting different types of costs generally occurs sequentially rather than simultaneously, this neutrality is unlikely to be observed in practice, and we can expect technological change to affect procurement more often than not.

Finally, to evaluate the effects technical progress, it is necessary to examine factors which are not affected by technical progress. This result was illustrated in the model in two ways. First, when technological change affects one type of cost, it may reduce the importance of this type of cost in the determination of procurement type, increasing the importance of other factors, for which technology has, in fact, not changed. Second, through their impact on the relative importance of efficiency and control effects, costs not affected by technical change can influence the way procurement responds to technological change.

5.4 Changes in the coordination intensity of the technology

Up to now comparative statics analysis has focussed on changes in technological parameters. It is useful to consider the impact of changes in the production intensity of the technology, that is, changes in the magnitudes of $\bar{c}$ and $\bar{i}$. An increase in $\bar{c}$ can correspond to the addition of production stages, making the technology more production intensive, and less coordination intensive. The lower $\bar{c}/\bar{i}$, the more coordination intensive the technology is. In this section it is assumed, for the sake of simplicity, that the hazard rate does not vary with $\bar{c}$ or $\bar{i}$. Consider the impact of an increase in $\bar{c}$, which represents an increase in the production intensity of the technology.

Proposition 8. *($dI(c)/d\bar{c}<0$). An increase in the production intensity of the technology shifts $I(c)$ to the right, but has an ambiguous effect on procurement.*

An increase in $\bar{c}$ has two effects on procurement. It increases the cost disadvantage of the firm, thereby inducing more outsourcing. This effect is represented on figure 12 by the eastward shift in *I(c)*. However, it also increases the parameter space over which the firm chooses internal provision. This effect is represented on figure 12 by the change in the size of the box. Depending on which of these two effects dominates, an increase in $\bar{c}$ may affect procurement either way.

An increase in $\bar{c}$ increases internal costs more than external costs (under the assumption made above regarding the hazard rate). This should lead, one would think, to more subcontracting. The above analysis shows that this is not necessarily true, given the change in the parameter space.[23] Note, however, that if intermediate cost realizations are more likely than extreme ones, then an increase in $\bar{c}$ will lead more often than not to more subcontracting.

5.5 Competition and monitoring

In this section we discuss informally the predictions of the model regarding the effects of changes in the level of competition between suppliers and of improvements in monitoring technologies, on the decision criterion of the firm and on the effect of technological change on that decision criterion. The static effects of better monitoring or increased competition between suppliers on the level of vertical integration differ from their dynamic effects on the impact of technical change.

Consider first competition. Consider the impact of introducing competitive bidding between subcontractors (while maintaining a single internal division). This would have the direct effect of increasing the level of subcontracting, by reducing the expected production cost and the rents of the selected subcontractor.

However, this increase in competition would also have an indirect impact on the impact of technological progress on the procurement decision. For technical progress regarding the level of production costs, this change would increase the production efficiency effect (by reducing the expected *c*, thus increasing the production cost differential in favour of the subcontractor) and would reduce the production control effect (by reducing the rent of the selected subcontractor). These two effects compound to make it more likely that technical progress on production costs leads to more vertical integration when there is competition

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23.A corollary is that an increase in the relative importance of coordination costs would shift *I(c)* to the left, but would have an ambiguous effect on procurement.

between subcontractors. As for technical progress regarding the level of coordination costs, competition between subcontractors would reduce the coordination control effect (by reducing the expected rent of the employee), and would have no impact on the coordination efficiency effect. This translates into a greater likelihood that technical progress on coordination costs leads to more subcontracting. Therefore the model predicts that the higher competition is between subcontractors, the more likely it is that technological progress on production (coordination) costs will lead to more vertical integration (subcontracting). This dynamic effect of competition differs from its static effect, which is to induce more subcontracting.

Consider next monitoring. In section 2.1 the effects of IT on monitoring were discussed. While the model does not incorporate a monitoring technology (the focus being on production and coordination costs), it provides insights as to the effects of a general improvement in monitoring. Monitoring would make it more difficult for agents to misreport their types. This would have the effect of reducing internal coordination rents and external production rents, essentially (see assumptions 3 and 4). This could affect the procurement decision either way. However, if production costs are quantitatively more important than coordination costs, the reduction in external costs will be more important, and this will lead to more subcontracting. Therefore the model can explain how a reduction in monitoring costs both inside and outside the firm, and for both production and coordination costs, leads to more subcontracting.

At the same time, monitoring would change the impact of technical progress. By reducing the rents of the agents, improved monitoring would reduce control effects. It follows that technical change on production (coordination) costs is more likely to lead to more vertical integration (subcontracting) under a better monitoring technology. Again, the static and dynamic effects of monitoring differ.

6. Conclusions

The model studied in this paper explained how, in a world of uncertainty and asymmetric information, different types of technological change regarding production and coordination costs affect the boundaries of the firm. It was found that technological progress on production and coordination costs tends to have diametrically opposite effects on procurement. In general, technological progress on production costs leads to more vertical integration, whereas technological progress on coordination costs leads to more subcontracting. However, the opposite result obtains in many cases. When technological change concerns the level of costs, its effect on procurement depends on the cost differential between the firm and the market; whereas, when technological change affects the effect or disutility of effort, its effect on procurement is unambiguous. The static and dynamic effects of competition and monitoring on the frontiers of the firm were analysed. It was shown how increased competition between subcontractors, or improved monitoring (both in the firm and in the market), lead to more subcontracting, but make it more likely that technical change on production (coordination) costs leads to more vertical integration (subcontracting).

The results complement those obtained by Lewis and Sappington (1991) concerning production technology and those of Reddi (1994) concerning IT. Lewis and Sappington (1991) found that technical progress on production costs leads uniformly to more vertical integration, a prediction that is not corroborated by empirical evidence. For instance, Empey (1988) finds that outsourcing is increasing faster in those industries in which technological change and productivity gains are more important (see also the discussion in section 2.2). The model studied in this paper shows how technological progress on either production or coordination costs can lead to either more vertical integration or more subcontracting. Comparing the results obtained here with those of Lewis and Sappington shows that failing to account for coordination costs not only prohibits us from analysing the effect of technical change pertaining to coordination costs, but also yields incorrect results regarding the effect of technical change pertaining to production costs.

In the real world, investments in IT have grown faster than investments in production technologies,[24] from which we can conclude that productivity gains in information transmission and manipulation have been more important than productivity gains in physical production. The model predicts that technological progress on coordination costs is more likely to induce more subcontracting,[25] while technological progress on production costs is more likely to induce more vertical integration. And this is what is observed empirically: an inverse relation between investments in IT and the level of integration of firms (Kambil, 1991; Komninos, 1994; Carlsson, 1988; Brynjolfsson et al., 1994; Shin, 1996). The model can explain why more activities are being outsourced in industries where investments in IT are important.

24.For instance, during the period 1975-1985, American manufacturing firms have increased their IT stock by 600%, compared to 40% for total capital stock (Kambil, 1991).

25.The delay of adjustment of firms to IT can be important: "adjustment to new information technology is a slow and gradual process, as it works through changes in fundamental altitudes, incentives and culture in the firm" (Bröchner, 1990:215).

However, the model also points to cases where the opposite may occur. Empirically, there are instances where IT have led to increased integration. For instance, more hotel chains are centralising reservations management (Gurbaxani and Whang, 1991). Beede and Montes (1997) analyse 46 American industries and find no economy-wide relation between IT investments and the share of auxiliary employment. Bröchner (1990) predicts that, in the construction industry, one of the consequences of IT will be the emergence of more specialized contractors who will tend to integrate backwards into the supply of specialized materials and equipment.

The paper constitutes a bridge between agency and contractual explanations on the one hand, and technological explanations on the other hand, of the existence and frontiers of the firm. While pre-transaction costs explanations of vertical integration were characterized by technological determinism, post-transaction costs explanations suffer from what Englander (1988) calls *transaction cost determinism*. Williamson has repeatedly argued that transaction costs are sufficient to explain the boundaries of the firm, and that technology is mainly irrelevant. However, as Englander argues, technological solutions to transaction costs are implicit in Williamson's arguments. Elements such as learning by doing and coordination are fundamentally technological phenomena. Moreover, asset specificity, which is at the heart of transaction costs theory, is strongly related to technological considerations.

Chandler (1982) has criticized Williamson for his neglect of technological considerations in the establishing of a theory of the firm. North (1981) criticizes both Williamson and Chandler for focussing on one dimension while neglecting the other, and gives more weight to the interactions between technology and transaction costs. The results of the model favour North's open position. When both technological change and informational asymmetry are present, the effect of technological change on procurement cannot be understood without taking into account informational asymmetries in markets and firms. The results here go even further than what Englander suggested, for his focus was -mainly- on the interactions between organizational technology and transaction cost, whereas here it is shown that even physical capital technology can affect transaction costs. In a more dynamic framework, the firm may choose technology and organizational forms so as to minimize management and transaction costs, which makes the interactions between transaction costs and technology even more stringent.[26]

Hubbard (1998) finds that the benefits of IT in the trucking industry vary with the nature of the transaction. They are more coordination related under spot markets, and more incentive related under long term contracts or vertical arrangements. These results are consistent with the model. In the model, from an incentive point of view, IT reduce internal rents, while they reduce external coordination costs more than internal coordination costs. This parallel should be drawn with caution, however, because the assumptions of the model do not necessarily fit the trucking industry.

The disaggregation of the relation between technological progress and the level of integration of firms is essential in order to isolate the different tendencies at play. At the firm level, simultaneous progress on production and IT may leave the level of integration unchanged, not because there are no effects, but because effects cancel out (see proposition 7). At the industry level, some firms may invest more in IT, while other firms may invest more in production technologies. The level of integration can decrease in the former, and increase in the latter. At the aggregate level, some industries may be investing more in IT, while other industries are investing more in production technologies. The level of integration may decline in the former, and increase in the latter. Again, the lack of disaggregation will hide important sectoral effects.

It is well known that the choice of procurement mode is more complex than a simple make or buy decision. There are many intermediate forms of procurement that firms and suppliers can adopt: strategic alliances, networks, virtual organizations, telework, etc. Picot et al. (1996) discuss the role of IT in the emergence of these new organizational forms. Even though our model considers extreme forms of make or buy, the types of tradeoffs found here (e.g. efficiency and control effects) are likely to emerge -maybe under different forms- in these intermediate organizational modes. The results obtained here shed light on, and provide a methodology for the analysis of, the effects of technical progress in the choice between procurement modes other than classical vertical integration and arms length transactions. Moreover, the advantages and disadvantages of a polar procurement mode are shared to varying degrees by those procurement modes close to it in terms of transaction attributes. Therefore a tendency to use more of a polar procurement mode can be seen as a proxy for a

26.K. Foss (1996) discusses how technological development can affect transaction costs when the latter arise from variability in the quality or performance of the product.

tendency to use more of procurement modes close to that mode.

The model has many potential extensions. One possibility concerns the timing of learning of c and i. It was assumed that c and i were learned before production took place. An alternative -and probably more realistic- timing would be that costs become known only at the end of the production process, after the firm has chosen its procurement mode. Another possible extension would be to consider other types of technical progress regarding production and coordination costs. It would be useful to study the effect of technological progress when subcontracting relies mainly on incentives, while internal provision relies on fixed wages, which is closer to what we observe. Finally, the model considered incremental technical improvements. The effect of radical innovations -which may change the cost function- on procurement is yet to be explored.

Figure 2 - The function *I(c)*

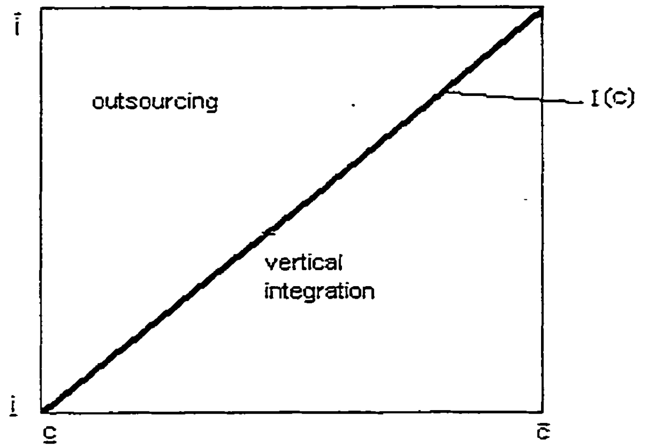
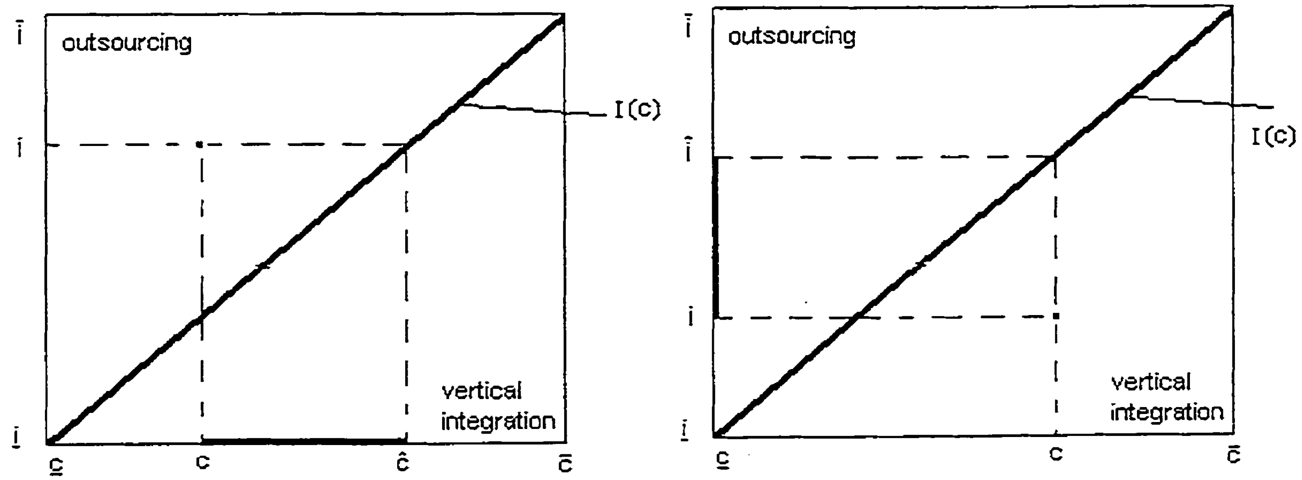


Figure 3 - Rent extraction



3a - Rent extraction by the subcontractor

3b - Rent extraction by the employee

Figure 4 - Different shapes of *I(c)*

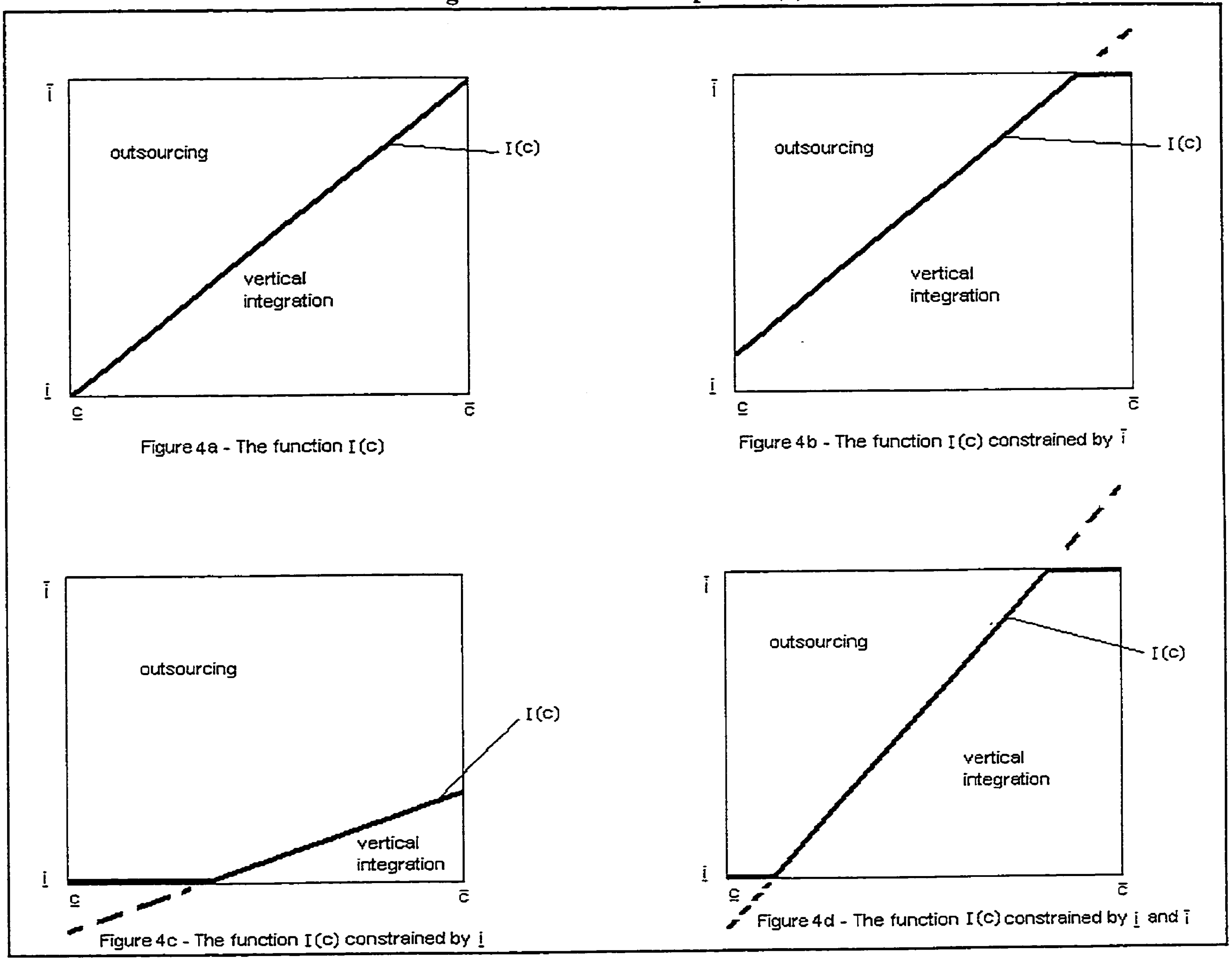


Figure 4a - The function I(c)

Figure 4b - The function I(c) constrained by $\bar{i}$

Figure 4c - The function I(c) constrained by $\underline{i}$

Figure 4d - The function I(c) constrained by $\underline{i}$ and $\bar{i}$

Figure 5 - The relation between *I(c)*, *i'* and *c'*

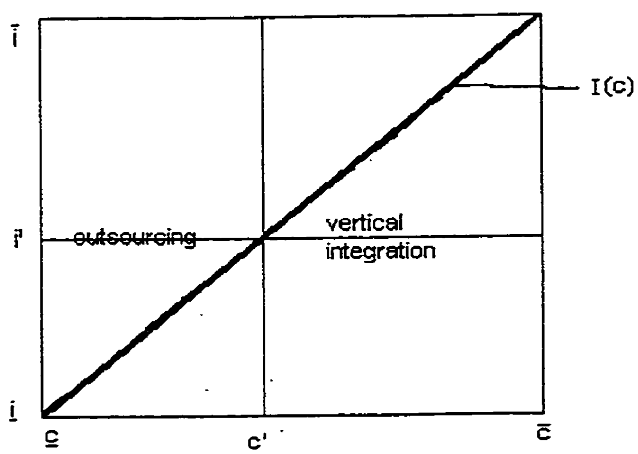


Figure 6 - Effect of a decline in t_c on $I(c)$

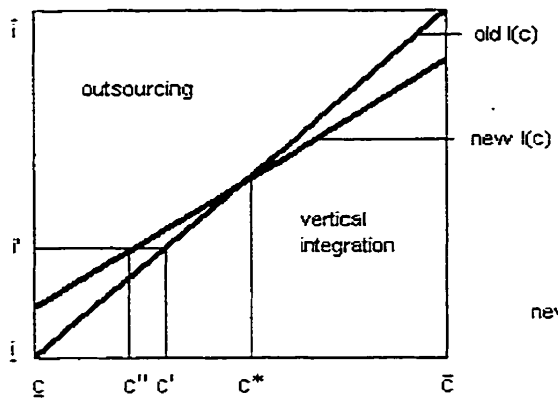


Figure 6a

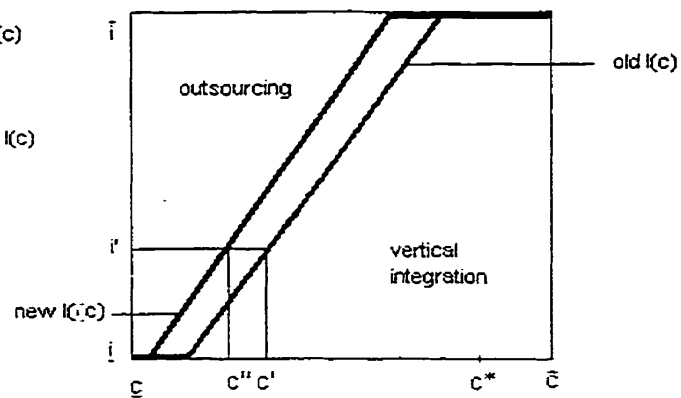


Figure 6b

Figure 7 - Effect of a decline in t_i on $I(c)$

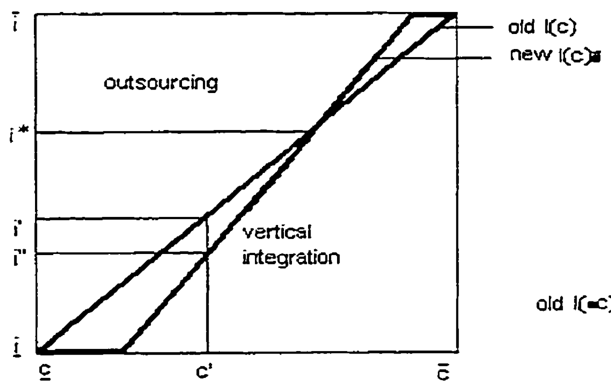


Figure 7a

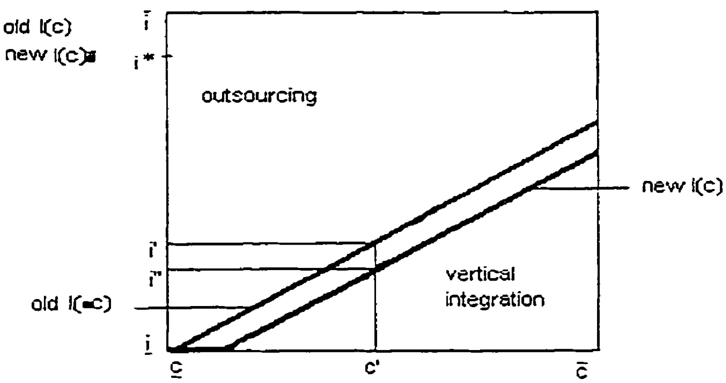


Figure 7b

Figure 8 - Effect of a decline in t_c^D or an increase in t_c^{ε} on $I(c)$

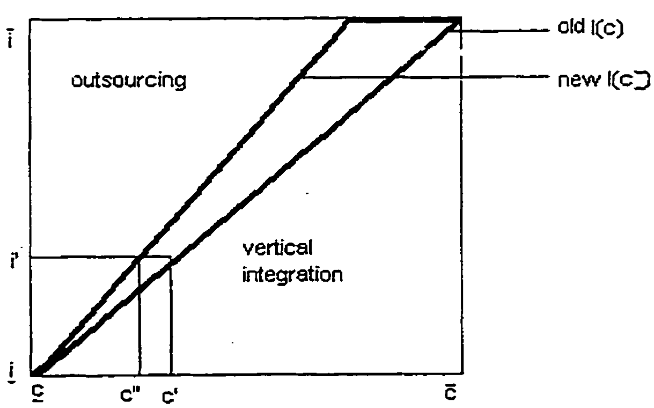


Figure 9 - Effect of a decline in t_i^D or an increase in t_i^{ε} on $I(c)$

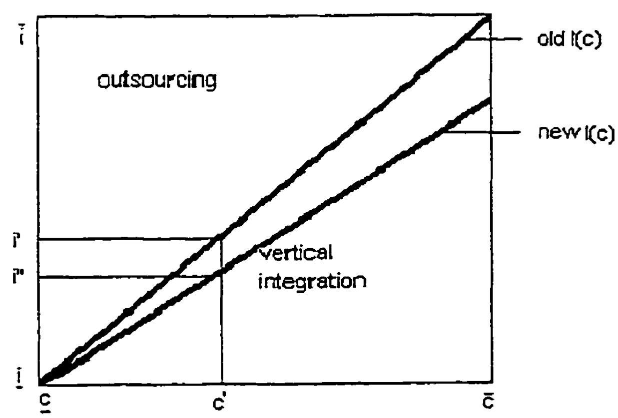


Figure 10 - Effect of a decline in T_c on $I(c)$

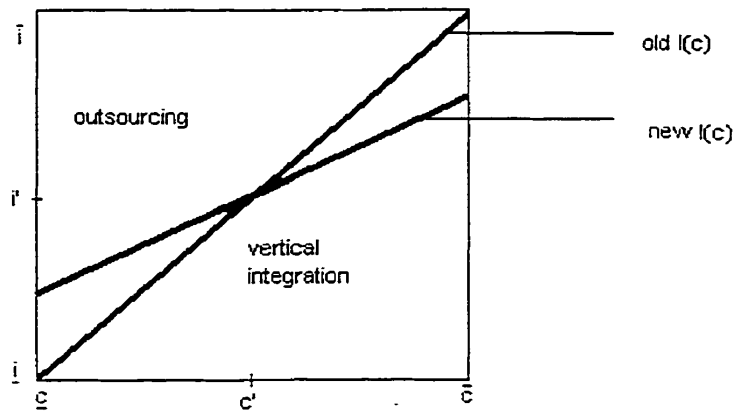


Figure 11 - Effect of a decline in T_i on $I(c)$

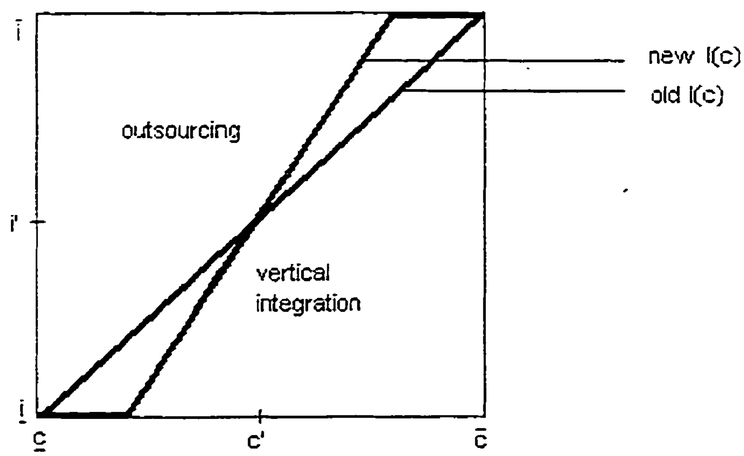
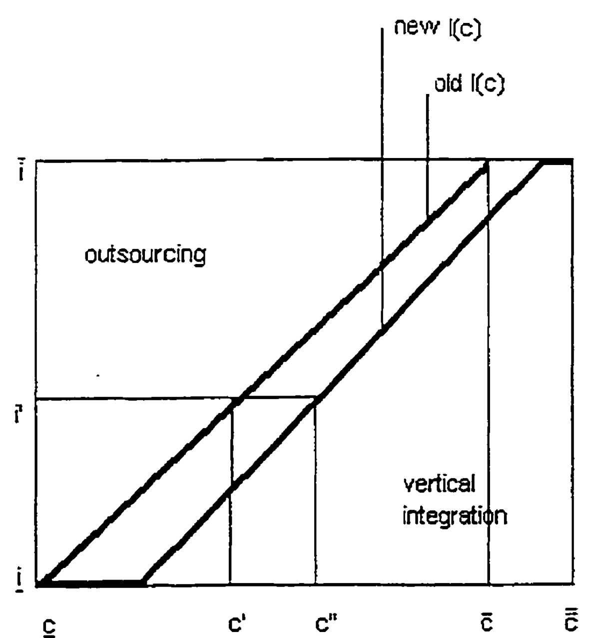


Figure 12 - Effect of an increase in $\bar{c}$ on $I(c)$



Appendix

Derivation of information rents

Given the characterization of $I(c)$ and $C(i)$ in the text the firm's expected profits can be rewritten (using the Fubini theorem) as

$$
\begin{aligned}
\pi_f &= \int_{\underline{c}}^{\bar{c}}\int_{I(c)}^{\bar{i}} [V-(t_c c-t_c^e e_c(c)+P_s+t_i\bar{i}-t_i^e e_i^{*}+t_i^D D(e_i^{*}))]\, f(c,i)\; di\; dc \\
&\quad+\int_{\underline{c}}^{\bar{c}}\int_{\underline{i}}^{I(c)} [V-(t_c\bar{c}-t_c^e e_c^{*}+t_c^D D(e_c^{*})+t_i i-t_i^e e_i(i)+P_e)]\, f(c,i)\; di\; dc \\
&= \int_{\underline{i}}^{\bar{i}}\int_{\underline{c}}^{C(i)} [V-(t_c c-t_c^e e_c(c)+P_s+t_i\bar{i}-t_i^e e_i^{*}+t_i^D D(e_i^{*}))]\, f_c(c)\, f_i(i)\; dc\; di \\
&\quad+\int_{\underline{c}}^{\bar{c}}\int_{\underline{i}}^{I(c)} [V-(t_c\bar{c}-t_c^e e_c^{*}+t_c^D D(e_c^{*})+t_i i-t_i^e e_i(i)+P_e)]\, f_c(c)\, f_i(i)\; di\; dc
\end{aligned}
\tag{17}
$$

Following Laffont and Tirole (1987), the payment made to the subcontractor is

$$
P_s(c,i) = t_c^D D(e_c(c))+\frac{t_c t_c^D}{t_c^e}\int_c^{C(i)} D'(e_c(\alpha))d\alpha \tag{18}
$$

and the payment made to the employee is

$$
P_e(c,i) = t_i^D D(e_i(i))+\frac{t_i t_i^D}{t_i^e}\int_i^{I(c)} D'(e_i(\gamma))d\gamma \tag{19}
$$

Note that the payment of each agent depends on both c and i.

We substitute P_s and P_e into (17):

$$
\begin{aligned}
\pi_f &= \int_{\underline{i}}^{\bar{i}}\int_{\underline{c}}^{C(i)} [V-(t_c c-t_c^e e_c(c)+t_c^D D(e_c(c))+\frac{t_c t_c^D}{t_c^e}\int_c^{C(i)} D'(e_c(\alpha))d\alpha+t_i\bar{i}-t_i^e e_i^{*}+t_i^D D(e_i^{*}))]\; f_c(c)\; f_i(i)\; dc\; di \\
&\quad+\int_{\underline{c}}^{\bar{c}}\int_{\underline{i}}^{I(c)} [V-(t_c\bar{c}-t_c^e e_c^{*}+t_c^D D(e_c^{*})+t_i i-t_i^e e_i(i)+t_i^D D(e_i(i))+\frac{t_i t_i^D}{t_i^e}\int_i^{I(c)} D'(e_i(\gamma))d\gamma)]\;\; f_c(c)\; f_i(i)\; di\; dc
\end{aligned}
\tag{20}
$$

Consider the term

$$
\int_{\underline{c}}^{C(i)} \frac{t_c t_c^D}{t_c^e}\int_c^{C(i)} D'(e_c(\alpha))d\alpha\; f_c(c)dc \tag{21}
$$

in (20). Integrating by parts yields transaction costs (which arise because of the private information of the subcontractor)

$$\int_{\underline{c}}^{C(i)} \frac{t_c t_c^D}{t_c^e} D'(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} f_c(c)dc \tag{22}$$

Consider next the term

$$\int_{\underline{i}}^{I(c)} \frac{t_i t_i^D}{t_i^e} \int_{i}^{I(c)} D'(e_i(\gamma))d\gamma \; f_i(i)di \tag{23}$$

in (20). Integrating by parts yields management costs (which arise because of the private information of the employee)

$$\int_{\underline{i}}^{I(c)} \frac{t_i t_i^D}{t_i^e} D'(e_i(i)) \frac{F(\bar{c},i)}{f_i(i)} f_i(i)\; di \tag{24}$$

Substituting (22) and (24) into (20), we obtain

$$\begin{aligned} \pi_f = & \int_{\underline{i}}^{\bar{i}} \int_{\underline{c}}^{C(i)} [V-(t_c c - t_c^e e_c(c) + t_c^D D(e_c(c)) + \frac{t_c t_c^D}{t_c^e} D'(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} + t_i \bar{i} - t_i^e e_i^* + t_i^D D(e_i^*))] \; f_c(c)\; f_i(i)\; dc\; di \\ & + \int_{\underline{c}}^{\bar{c}} \int_{\underline{i}}^{I(c)} [V-(t_c \bar{c} - t_c^e e_c^* + t_c^D D(e_c^*) + t_i i - t_i^e e_i(i) + t_i^D D(e_i(i)) + \frac{t_i t_i^D}{t_i^e} D'(e_i(i)) \frac{F(\bar{c},i)}{f_i(i)})] \;\; f_c(c)\; f_i(i)\; di\; dc \\ = & \int_{\underline{c}}^{\bar{c}} \int_{I(c)}^{\bar{i}} [V-(t_c c - t_c^e e_c(c) + t_c^D D(e_c(c)) + \frac{t_c t_c^D}{t_c^e} D'(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} + t_i \bar{i} - t_i^e e_i^* + t_i^D D(e_i^*))] \; f(c,i)\; di\; dc \\ & + \int_{\underline{c}}^{\bar{c}} \int_{\underline{i}}^{I(c)} [V-(t_c \bar{c} - t_c^e e_c^* + t_c^D D(e_c^*) + t_i i - t_i^e e_i(i) + t_i^D D(e_i(i)) + \frac{t_i t_i^D}{t_i^e} D'(e_i(i)) \frac{F(\bar{c},i)}{f_i(i)})] \; f(c,i)\; di\; dc \end{aligned} \tag{25}$$

Proof of lemma 1.

With no production costs (12) becomes

$$t_i \bar{i} - t_i^e e_i^* + t_i^D D(e_i^*) - t_i i' + t_i^e e_i(i') - t_i^D D(e_i(i')) - \frac{t_i t_i^D}{t_i^e} D'(e_i(i')) \frac{F(i')}{f(i')} = 0 \tag{26}$$

where i' replaced $I(c)$, $F(i)$ replaced $F(c,i)$, and $f(i)$ replaced $f_i(i)$. The first three terms represent the cost of subcontracting, while the last four terms represent the cost of internal provision. Subcontracting costs are independent of i', while internal provision costs are increasing in i'.■

Proof of lemma 2.

The proof is along the same lines of the proof of lemma 1, and is also identical to the proof of Lemma 1 in LS.

Proof of proposition 1.

$$\frac{\partial^2 \pi_f}{\partial I(c) \partial t_c} = c + \frac{t_c^D}{t_c^e} D'(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} - \bar{c} \tag{27}$$

From (12) and (14) we know that

$$sign(\frac{\partial^2 \pi_f}{\partial I(c) \partial t_c}) = sign(-[-t_c^e e_c(c) + t_c^D D(e_c(c)) + t_c^e e_c^* - t_c^D D(e_c^*) \tag{28}$$

$$+ t_i \bar{i} - t_i^e e_i^* - t_i I(c) + t_i^e e_i(I(c)) + t_i^D D(e_i^*) - t_i^D D(e_i(I(c))) - \frac{t_i t_i^D}{t_i^e} D'(e_i(I(c))) \frac{F(\bar{c}, I(c))}{f_i(I(c))}];$$

Let $x_c \equiv (\partial^2 \pi_f / \partial I(c) \partial t_c).(t_c)$, let y_c represent the first line of (28) (without the minus sign) and let z_c represent the second line. We are seeking the sign of x_c. From (12) we know that $x_c + y_c + z_c = 0$. And $y_c \geq 0$ by virtue of (2) and (10). Moreover $z_c \gtrless 0$. We have the following possibilities:

x_c	+	y_c	+	z_c	$= 0$	
(-)		(+)		(+)	$= 0$	for $c<c'$
(-)		(0)		(+)	$= 0$	for $c=c'$
(+ or -)		(+)		(-)	$= 0$	for $c>c'$

The signs in parentheses represent the signs of the corresponding terms for the range of parameters specified on the right. In the first and second cases x_c is unambiguously negative, meaning that a reduction in t_c leads to more vertical integration. In the third case $x_c \gtrless 0$.

Consider the ambiguous case. If $I(\bar{c}-\varepsilon) < \bar{i}$ for ε arbitrarily small, then $I(\bar{c}-\varepsilon)$ is an interior solution, and x_c has to be evaluated at $\bar{c}-\varepsilon$. It is immediate that $x_c(\bar{c}-\varepsilon)>0$. Together with the facts that $x_c(c')<0$, that x_c is continuous in c, and that $I'(c)>0$ at an interior solution, this implies that there exists a unique $c^* \in (c', \bar{c}]$ such that $\forall\, c \in (c', c^*)$, $x_c<0$, and $\forall\, c \in (c^*, \bar{c}]$, $x_c>0$.

We characterize c^*. Let $H(c, I(c), t_c)$ represent equation (12). At an interior solution to $I(c)$, $H(.)=0$. Let $H(c, I^+(c), t_c^+)$ represent (12) when t_c changes to t_c^+ (with $t_c^+ < t_c$) and, consequently, $I(c)$ changes to $I^+(c)$. We have that $H(c, I(c), t_c) = H(c, I^+(c), t_c^+) = 0$, for all $c \in [\underline{c}, \bar{c}]$ such that the solution of both $I(c)$ and $I^+(c)$ is interior. In particular, $H(c^*, I(c^*), t_c) = H(c^*, I^+(c^*), t_c^+)$. However,

$I(c^*)=I^+(c^*)$. Hence $H(c^*,I^+(c^*),t_c)=H(c^*,I^+(c^*),t_c^+)$. We eliminate redundant terms on both sides and rearrange to obtain

$$(t_c-t_c^-)\ [\bar{c}-c^*-\frac{t_c^D}{t_c^e}D'(e_c(c^*))\frac{F(c^*,\bar{i})}{f_c(c^*)}] = 0 \qquad (29)$$

The result follows from the fact that $t_c \neq t_c^+$.

Consider now the case where $I(\bar{c}-\varepsilon)=\bar{i}$ (so that x_c is not evaluated at $\bar{c}-\varepsilon$, because (27) is evaluated only at interior solutions). Two outcomes are possible: either $x_c<0$ for all $c\in(c',\bar{c}]$, or there exists $c^*\in(c',\bar{c}]$ such that $\forall\ c\in(c',c^*)$, $x_c<0$, and $\forall c\in(c^*,\bar{c}]$, $x_c>0$. When $I(c^*)=\bar{i}$, x_c is not evaluated at c^*, therefore $x_c<0$ for all $c\in(c',\bar{c}]$. ■

Proof of proposition 2.

The proof is along the same lines as the proof of proposition 1, and is therefore omitted.

Proof of proposition 3.

Consider first the decrease in t_c^D. The method used to derive this result is similar to that used by Lewis and Sappington (1989). For technical reasons this result is more easily derived when π_f is maximized *w.r.t.* $I^{-1}(i)$, rather than *w.r.t.* $I(c)$, as derived above. This entails mainly a change in the signs of the *f.o.c.*, but has no effect on the solution.

$$\frac{\partial^2\pi_f}{\partial I^{-1}(i)\partial t_c^D} = -D(e_c(I^{-1}(i)))-\frac{t_c}{t_c^e}D'(e_c(I^{-1}(i)))\frac{F(I^{-1}(i),\bar{i})}{f_c(I^{-1}(i))}+D(e_c^*) \qquad (30)$$

From (10) we know that

$$\frac{de_c(I^{-1}(i))}{dI^{-1}(i)} = -\frac{\frac{t_c}{t_c^e}D''\frac{d}{dI^{-1}(i)}[\frac{F(I^{-1}(i),\bar{i})}{f_c(I^{-1}(i))}]}{D''+\frac{t_c}{t_c^e}\frac{F(I^{-1}(i),\bar{i})}{f_c(I^{-1}(i))}D'''} \qquad (31)$$

Let $\theta_c\equiv F(I^{-1}(i),\bar{i})/f_c(I^{-1}(i))$ and let $G(I^{-1}(i))$ denote the r.h.s. of (30). Then

$$G'(I^{-1}(i)) = [-D' - \frac{t_c}{t_c^e} D'' \theta_c] \frac{de_c(I^{-1}(i))}{dI^{-1}(i)} - \frac{t_c}{t_c^e} D' \frac{d\theta_c}{dI^{-1}(i)} \tag{32.1}$$

$$= -\frac{t_c^e}{t_c^D} \frac{de_c(I^{-1}(i))}{dI^{-1}(i)} - \frac{t_c}{t_c^e} D' \frac{d\theta_c}{dI^{-1}(i)} \tag{32.2}$$

$$= \frac{t_c}{t_c^D} \frac{d\theta_c}{dI^{-1}(i)} [\frac{D''}{D'' + \frac{t_c}{t_c^e} \theta_c D'''} - \frac{t_c^D}{t_c^e} D'] \tag{32.3}$$

$$=_s D'' - \frac{t_c^D}{t_c^e} D'(D'' + \frac{t_c}{t_c^e} \theta_c D''') \tag{32.4}$$

$$= D''(1 - \frac{t_c^D}{t_c^e} D') + \frac{t_c t_c^D}{t_c^{e^2}} D' D''' \theta_c \tag{32.5}$$

$$= D''(\frac{t_c t_c^D}{t_c^{e^2}} D'' \theta_c) - \frac{t_c t_c^D}{t_c^{e^2}} D' D''' \theta_c \tag{32.6}$$

$$= \frac{t_c t_c^D}{t_c^{e^2}} \theta_c [(D'')^2 - D' D'''] \tag{32.7}$$

(The symbol "$=_s$" in (32.4) stands for "is of the same sign as"). (32.2) follows from (10), (32.3) follows from substituting (31) into (32.2), and (32.7) follows from substituting from (10). Under our assumptions on $D(.)$, (32.7) is always positive, and therefore $G'(I^{-1}(i))>0$. From (10) we know that $G(\underline{c})=0$. Hence $sign(G(I^{-1}(i)))=sign(G'(I^{-1}(i)))$. Hence $\partial^2\pi_f/\partial I^{-1}(i)\partial t_c^D>0$. It follows that $\partial^2\pi_f/\partial I(c)\partial t_c^D<0$.

Consider next the increase in t_c^e.

$$\frac{\partial^2 \pi_f}{\partial I(c) \partial t_c^e} = -e_c(c) - \frac{t_c t_c^D}{t_c^{e^2}} D'(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} + e_c^* \tag{33}$$

From (2) and (10) we know that

$$t_c^e e_c^* - t_c^D D(e_c^*) \geq t_c^e e_c(c) - t_c^D D(e_c(c)) \tag{34}$$

And from (30) we know that

$$t_c^D D(e_c^*) \geq t_c^D D(e_c(c)) + \frac{t_c t_c^D}{t_c^e} D'(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} \tag{35}$$

Equations (34) and (35) imply that (33) is positive (nil at $\underline{c}$), meaning that technical progress on t_c^e induces more vertical integration. ■

Proof of proposition 4.

The proof is along the same lines as the proof of proposition 3, and is therefore omitted.

Proof of proposition 5.

$$\frac{\partial^2 \pi_f}{\partial I(c) \partial T_c} = t_c c - t_c^e e_c(c) + t_c^D D(e_c(c)) + \frac{t_c t_c^D}{t_c^e} D'(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} - t_c \bar{c} + t_c^e e_c^* - t_c^D D(e_c^*) \tag{36}$$

By lemma 2 this expression is positive if $c>c'$, and negative if $c<c'$. ■

Proof of proposition 6.

The proof is along the same lines as the proof of proposition 5, and is therefore omitted.

Proof of proposition 7.

$$\begin{aligned}\frac{\partial^2 \pi_f}{\partial I(c) \partial T} = {} & t_c c - t_c^e e_c(c) + t_c^D D(e_c(c)) + \frac{t_c t_c^D}{t_c^e} D'(e_c(c)) \frac{F(c,\bar{i})}{f_c(c)} + t_i \bar{i} - t_i^e e_i^* + t_i^D D(e_i^*) \\ & - t_c \bar{c} + t_c^e e_c^* - t_c^D D(e_c^*) - t_i I(c) + t_i^e e_i(I(c)) - t_i^D D(e_i(I(c))) - \frac{t_i t_i^D}{t_i^e} D'(e_i(I(c))) \frac{F(\bar{c},I(c))}{f_i(I(c))}\end{aligned} \tag{37}$$

This derivative is nil by (12). ■

Proof of proposition 8.

$$\begin{aligned}\frac{\partial^2 \pi_f}{\partial I(c) \partial \bar{c}} = {} & -\ [V - (t_c \bar{c} - t_c^e e_c + t_c^D D(e_c) + \frac{t_c t_c^D}{t_c^e} D'(e_c) \frac{F(\bar{c},\bar{i})}{f_c(\bar{c})} + t_i \bar{i} - t_i^e e_i^* + t_i^D D(e_i^*))]\ f(\bar{c}, I(\bar{c})) \\ & +\ [V - (t_c \bar{c} - t_c^e e_c^* + t_c^D D(e_c^*) + t_i I(\bar{c}) - t_i^e e_i + t_i^D D(e_i) + \frac{t_i t_i^D}{t_i^e} D'(e_i) \frac{F(\bar{c}, I(\bar{c}))}{f_i(I(\bar{c}))})]\ f(\bar{c}, I(\bar{c})) \\ & -\ \int_{\underline{c}}^{\bar{c}} f(c, I(c))\, dc\end{aligned} \tag{38}$$

The first two terms cancel out when $I(c)$ is optimally chosen (and internal), therefore $dI(c)/d\bar{c}<0$. $I(c)$ shifts to the right as $\bar{c}$ increases, inducing more outsourcing. However, because of the increase in $\bar{c}$, the area of the region over which vertical integration is chosen has increased. ■

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VERTICAL R&D SPILLOVERS, COOPERATION, MARKET STRUCTURE, AND INNOVATION

1. Introduction

Lately there has been an intensification of Research Joint Ventures and technological alliances between firms. For instance, Hagedoorn et al. (2000) note that the number of new technology partnerships set up annually went from 30-40 in the early 1970s to around 600 during the 1980s and 1990s. Appropriability is an important dimension of R&D which has been the subject of a large theoretical and empirical literature. Although spillover analysis can be traced back to Ruff (1969), the modern theoretical treatment of the subject builds on the seminal papers by Spence (1984) and d'Aspremont and Jacquemin (1988).

Many variants of this basic model have been studied.[1] Almost all of the studies in the strategic investment literature deal with horizontal spillovers between competing firms. Spillovers between buyers and sellers, which I call vertical spillovers, are one instance of interindustry spillovers. The main difference between horizontal and vertical spillovers is that the former are involuntary and (generally) undesirable from the point of view of the innovating firm, whereas the latter are desirable (and are more often voluntary). Another difference is that while horizontal R&D cooperation may mitigate competition between firms, and is often closely monitored by competition authorities, vertical cooperation is less likely to hinder competition. Intraindustry cooperation is generally sufficient for firms to internalize horizontal spillovers. However, the internalization of vertical spillovers requires interindustry coordination. When vertical and horizontal spillovers are linked, a strong patent protection policy aiming at prohibiting competitors from acquiring the innovation may also harm vertically related firms (as well as firms in demand unrelated industries).

Whereas the empirical literature shows that vertical technological flows are significant, little theoretical treatment has focussed on this dimension of appropriability. Two exceptions are Peters (1995) and Harhoff (1991). Peters (1995) studies a model of vertical spillovers. He finds that more concentrated industries tend to spend more on R&D (however, this result may be reversed for high values of interindustry spillovers and some specific values of horizontal spillovers), horizontal spillovers may increase or decrease R&D, and vertical spillovers increase R&D investments, profits, and welfare. The model suffers from some restrictive

[1] Some of the issues examined are absorptive capacities (Cohen and Levinthal, 1990), price vs. quantity competition (Delbono and Denicolo, 1990), Stackelberg leadership (Goel, 1990), process vs. product innovation (Levin and Reiss, 1988), partial cartelization (Kamien and Zang, 1993; Poyago-Theotoky, 1995; De Bondt and Wu, 1997), asymmetric firms (Rosen, 1991; Poyago-Theotoky, 1996), asymmetric spillovers (Jarmin, 1993), and spillovers between demand unrelated industries (Steurs, 1994; 1995). Kamien et al. (1992) generalize this framework and study different combinations of cooperation and information sharing.

assumptions: spillovers are in one direction only, from suppliers to customers; upstream firms do not benefit from their own R&D investments: all benefits accrue to downstream firms; upstream firms cannot adjust their output to their R&D investments: finally, cooperation is not addressed. In a related paper Becker and Peters (1995) study R&D competition between two vertical corporate networks in a patent race framework.

Harhoff (1991) studies a model of product R&D spillovers between vertically related industries. He finds that upstream and downstream R&D are generally substitutes: with an exogenous market structure and perfect vertical spillovers (in one direction only), only one of the two industries spends on imperfectly appropriable R&D.[2] However, his model suffers from some restrictive assumptions. The presence of a Stackelberg upstream monopolist makes the results applicable only to very asymmetric markets. Moreover, this market structure makes it impossible to study upstream horizontal spillovers along with downstream horizontal spillovers. Another restrictive assumption is that when (downstream) horizontal spillovers are allowed for, upstream prices are fixed exogenously. Moreover, vertical spillovers are perfect, and they accrue only from the seller to the buyers. Finally, cooperation is not addressed.[3]

This paper studies vertical spillovers, allowing for different market structures, appropriability conditions, and types of cooperation. The model incorporates two vertically related industries, with horizontal spillovers within each industry and vertical spillovers between the two industries, in a three-stage game theoretic framework. The contribution of the paper is threefold. First, this is the first paper to formalize vertical spillovers in a relatively general framework. Second, the study of cooperation goes further than existing studies by considering four different cooperative structures: no cooperation, interindustry and intraindustry cooperation, interindustry cooperation only, and intraindustry cooperation only. Finally, the paper addresses market structure explicitly, and provides a theory of innovation and market structure. The paper incorporates a large number of issues: horizontal spillovers, vertical spillovers, R&D cooperation, market structure, endogenous cooperation. While this complicates the analysis and presentation of the results, I believe that omitting any of these variables would obscure some of the most important parts of the problem, such as the interplay between R&D cooperation, spillovers, and market structure.

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[2]This is contrary to the results of Steurs (1994,1995), Peters (1995), and -as will be seen- our model, where it is found that there is a strong complementarity between interindustry research efforts.

[3]Vertical R&D cooperation has been briefly addressed in the agricultural economics literature. See Freebairn et al. (1982) and Alston and Scobie (1983).

Here is a summary of the main findings of the paper. Vertical spillovers affect R&D investments directly and indirectly, through their influence on the impact of horizontal spillovers and of R&D cooperation. Whereas horizontal spillovers may increase or decrease innovation and welfare depending on prevailing cooperation types, vertical spillovers always increase them. Cooperative settings are compared in terms of R&D. It is shown that no type of cooperation uniformly dominates the others. The type of cooperation yielding more R&D depends on horizontal spillovers, vertical spillovers, and market structure. The ranking of cooperative structures hinges on the signs and magnitudes of three competitive externalities (vertical, horizontal, and diagonal) which capture the effect of the R&D of a firm on the profits of other firms. The type of cooperation inducing firms to internalize a larger positive sum of competitive externalities yields more R&D. In particular, one of the basic results of the strategic investment literature is that cooperation between competitors increases (decreases) R&D when horizontal spillovers are high (low); the model shows that this result does not necessarily hold when vertical spillovers and vertical cooperation are taken into account. A theory of innovation and market structure is proposed: the effect of competition in one industry on total innovation depends on horizontal spillovers, vertical spillovers, cooperative settings, and competition in the other industry. The relation between competition and innovation can be understood in terms of the horizontal, vertical, and diagonal competitive externalities. Finally, the analysis of the private incentives for cooperation shows that buyers and sellers have different preferences over cooperative settings: sellers prefer vertical cooperation, whereas buyers (generally) prefer horizontal cooperation. Higher spillovers increase the likelihood of cooperation, but the multiplicity of equilibria makes the decentralized choice of socially optimal cooperative settings uncertain.

The paper is organized as follows. Section 2 provides some background on vertical spillovers and vertical cooperation. The model is presented and solved in section 3. Comparative statics are studied in section 4. Section 5 compares R&D expenditures between types of cooperation. In section 6 the relation between market structure and innovation is addressed. The private incentives for cooperation are studied in section 7. Section 8 concludes.

2. Background

There is ample evidence that interindustry spillovers -of which vertical spillovers are one instance- are significant. Bernstein (1988) and Jaffe (1986) find that interindustry spillovers have more effects on cost reduction than intraindustry spillovers. Bernstein finds that unit costs decrease more in response to an increase in intraindustry (interindustry) spillovers in industries with large (small) R&D cost shares. Pavitt (1984) finds that out of 2,000 innovations in the UK, only 40% emanated from the sector using the innovation.

Some evidence points more explicitly to vertical spillovers.[4] Goto and Suzuki (1989) find that in the electronics industry, technological diffusion through spillovers is more important than technological diffusion through inputs. Ward and Dranove (1995) find important vertical spillovers within the American pharmaceutical industry. Suzuki (1993) and Branstetter (199?) find significant vertical spillovers in Japanese *keiretsu*.[5] As Mohnen notes: "Interindustry knowledge spillovers are more likely to occur ... when one innovation naturally calls for the development of complementary products or innovations in an upstream input supply sector in order to reach its full potential." (Mohnen, 1989:5)

The role of vertically related firms in the development of new technologies is well documented. In the auto industry, much of the innovation comes from suppliers (Jorde and Teece, 1990). Clark et al. (1987) show the importance of the role played by die suppliers for new product development by Japanese automobile firms. Vanderwerf (1992) shows that upstream firms often create downstream innovations, even when the direct profit from the innovation accrues to downstream firms. This can be explained by the increase in final demand due to the innovation. Von Hippel (1988) finds that more than two thirds of first-to-market innovations concerning scientific instruments and process machinery in semiconductor and electronic subassembly manufacturing are dominated by end-users.

In some cases the complementarity between upstream and downstream innovation is sufficiently strong to require explicit vertical cooperation. "*Vertical research joint ventures* ..(*RJVs*), which constitute a substantial fraction of *RJVs*, are designed to bring together complementary assets, usually research capacity and manufacturing or marketing" (Aghion and Tirole, 1993:7). Vertical technological cooperation is widely observed. It is sometimes argued that the high levels of vertical cooperation in the Japanese economy are responsible for much

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[4]The ongoing trend toward more outsourcing increases the importance of the study of vertical spillovers. When firms had higher levels of vertical integration, a good part of vertical spillovers were internalized. However, with outsourcing, spillovers which were intra-firm become inter-firm/interindustry spillovers.

[5]Suzuki finds that spillovers from the core firm to its subcontractors are significant: a percentage increase in technology transfer reduces the unit variable cost of the subcontractor by 0.09%. In the study of a sample of 208 Japanese manufacturing firms, Branstetter (199?) finds that production keiretsu promote innovative activity, as measured by firm-level spending on research and development. Moreover, he finds evidence that affiliation with production keiretsu groups promotes the exchange of technological knowledge across firms within groups.

of Japan's competitive edge (Dyer and Ouchi, 1993). Sako (1995) argues that inter-supplier coordination (through *kyoryokukai*) in the Japanese automotive industry is also important. Moreover, suppliers with above (below) average technological capabilities prefer vertical (horizontal) technological cooperation. This is to be expected, since mutual learning between suppliers is more valuable when there is no fear of information leakage to competitors. Cassiman and Veugelers (1998), from the study of a sample of firms from the Belgian manufacturing industry, find that most cooperative agreements are vertical or with research institutes, rather than horizontal; they find that vertical cooperation is driven by the search for external knowledge and complementarities, rather than by sharing high costs or high risks of research. Veugelers (1993) finds that vertical relations account for 38% of Joint Ventures and for 25% of cooperative agreements. Since its foundation, SEMATECH (the Semiconductor Manufacturing Technology Consortium) has shifted from horizontal to vertical cooperation (Grindley et al., 1994).

Vertical cooperation has an important legal dimension. American antitrust laws are more restrictive regarding inter-firm technological cooperation than their European and Japanese counterparts (Jorde and Teece, 1990, 1992). For instance, European antitrust authorities grant cooperative R&D agreements exemption from Article 85 of the Treaty of Rome governing broad aspects of competition among firms. The exemption applies for five years, regardless of market share, if the participants are vertically related and do not compete directly in the relevant market.

3. The model

The standard duopoly framework used in much of the strategic investment literature is quite restrictive. Here we use a more general market structure, for both upstream and downstream industries. This allows us to see how changes in market structure affect the relative desirability of different types of R&D cooperation. Indeed, it will be shown that this comparison depends critically on market structure. Also, this allows us to analyze the effects of spillovers and cooperation on the relation between market structure and innovation. This yields results that are related to the literature studying the effect of the technological environment on the Schumpeterian hypothesis.

There are m identical buyers of a standardized input, and n identical suppliers providing this input. This market structure is given, so entry issues are put aside. If no R&D is undertaken, suppliers incur a constant unit production cost of s and sell the input at a unit price of t to buyers. Buyers pay the suppliers t for each unit bought, and incur an additional internal production cost of r. Finally, buyers sell the product to consumers at price p.[6] Buyers face the linear inverse demand

$$p = a - w\sum_{i=1}^{m} y_{bi}$$

where y_{bi} denotes buyer's i output.

Firms can engage in cost-reducing R&D activities. The dollar cost of x units of R&D for firm i is ux_i^2, where x_i represents the R&D output of firm i, and $u>0$ represents a cost parameter. It is assumed that u is sufficiently high for the profit function to be concave, and sufficiently low for firms to choose strictly positive amounts of R&D. Convex R&D costs can be justified by the observation of decreasing returns to scale in R&D.[7] With quadratic costs, many small research labs will be more cost effective than one big research unit. However, each firm is assumed to operate exactly one research lab, for the sake of simplicity. Total R&D output will be denoted X.

Each unit of R&D by a firm reduces its own cost by one dollar, reduces the cost of each of its competitors by h dollars (horizontal spillovers), and reduces the cost of each firm in the other industry by v dollars (vertical spillovers),[8 9] with $h, v \in [0,1]$.[10] The spillovers h and v can differ for many factors: different absorptive capacities between suppliers/distributors and competitors, different levels of technological complementarities, differences in the efficiency of communication channels, and linkages between the degree of information leakage and the

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[6]The vertical chain contains only two industries for the sake of simplicity, but this assumption can also be justified by the empirical result that even though interindustry spillovers are important, each industry receives spillovers from a limited range of industries (Bernstein and Nadiri, 1988).

[7]See, for instance, Kamien and Schwartz, 1982. However, this issue remains controversial; see Nadiri, 1993.

[8]An important difference with Peters (1995) is that Peters assumes that vertical spillovers accrue only from suppliers to customers. However, there is no a priori reason why vertical spillovers should not be bi-directional. For instance, Suzuki (1993) finds vertical spillovers in both directions between core firms and their subcontractors in *keiretsu*.

[9]Spillovers from a firm need not be limited to its own buyers/suppliers. Suzuki (1993) identifies spillovers between the core firm in a *keiretsu* and the subcontractors belonging to other *keiretsus*. A percentage increase in technology transfer reduces the unit variable cost of the subcontractors by 0.11%, an even larger spillover than between the firm and its own subcontractors. Those vertical spillovers (although in the second case one should speak of cross or diagonal spillovers) are found to be even more important than technological transfers between core firms from different *keiretsus* (horizontal spillovers), which are of the order of 0.08%. *Keiretsu* provide an example where vertical spillovers are just as important empirically as, perhaps even more important than, horizontal spillovers.

[10]Imperfect spillovers can represent imperfect information leakage, the productivity of transferred knowledge (Peters, 1995), novelty requirements (Henriques, 1991), perfect information leakage with an absorption cost (for instance Levin et al. (1987) find that patents raise imitation costs and time), or perfect information leakage with differences in technology which cause only some of the information to be useful.

type of inter-firm interaction. The unit cost of production of a downstream firm is

$$c_{bi} = t+r-x_{bi}-h\sum_{j\neq i}^{m} x_{bj}-v\sum_{i=1}^{n}x_{si}.$$

The unit cost of production of an upstream firm is

$$c_{si} = s-x_{si}-h\sum_{j\neq i}^{n} x_{sj}-v\sum_{i=1}^{m}x_{bi}.$$

Consequently, the final unit cost of a firm depends on its R&D choice as well as on that of all other firms. Buyers benefit from sellers' R&D through a reduction in the cost of their input, and through vertical spillovers. Sellers benefit from buyers' R&D through the reduction in buyers' cost, and through vertical spillovers. Note that whereas R&D expenses are independent of output, its benefits are linked to output, since the higher output is, the higher the number of units that benefit from cost reduction.

Parameters are assumed to be such that the following nonnegativity constraints are satisfied:

$$r > x_{bi}+h\sum_{j\neq i}^{m} x_{bj}+v\sum_{i=1}^{n}x_{si},\ i=1,...,m$$
$$s > x_{si}+h\sum_{j\neq i}^{n} x_{sj}+v\sum_{i=1}^{m}x_{bi},\ i=1,...,n.$$

These constraints ensure that production costs after R&D is undertaken are strictly positive.

The game has three stages: one R&D stage and two output stages. In the first stage all firms decide on their R&D simultaneously. In the second stage upstream firms compete in Cournot, taking into account the derived demand curve of the downstream industry. In the third stage there is a Cournot game among all downstream firms, taking the price of the intermediate good as given. The output stages follow the successive oligopoly structure suggested by Greenhut and Ohta (1979). The price of the intermediate good is determined by Cournot competition in the upstream industry, based on the derived demand curve of buyers. In horizontal models of R&D investments, the output game is generally assumed to be simultaneous. Here, however, the vertical structure of the market implies that sellers are Stackelberg leaders.[11]

[11]The use of a sequential model is one of the restrictive assumptions of the model. A simultaneous game for vertically related firms would avoid "the potentially restrictive assignment of leader-follower roles required by the Stackelberg solution." (Young, 1991:717). However, in a vertical market with prices as strategic variables, no equilibrium can be obtained in a simultaneous game; a simultaneous game would require the use of markups, not prices, as strategic variables (Young, 1991; Irmen, 1997). Other negotiation mechanisms could be used to obtain simultaneous output decisions between buyers and sellers. However, for the purpose of obtaining results which are comparable with other studies in this literature, and to maintain tractability, it is assumed that firms compete in output, implying sellers' leadership.

3.1 Output stages

We begin with the third stage where buyers decide non-cooperatively on their output, guaranteeing the perfectness of the equilibrium. Buyers's i problem is

$$Max_{y_{bi}} \quad \pi_{bi} = (p(Y)-c_{bi})y_{bi}-ux_{bi}^{2} \qquad (1)$$

where $Y \equiv y_{b1}+...+y_{bm}$. Given that buyers are identical ex ante, they take the same decisions ex post. Simultaneous maximization of (1) for $i=1,...,m$ and solving of the m f.o.c. yields

$$y_{bi} = \frac{a-t-r+(m-(m-1)h\ )x_{bi}-(1-2h)\Sigma_{j\neq i}^{m}x_{bj}+v\Sigma_{i=1}^{n}x_{si}}{w(m+1)} \qquad (2)$$

$$p = \frac{a+m(t+r)-(1+(m-1)h)\Sigma_{i=1}^{m}x_{bi}-mv\Sigma_{i=1}^{n}x_{si}}{m+1}$$

From (2) we derive the inverse demand curve suppliers face

$$t = \frac{m(a-r)+(1+(m-1)h)\Sigma_{i=1}^{m}x_{bi}+mv\Sigma_{i=1}^{n}x_{si}-w(m+1)\Sigma_{i=1}^{n}y_{si}}{m} \qquad (3)$$

We now turn to the second stage of the game, where suppliers decide non-cooperatively on their output, based on the derived inverse demand of downstream firms (3). Supplier i maximizes

$$Max_{y_{si}} \quad \pi_{si} = (t(Y)-c_{si})y_{si}-ux_{si}^{2}.$$

The identical costs of sellers imply that they will occupy identical positions ex post. Maximization and simultaneous solving of the n f.o.c. yields

$$y_{si} = \frac{m(a-r-s)+(1+(m-1)h+mv)\Sigma_{i=1}^{m}x_{bi}+m(n-(n-1)h+v)x_{si}+m(-1+2h+v)\Sigma_{j\neq i}^{n}x_{sj}}{w(mn+m+n+1)}$$

Given that each unit bought from suppliers is transformed into one unit sold by buyers to consumers, total output is the same for upstream and downstream industries. Total output is

$$Y = \frac{mn(a-r-s)+n(1+(m-1)h+mv)\Sigma_{i=1}^{m}x_{bi}+m(1+(n-1)h+nv)\Sigma_{i=1}^{n}x_{si}}{w(mn+m+n+1)}$$

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comparable with other studies in this literature, and to maintain tractability, it is assumed that firms compete in output, implying sellers' leadership.

and the final price is

$$p = \frac{(m+n+1)a+mn(r+s)-n(1+(m-1)h+mv)\sum_{i=1}^{m}x_{bi}-m(1+(n-1)h+nv)\sum_{i=1}^{n}x_{si}}{mn+m+n+1}.$$

The price charged by suppliers is[12]

$$t = \frac{m(a-r+ns)+(1+(m-1)h-mnv)\sum_{i=1}^{m}x_{bi}-m(1+(n-1)h-v)\sum_{i=1}^{n}x_{si}}{m(n+1)}.$$

3.2 R&D stage

In the first stage of the game all firms decide simultaneously on R&D levels. Whereas output is always chosen non-cooperatively, four types of cooperation (*TOC*) will be considered for R&D decisions: a non-cooperative equilibrium (*NCE*), a generalized cooperative equilibrium (*GCE*), a horizontal cooperative equilibrium (*HCE*), and a vertical cooperative equilibrium (*VCE*). Figure 1 illustrates the different *TOC*. Note that in all four environments the source and destination (and also the level) of spillovers is independent of the *TOC*. That is, even when there are cooperating groups of firms, spillovers originate and end at individual firms. This is in contrast to empirical modelisation, where spillovers originate from industries.

Horizontal cooperation (*HC*) represents cooperation with competitors, while vertical cooperation (*VC*) represents cooperation with suppliers/distributors. Generalized cooperation (*GC*) reflects the complexity of some research joint ventures: with the multiplication of research projects, firms may be adopting more than one structure simultaneously. Firms may engage in *HC* on one project, and in *VC* on another project. Many cooperative agreements involve both horizontal and vertical linkages. For instance, cooperation with a competitor may involve working with its suppliers.

Let $\beta \equiv \{x_{b1},\ldots,x_{bm},x_{s1},\ldots,x_{sn}\}$. Using the results of the second and third stages, we can write profit functions as functions of β. The profit of buyer i is

$$\pi_{bi} = (p(\beta)-c_{bi}(\beta))y_{bi}(\beta)-ux_{bi}^2.$$

The profit of seller i is

$$\pi_{si} = (t(\beta)-c_{si}(\beta))y_{si}(\beta)-ux_{si}^2.$$

In the first *TOC*, the *NCE*, each firm chooses its R&D so as to maximize its own

[12]Note that t depends on the number of downstream firms; this is due to the presence of R&D. In the absence of R&D, with a linear demand (and also with a log-linear demand), t is independent of m (Choe, 1998).

profits, given that other firms do the same. The problem of buyer i is

$$Max_{x_{bi}}\ \pi_{bi} \qquad \textbf{(4)}$$

and the problem of seller i is

$$Max_{x_{si}}\ \pi_{si} \qquad \textbf{(5)}$$

Maximization and simultaneous solving of the $m+n$ f.o.c. of (4) and (5) yield research efforts in the *NCE* by each buyer and each seller:[13 14]

$$x_{bi}^{NC} = \frac{n(1-h-m^2+hm^2-hmn-vmn-m^2n+hm^2n)(-a+r+s)}{\gamma^{NC}}$$

$$x_{si}^{NC} = \frac{m^2(1+m)(h+v+n-hn)(a-r-s)}{\gamma^{NC}}$$

where

$$\begin{aligned}\gamma^{NC} = {} & -hm^2+h^2m^2-vm^2+hvm^2-hm^3+h^2m^3-vm^3+hvm^3+n-2hn+h^2n+hmn \\ & -h^2mn+vmn-hvmn-2m^2n+4hm^2n-3h^2m^2n-2hvm^2n-v^2m^2n-m^3n+hm^3n \\ & -h^2m^3n-vm^3n-hvm^3n-v^2m^3n-hmn^2+h^2mn^2-vmn^2+hvmn^2-m^2n^2 \\ & +hm^2n^2-h^2m^2n^2-vm^2n^2-hvm^2n^2-v^2m^2n^2-2hm^3n^2+2h^2m^3n^2-2vm^3n^2 \\ & +2hvm^3n^2+uw(m+2m^2+m^3+2mn+4m^2n+2m^3n+mn^2+2m^2n^2+m^3n^2)\end{aligned}$$

In the *GCE* each firm chooses its R&D to maximize the total profits of all firms:

$$Max_{\beta}\ \ \Sigma_{i=1}^{m}\pi_{bi} + \Sigma_{i=1}^{n}\pi_{si} \qquad \textbf{(6)}$$

Maximization of (6) with respect to x_{bi}, $i=1,...,m$ and x_{si}, $i=1,...,n$ yields research efforts in the *GCE*:

$$x_{bi}^{GC} = \frac{-(1-h+hm+vm)n(1+m+n)(a-r-s)}{\gamma^{GC}}$$

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[13]The Salant and Shaffer (1998) critique of the use of symmetric R&D strategies does not apply here, because there are no side payments and there is only one output market. Moreover, the very idea of side payments goes counter to the pre-competitive nature of R&D collaboration.

[14]Under all *TOC*, R&D expenditures depend on the sum $r+s$, not on the distribution of these two activities between upstream and downstream firms. Therefore, changes in the frontiers of firms have no effect on R&D or welfare, subject to the fact that the constraint of nonnegativity of costs is nonbinding.

$$x_{si}^{GC} = \frac{m(1+m+n)(1-h+hn+vn)(-a+r+s)}{\gamma^{GC}}$$

where

$$\begin{aligned}\gamma^{GC} = {} & m-2hm+h^2m+m^2-2hm^2+h^2m^2+n-2hn+h^2n+2mn-2h^2mn \\ & +4vmn-4hvmn+4hm^2n-3h^2m^2n+4vm^2n-2hvm^2n+v^2m^2n+h^2m^3n+2hvm^3n \\ & +v^2m^3n+n^2-2hn^2+h^2n^2+4hmn^2-3h^2mn^2+4vmn^2-2hvmn^2+v^2mn^2 \\ & +2h^2m^2n^2+4hvm^2n^2+2v^2m^2n^2+h^2mn^3+2hvmn^3+v^2mn^3 \\ & -uw(1+2m+m^2+2n+4mn+2m^2n+n^2+2mn^2+m^2n^2)\end{aligned}$$

In the *HCE* there is intraindustry cooperation but no interindustry cooperation. Buyers maximize

$$Max_{x_{b1},\ldots,x_{bm}} \quad \sum_{i=1}^{m} \pi_{bi} \qquad (7)$$

and sellers maximize

$$Max_{x_{s1},\ldots,x_{sn}} \quad \sum_{i=1}^{n} \pi_{si} \qquad (8)$$

Simultaneous solving of the $m+n$ f.o.c. of (7) and (8) yields research efforts in the *HCE*:

$$x_{bi}^{HC} = \frac{(1-h+hm+vm)n^2(-a+r+s)}{\gamma^{HC}}$$

$$x_{si}^{HC} = \frac{m(1+m)(1-h+hn+vn)(-a+r+s)}{\gamma^{HC}}$$

where

$$\begin{aligned}\gamma^{HC} = {} & m-2hm+h^2m+m^2-2hm^2+h^2m^2+2hmn-2h^2mn+2vmn-2hvmn+2hm^2n \\ & -2h^2m^2n+2vm^2n-2hvm^2n+n^2-2hn^2+h^2n^2+2hmn^2-h^2mn^2+2vmn^2+v^2mn^2 \\ & +2h^2m^2n^2+4hvm^2n^2+2v^2m^2n^2-uw(1+2m+m^2+2n+4mn+2m^2n+n^2+2mn^2+m^2n^2)\end{aligned}$$

In the *VCE* there is interindustry cooperation, but no intraindustry cooperation. Each buyer cooperates with one seller, but buyers do not cooperate among themselves, nor do sellers. Given that buyers are identical, as well as sellers, it is irrelevant which buyer cooperates with each seller. The *VCE* requires $m=n$ to exclude asymmetric strategies. Without loss of generality, let bi cooperate with si, $i=1,\ldots,m$ $(m=n)$. Firms bi and si maximize

$$Max_{x_{bi},x_{si}} \quad \pi_{bi}+\pi_{si} \qquad (9)$$

Following the maximization of (9) we find research efforts in the *VCE* to be

$$x_{bi}^{VC} = \frac{(n^2+vn^2+n^3+hn^3+2vn^3+n^4-hn^4)(a-r-s)}{\gamma^{VC}}$$

$$x_{si}^{VC} = \frac{n(n+vn+n^2+hn^2+2vn^2+n^3-hn^3)(a-r-s)}{\gamma^{VC}}$$

where

$$\begin{aligned}\gamma^{VC} = & -2n^2+2hn^2-2vn^2+2hvn^2-2n^3-2hn^3+2h^2n^3-6vn^3+2hvn^3-2v^2n^3-2n^4 \\ & +2hn^4-4h^2n^4-2vn^4-6hvn^4-4v^2n^4-2hn^5+2h^2n^5-2vn^5+2hvn^5 \\ & +uw(n+4n^2+6n^3+4n^4+n^5)\end{aligned}$$

The following sections analyse the results derived above.

4. Comparative statics

The question addressed in this section is: what is the effect of changes in vertical and horizontal spillovers on R&D and welfare,[15] under different *TOC*? This analysis is performed in a bilateral duopoly framework. Proposition 1 summarises the effects of spillovers on R&D and welfare.

Proposition 1. *Let m=n=2. Then*

i) Vertical spillovers always increase R&D by all firms, as well as welfare.

ii) Horizontal spillovers increase R&D by all firms in the GCE and the HCE, and reduce R&D by all firms in the NCE and the VCE.

iii) Horizontal spillovers increase welfare in all three cooperative equilibria (even when they reduce R&D), and have an ambiguous effect on welfare in the NCE.

iv) A simultaneous and equal increase in horizontal and vertical spillovers (starting from the same level) reduces x_{bi} and increases x_{si} in the NCE (with an ambiguous effect on total R&D), and increases R&D by all firms in all other TOC.

v) In the NCE and the VCE, v reinforces the negative effect of h, and h mitigates the positive

[15] Note that we focus on R&D output, not effective (produced+received) R&D. While the latter is more meaningful from a social point of view, R&D output is more amenable to empirical testing. Moreover, in this type of model there is generally a monotonic relationship between effective spillovers and welfare, therefore the welfare analysis implicitly addresses effective spillovers.

effect of v. In the GCE and the HCE, h and v reinforce the positive effects of each other.

Table 1 summarizes the comparative statics of the model. Comparative statics are obtained by substituting $m=n=2$ into the solutions for R&D and performing the relevant differentiations. Figure 2 illustrates the effect of h and v on total R&D.[16]

Table 1- Summary of comparative statics ($m=n=2$)

	No cooperation	Generalized cooperation	Horizontal cooperation	Vertical cooperation
$\partial x_{bi}/\partial v$	+	+	+	+
$\partial x_{si}/\partial v$	+	+	+	+
$\partial W/\partial v$	+	+	+	+
$\partial x_{bi}/\partial h$	-	+	+	-
$\partial x_{si}/\partial h$	-	+	+	-
$\partial W/\partial h$	±	+	+	+
$\partial x_{bi}(h=g)/\partial h$	-	+	+	+
$\partial x_{si}(h=g)/\partial h$	+	+	+	+
$\partial X(h=g)/\partial h$	±	+	+	+
$\partial^2 X/\partial h \partial v$	-	+	+	-

An increase in v increases R&D by all firms, in all equilibria. As v increases, the flow of spillovers between the two industries increases, reducing the costs of all firms; this reduction in costs translates into an increase in output. This increase in output increases the value of cost reduction, inducing a further increase in R&D. In contrast to h, vertical spillovers benefit all firms, and induce no disincentives for cost reduction.[17]

In the *NCE* and the *VCE*, an increase in h reduces the private benefit from R&D,

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[16]This figure, and all other numerical simulations in the paper, are based on the following numerical parameterization of the model: $a=1000$, $w=1$, $r=s=50$, $u=600$.

[17]Vertical spillovers can have a (negligible) negative effect on a firm. When v increases, the flow of spillovers to the firm from its suppliers/distributors increases, but the same also applies to competitors. When firms are identical, the positive effect of the reduction in own cost dominates the marginal negative effect of the reduction in competitors' (and the competitors' suppliers) costs. In a situation with strong asymmetries between firms, it could be the case that small firms lose from v, because most of the benefits go to their competitors, deteriorating further their initial cost disadvantage. Moreover, when a large firm has many suppliers, suppliers may worry about information leakage to the buyer, since this information may go to the supplier's competitors. Such a concern has arisen within SEMATECH (the Semiconductor Manufacturing Technology Consortium), where Semiconductor materials and equipment suppliers sharing information with SEMATECH members feared of information leakage to their competitors (Grindley et al., 1994).

thereby reducing R&D by all firms.[18] However, vertical cooperation reduces the negative effects of horizontal spillovers. Formally, in general we have that $|\partial X^{VC}/\partial h|<|\partial X^{NC}/\partial h|$: horizontal spillovers reduce R&D spending less under vertical cooperation than under no cooperation. With vertical cooperation, cost reduction is more highly valued, therefore leakages to competitors reduce R&D to a lesser degree than in the absence of cooperation. In the *GCE* and the *HCE*, there is intraindustry cooperation, and, consequently, the positive externality is internalized: an increase in h increases R&D by all firms.

Note the asymmetric effects of spillovers on R&D: $\partial X/\partial h<0$ when there is no intraindustry cooperation (*NC* or *VC*), whereas $\partial X/\partial v>0$ even without interindustry cooperation (*NC* or *HC*).

Consider next the effect of a simultaneous and equal increase in vertical and horizontal spillovers ($dh=dv$). Here h and v increase equally and simultaneously, assuming they are initially at the same level. This result is useful in a context where (desirable) leakage of information to suppliers implies the (undesirable) leakage of the same information to competitors. That effect is obtained by setting $h=v$ and differentiating with respect to the spillover level. As table 1 shows, in the three cooperative equilibria all firms increase their R&D. In the *NCE*, buyers decrease, and sellers increase, their R&D. Remember that, in the *NCE*, an increase in (only) v increased R&D by all firms whereas an increase in (only) h decreased R&D by all firms. This means that, when both types of spillovers increase simultaneously, the positive effect of v dominates for sellers, while the negative effect of h dominates for buyers. The effect on total R&D is ambiguous, depending on which dominates between the increase in R&D by sellers and the decrease in R&D by buyers.[19]

However, further analysis shows that the effect of a simultaneous increase in h and v in the *NCE* and the *VCE* tends to become negative as competition intensifies, due to the negative effect of non internalized h on R&D. Therefore, when the diffusion of technological information to vertically related firms makes this information available to competitors, and this (horizontal) externality is not internalized, it is preferable to limit the diffusion of information.

There is an -asymmetric- interaction between the effects of h and v. In the *NCE* and the

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[18]In the case of the derivatives $\partial x_b^{VC}/\partial h$ and $\partial x_{si}^{VC}/\partial h$, it could not be formally proved that they are always negative, however numerical simulations show that whenever any of them is positive at least one of the nonnegativity constraints on costs is violated.

[19]Steurs (1994,1995) finds that the total effect of an increase in intra and interindustry spillovers is ambiguous, and is more likely to be positive for lower levels of spillovers.

VCE, $\partial^2 X/\partial h \partial v<0$, meaning that v reinforces the negative effect of h, and that h mitigates the positive effect of v.[20] In this case not only does h reduce R&D, but it also mitigates the positive effect of v. In the GCE and the HCE, $\partial^2 X/\partial h \partial v>0$: h and v reinforce the positive effects of each other.

The effects of appropriability on profits and welfare depends on who benefits from information leakages (competitors or vertically related firms) and the prevailing TOC. In all three cooperative equilibria, an increase in h always increases profits, consumer surplus and welfare. This is true even though $\partial X^{VC}/\partial h<0$. In the NCE, $\partial W^{NC}/\partial h \gtrless 0$ even though $\partial X^{NC}/\partial h<0$. At low levels of h, increases in h benefit firms and consumers. This suggests that appropriability problems that induce firms to refrain from innovating are not necessarily undesirable, given that this loss in innovation is more than compensated for by the increase in knowledge received by other firms. For very high levels of h, however, the reduction in R&D is so drastic that welfare suffers. In some cases, firms may be benefiting from the increase in h at the expense of consumers. Thus, the effect of changes in h on welfare depends on its initial level. This analytical ambiguity of the effect of h on prices and costs is in contrast to the empirical finding that spillovers generally induce output expansions and price reductions.

On the other hand, in all TOC, an increase in v always increases profits, consumer surplus, and welfare. These findings are consistent with those of Peters (1995) and Steurs (1994,1995).

5. Comparison of cooperative structures

In this section the different types of cooperation are compared in terms of R&D. This comparison is important given that in the literature, most studies have focussed on comparing cooperation vs. no cooperation. However, the choices firms face with respect to R&D cooperation are much more complex than this binary decision. Firms must decide not only whether to cooperate or not, but also with whom to cooperate. Two important potential partners for cooperation are competitors and suppliers/customers. The four types of R&D cooperation studied in this paper are: no cooperation, horizontal cooperation, vertical cooperation, and generalized (simultaneous horizontal and vertical) cooperation. They have been explained in detail in section 3.

[20] Steurs (1994,1995) also finds that spillovers between demand independent industry, although they affect R&D positively, reinforce the negative effect of intraindustry spillovers.

R&D cooperation induces firms to internalize the effect of their R&D expenditures on the profits of their partners. Let a "competitive externality" represent the marginal effect of the R&D of a firm on the profits of other firms (this effect is generally non-nil, even when there are no spillovers). In this model there are three types of competitive externalities: the horizontal competitive externality (*H*), the vertical competitive externality (*V*), and the diagonal competitive externality (*D*). *H* represents the sum of the marginal effects of a firm's R&D on the profits of its competitors; this externality is internalized in the *HCE* and the *GCE*. *H* can be positive or negative, depending on whether an increase in R&D by a firm increases or decreases the profits of its competitors. *H* increases with horizontal spillovers, and generally also with vertical spillovers. *V* represents the sum of the marginal effects of a firm's R&D on the profits of its customers/suppliers; this externality is internalized in the *VCE* and the *GCE*. It is positive, given that an increase in R&D by a firm always increases the profits of its customers/suppliers. *D* represents the sum of the marginal effects of a firm's R&D on the profits of firms in the other industry, which are neither competitors nor customers/suppliers; this externality is always positive, and is internalized in the *GCE* only. *V* and *D* are always positive, but are larger when horizontal and vertical spillovers are higher. No competitive externalities are internalized in the *NCE*. The following lemma characterizes the relation between competitive externalities and the ranking of *TOC*.

Lemma 1. *Let m=n=2. Let the horizontal competitive externality H be given by*

$$H \equiv \frac{\partial \pi_{b2}}{\partial x_{b1}} + \frac{\partial \pi_{b1}}{\partial x_{b2}} + \frac{\partial \pi_{s2}}{\partial x_{s1}} + \frac{\partial \pi_{s1}}{\partial x_{s2}}$$

Let the vertical competitive externality V be given by

$$V \equiv \frac{\partial \pi_{s1}}{\partial x_{b1}} + \frac{\partial \pi_{s2}}{\partial x_{b2}} + \frac{\partial \pi_{b1}}{\partial x_{s1}} + \frac{\partial \pi_{b2}}{\partial x_{s2}} > 0$$

Let the diagonal competitive externality D be given by

$$D \equiv \frac{\partial \pi_{s2}}{\partial x_{b1}} + \frac{\partial \pi_{s1}}{\partial x_{b2}} + \frac{\partial \pi_{b2}}{\partial x_{s1}} + \frac{\partial \pi_{b1}}{\partial x_{s2}} > 0$$

Then, between any two TOC, the one internalizing a larger (more positive) sum of competitive externalities will yield more R&D.

Proof. The inclusion of positive (negative) externalities in the first order condition of a firm increases (decreases) its R&D, given that the profit of a firm is concave in its own R&D.

The comparison between *TOC* rests on the signs and magnitudes of those externalities: the *TOC* yielding more R&D will be the one which internalizes a larger sum of competitive externalities.[21] This is because internalizing a positive competitive externality increases R&D, while internalizing a negative competitive externality reduces R&D.[22] This result is quite general, and can be particularly useful in comparing different cooperative structures even when no closed form solutions exists or that the levels of R&D investments are not known. In what follows we use those three competitive externalities to analyse the classification of *TOC*.

Before proceeding with the analysis it will be useful to restate the basic result of the strategic investment literature, that with low horizontal spillovers R&D competition yields more innovation than (horizontal) R&D cooperation. When h is high, information leakage is important, and firms underinvest. Consequently cooperation induces them to internalize this positive externality, and R&D is increased. On the other hand, when h is low, information leakage is negligible, and the private gains from R&D outweigh the spillover. Accordingly firms give less weight to the spillover, and overinvest in R&D. In this context intraindustry cooperation reduces R&D, since firms internalize this negative externality. As the analysis to follow will show, accounting for vertical spillovers and vertical cooperation can seriously alter this result.

The analysis starts in a bilateral duopoly framework, and the effect of market structure is introduced later. The following proposition summarizes the ranking of *TOC* when $m=n=2$.

Proposition 2. *Let* $m=n=2$. *Then*

a) $X^{VC}>X^{NC}$.

b) $X^{GC}>X^{HC}$.

c) $sign(X^{VC}-X^{HC})=sign(1-h)$.

d) $sign(X^{NC}-X^{GC})=sign(1-11h-10v)$.

e) $sign(X^{NC}-X^{HC})=sign(13-23h-10v)$.

f) $sign(X^{GC}-X^{VC})=sign(7h+5v-2)$.

Proof. These results follow from lemma 1. They can also be obtained by analysing the differences between total R&D expenditures under pairs of *TOC*.

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[21]Boivin and Vencatachellum (1998) develop a related concept of a competitive externality given by $\partial y_j/\partial x_i$. They show that this externality is of the same sign as $\partial \pi_j/\partial x_i$.

[22]I am indebted to Caroline Boivin for suggesting this line of analysis.

Part *a* of proposition 2 states that $X^{VC}>X^{NC}$. In the *NCE* no competitive externality is internalized. In the *VCE* firms internalize the vertical competitive externality, which is always positive, pushing R&D up. When $v>0$, firms internalize the effect of their R&D on the production cost and the profits of their customer/supplier. Even when $v=0$, firms internalize the effect of their own cost reduction on the increase in the size of the market and profits of their customer/supplier, thus increasing their R&D compared with the *NCE*.

Part *b* of proposition 2 compares the *GCE* with the *HCE*. In all cases $X^{GC}>X^{HC}$. Generalized cooperation internalizes *V*, *H*, and *D*, while horizontal cooperation internalizes *H*. Taking the difference between the two, $(V+H+D)-H=V+D>0$: generalized cooperation dominates horizontal cooperation because it internalizes the same horizontal externality (which may be positive or negative, but this is irrelevant here) and, in addition, internalizes the positive *V* and *D*.

Part *c* of proposition 2 compares *HC* with *VC*. *VC* dominates, except when $h=1$, where $X^{VC}=X^{HC}$. *VC* internalizes *V*, while *HC* internalizes *H*. When horizontal spillovers are low, *H* is negative (because an increase in R&D by a firm reduces the profits of its competitor), therefore $V>H$. But even when horizontal spillovers are high, so that $H>0$, *V* is larger than *H*: the vertical competitive externality internalized through vertical cooperation is larger than the horizontal competitive externality internalized through horizontal cooperation. It is only when $h=1$ that the two *TOC* yield equal levels of R&D.

The relation between the *NCE* and the *GCE* (part *d* of proposition 2) depends on the levels of *h* and *v*. When *h* and *v* are very low, *NC* dominates, because in that case cooperation between competitors reduces R&D. The negative horizontal effect dominates the positive vertical and diagonal effects: $|H|>V+D$. When *h* and *v* are high, the horizontal competitive externality (*H*) becomes less negative, and eventually positive, therefore $V+D+H>0$. In that case $X^{GCE}>X^{NCE}$. However, contrary to the established result in the literature, that increase comes for levels of horizontal spillovers much smaller than $h=1/2$. In fact, as proposition 2 establishes, even when $h=0$, *GC* can increase R&D. This is due to the presence of the vertical and diagonal competitive externalities, which may dominate the negative *H* when horizontal spillovers are low.

Part *e* of proposition 2 states that $X^{NC}>X^{HC}$ when *h* and *v* are low, while the inequality is reversed for high spillovers. *HC* increases R&D compared to *NC* when $H>0$, that is, when the horizontal competitive externality internalized through horizontal cooperation is positive. As explained above, a low h induces overinvestment in the *NCE*, therefore *HC* reduces R&D; conversely, a high h induces underinvestment in the *NCE*, therefore *HC* increases R&D.

The effect of v is novel, however, and needs to be explicited. *HC* is more likely to increase R&D when v is high. This result can be understood in terms of the strategic interaction of research efforts. In the *NCE* and the *HCE*, buyers' research expenditures are strategic substitutes iff $7>11h+4v$, and sellers' research expenditures are strategic substitutes iff $1>2h+v$. R&D cooperation between firms whose research efforts are strategic substitutes (complements) decreases (increases) R&D. v contributes to strategic complementarity between competitors: a higher v increases the benefit a firm extracts from its competitor's R&D, trough the effect of that R&D on the cost of the customer/supplier of the firm. For instance, an increase in x_{b2} benefits $b1$ directly through h, but also indirectly through the reduction in c_{s1} (the cost of the supplier of $b1$) induced by v. As vertical spillovers contribute to horizontal strategic complementarity, they reduce the level of horizontal spillovers required for *HC* to increase R&D. In other words, with high vertical spillovers, horizontal cooperation can increase R&D even with low horizontal spillovers. This result is contrary to what is established in the literature, and shows the importance of accounting for vertical spillovers in the analysis of R&D cooperation.

Part f of proposition 2 states that when spillovers are very low, *VC* dominates *GC*, while this relation is reversed for moderate and high spillovers. *VC* internalizes *V*, while *GC* internalizes, *H*, *V* and *D*. Therefore, $X^{GC}>X^{VC}$ iff $H+V+D>V$, i.e. iff $H+D>0$. When spillovers are low, H is negative, and dominates the positive D: the negative effect of internalizing the horizontal competitive externality dominates the positive effect of internalizing the diagonal competitive externality. As horizontal and vertical spillovers increase, H becomes less negative, and eventually positive, therefore for high spillovers $X^{GC}>X^{VC}$.

The comparisons in proposition 2 have been performed pairwise. It is useful to be able to rank all *TOC* for given levels of spillovers. Figure 3 illustrates the ranking of *TOC* in the hxv space, based on the conditions stated in proposition 2. This figure is divided into 5 regions, each region being characterized by a ranking of the *TOC*. The following table summarizes the relation between the competitive externalities and the magnitude and sign of H in each region.

Table 2 - Ranking of types of cooperation

Region (fig. 3)	Spillovers' values	Ranking of *TOC*	Competitive externalities	Magnitude of *H*	Sign of *H*
Region 1	$v<(1-11h)/10$	$VC>NC>GC>HC$	$V>0>V+H+D>H$	$\|H\|>V+D$	$H<0$
Region 2	$(1-11h)/10<v<(2-7h)/5$	$VC>GC>NC>HC$	$V>V+H+D>0>H$	$\|H\|>D$	$H<0$
Region 3	$(2-7h)/5<v<(13-23h)/10$	$GC>VC>NC>HC$	$V+H+D>V>0>H$	$\|H\|<D$	$H<0$
Region 4	$v>(13-23h)/10,\ h\neq 1$	$GC>VC>HC>NC$	$V+H+D>V>H>0$	$H<V$	$H>0$
Region 5	$h=1$	$GC>VC=HC>NC$	$V+H+D>V=H>0$	$H=V$	$H>0$

Region 1 is characterized by low spillovers. In this region $VC>NC>GC>HC$. H is negative and sufficiently large to cause the *GCE* to reduce R&D compared to the *NCE*. As spillovers increase, we move into region 2, where the ranking of *GC* and *NC* is reversed: $VC>GC>NC>HC$. H is still negative enough to outweigh D (therefore $X^{GC}<X^{VC}$), but not negative enough to outweigh $V+D$ (therefore $X^{GC}>X^{NC}$). As spillovers increase further, we move into region 3, where *GC* comes to dominate all other *TOC*. H is still negative, but is smaller than D, therefore $X^{GC}>X^{VC}$. When spillovers increase further, we move into region 4: the horizontal competitive externality becomes positive, therefore $X^{HC}>X^{NC}$.[23] Finally, when $h=1$ (region 5), and independently of v, the horizontal competitive externality increases further: $H=V$, therefore $X^{HC}=X^{VC}$.

As we move north-east (i.e. as spillovers increase), the ranking of *VC* and *NC* deteriorates, while the ranking of *GC* and *HC* improves. It is surprising that as vertical spillovers increase, the ranking of *VC* deteriorates, as it becomes dominated by *GC*, which has the advantage of allowing competitors to cooperate, and of inducing a firm to internalize the effect of its R&D on all the firms in the other industry, and not only on its own supplier/customer (as would be the case with *VC*). Note that for the largest part of the spillovers space, *GC* dominates all other *TOC*, followed by *VC*. This shows the importance of interindustry cooperation, whether there is intraindustry cooperation or not. *VC* is a

[23] Note that at $v=0$ and $h=1/2$, $X^{NC}>X^{HC}$, while the literature would predict equality between the two *TOC* in that case. The reason is that in this model buyers and sellers have different conditions of strategic interaction (as specified above). The line determining strategic interaction for buyers ($7-11h-4v$) in the *NCE* and the *HCE* lies slightly to the right of the line separating regions 3 and 4 ($13-23h-10v$), while the line determining strategic interaction for sellers ($1-2h-v$) lies slightly to the left of that line. In fact, the line separating regions 3 and 4 can be expressed as a linear combination of the lines determining strategic interaction for buyers and sellers, since $(7-11h-4v)+6(1-2h-v)=13-23h-10v$. Therefore, at $v=0$ and $h=1/2$, the passage from *NC* to *HC* does not change sellers' R&D, but decreases buyers' R&D, therefore total R&D decreases. On the line separating regions 3 and 4, the passage from *NC* to *HC* increases sellers' R&D and decreases buyers' R&D by offsetting amounts.

complement, not a substitute, to *HC*.[24]

Many important results emerge from the preceding analysis. First, one of the basic results of the strategic investment literature is that cooperation between competitors increases (decreases) R&D when horizontal spillovers are high (low). The model shows that this result does not necessarily hold when vertical spillovers and vertical cooperation are taken into account. It is necessary to account for the horizontal, vertical, and diagonal internalization effects in comparing different types of R&D cooperation.

Second, even if all forms of cooperation do not always increase R&D compared with the *NCE*, in all cases, at least one form of cooperation does. The only form of cooperation always (strictly) dominating the *NCE* is *VC*. The question of whether cooperation is desirable or not has to be addressed with reference to specific cooperative schemes.

Third, no *TOC* constantly dominates the others. The relative efficiency of different *TOC* cannot be studied without explicit reference to appropriability. This suggests that optimal structures may vary *i)* across industries, *ii)* within the same industry, for different technologies having different appropriability characteristics, and *iii)* over time for a given industry, as technology changes.

Finally, comparing parts *a* and *e* of proposition 2 shows that there is an important asymmetry between *HC* and *VC*. *VC* is beneficial irrespective of the level of spillovers, whereas whether *HC* is beneficial depends on both horizontal and vertical spillovers. This is because the vertical internalization effect is always positive, while the horizontal internalization effect may be positive or negative.

The comparison between *TOC* has been performed in a bilateral duopoly case. A legitimate question is how sensitive are the results to this specific market structure. As the analysis to follow shows, market structure affects the size of the gap between R&D expenditures, and affects the tradeoff between horizontal and vertical cooperation. To answer that question, we perform the comparison between *TOC* for a more general market structure: $m=n\in[1,20]$. While it is possible to study this question for all levels of m and n within the space defined above, the *VCE* requires $m=n$. For the purpose of comparability between *TOC*, the analysis is restricted in this section to the case $m=n$. Moreover, in order to reduce the

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[24]This is in accord with the following quote by Jorde and Teece: "Successful new product and process development innovation often requires horizontal and lateral as well as vertical cooperation." (Jorde and Teece, 1990:81). Jorde and Teece (1992) note that horizontal and hybrid (horizontal + vertical) cooperative arrangements face a larger degree of uncertainty from US antitrust laws.

dimensionality of the problem, the analysis is restricted to polar appropriability environments: no spillovers ($h=v=0$), perfect spillovers ($h=v=1$), perfect horizontal spillovers only ($h=1, v=0$), and perfect vertical spillovers only ($h=0, v=1$). For brevity's sake let (h, v) represent appropriability conditions. For each polar case of spillovers, R&D is ranked across *TOC*, allowing for a variable market structure. Numerical simulations are used to compare (not to generate, therefore there is no loss of generality) elaborate analytical expressions.[25] While it is possible to compare directly the analytical expressions, numerical simulations make the presentation of results, and the comparison between different *TOC* much smoother. Figure 4 compares *TOC* for a given appropriability environment.[26]

The ranking of *TOC* at $m=n=2$ on figure 4 is consistent with proposition 2, and will not be discussed again. However, two important insights come from the analysis of a more general market structure. First, figure 4 illustrates an important distinction between horizontal and vertical cooperation in terms of the magnitudes of the increases and reductions in R&D investments (compared to the *NCE*) they cause. *VC* always increases R&D, while *HC* may increase or decrease R&D. However, when *HC* is beneficial, its benefits compared with the *NCE* are much larger than the benefits of *VC*, which are marginal. Formally, in general $|X^{HC}-X^{NC}|>|X^{VC}-X^{NC}|$. This is because the internalization of horizontal spillovers changes the sign of the externality, whereas the internalization of v merely reinforces its (always positive) effect, without changing its sign. Therefore, even though *VC* is always beneficial, it is generally only marginally so. In contrast, when *HC* is beneficial, its benefits are substantial.[27]

Second, as figures 4b and 4d show, when $h=1$, $X^{VC}=X^{HC}$ for $m=n=2$, but $X^{VC}<X^{HC}$ for all $m=n>2$. Therefore the result obtained above that in the bilateral duopoly case $X^{VC}\geq X^{HC}$ is heavily dependent upon market structure. With $m=n=2$, horizontal effects are negligible because of the small number of firms, and the two *TOC* yield equal amounts of R&D. However, as competition intensifies the importance of the horizontal externality increases, and *HC*, which internalizes this externality, gains in importance. To see that, note that in a market with $m=n$ firms in each industry, the number of terms constituting H is $2m(m-1)$, while the number of terms constituting V is $2m$. As m increases, the number of terms constituting H

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[25]Numerical simulations are based on the numerical parameterization specified in note 16.

[26]On figure 4 curves may overlap for some values of m and n. The labelling of curves corresponds to their ranking at $m=n=20$, but not necessarily to their ranking at other values of m and n.

[27]The same can be said about *GC*. Moreover, the dominance of the diagonal effect -which may induce cooperation between competitors to increase innovation even with a low h- on direct vertical effects can be seen from the large difference between X^{GC} and X^{NC}, compared with the small difference between X^{VC} and X^{NC}, on figure 4c.

grows much more rapidly (of course the magnitudes of the terms matter, but their number is indicative of the relative importance of the two effects). Thus, the model provides a preliminary answer to the question of which is more socially beneficial between horizontal and vertical cooperation. When horizontal spillovers are low, *VC* yields more R&D than *HC*. When horizontal spillovers are high, the result depends on market structure: *VC* tends to dominate when $m=n=2$, but *HC* yields more R&D for $m=n>2$ (moreover, with high concentration *HC* is more likely to lead to collusion, but this is outside the scope of the model).

This result shows the importance of analysing the effect of market structure on the relative desirability of different *TOC*. For instance, Steurs (1995), who studies spillovers and cooperation between demand unrelated industries, finds that whether interindustry cooperation is more or less beneficial depends on spillovers: interindustry cooperation is likely to be more beneficial than intraindustry cooperation when interindustry spillovers are high and intraindustry spillovers are low. Here, it is also true that interindustry cooperation is more beneficial when intraindustry spillovers are low. However, when intraindustry spillovers are high, the result depends on market structure.

A related question is how cooperation affects welfare. Overall there is a monotonic relation between R&D spending and welfare. A notable exception is when there are no spillovers, where firms tend to overspend on R&D compared with the social optimum[28] in the *NCE* and the *VCE*. Namely, firms overspend on R&D *i)* in the *NCE*, with no spillovers, $min\{m,n\}\geq 3$ or $\{m=2, n\geq 5\}$ or $\{m\geq 5, n=2\}$, and *ii)* in the *VCE*, $m=n\geq 3$ with no spillovers.[29] Consumer surplus is always higher than in the social optimum when there is overspending on R&D. However, one should be cautious before exaggerating the importance of overspending on R&D. First, the -static- modelization does not necessarily exhaust all the -static and dynamic- benefits of R&D. Second, empirical studies suggest that usually there is

[28]The social optimum could be defined with respect to the levels of output and R&D maximizing the sum of producer and consumer surplus. However, Suzumura (1990) questions the relevance of this "first best" outcome, since governments may have more latitude in affecting firms' R&D decisions than in affecting their output decisions. Suzumura adopts a "second best" concept of the social optimum, where welfare is maximized with respect to R&D, but not with respect to output. This second best social optimum concept is used here.

[29]This is not the first study to identify instances of overspending on R&D. Suzumura (1992) finds that firms overspend on R&D with no spillovers in the non-cooperative equilibrium (in a one-industry model) when the number of firms is large. Dasgupta and Stiglitz (1980) find that when demand is highly inelastic and that free entry is allowed, R&D spending may exceed the socially optimal level. Bester and Petrakis (1993), in a model of cost reduction with no spillovers, find that overinvestment in R&D may occur when goods produced by different firms are close substitutes.

underinvestment, not overinvestment, in R&D.[30] Third, the model shows that overspending occurs less often, and in smaller magnitudes, than underspending. Finally, although total welfare suffers from this overspending on R&D, consumers benefit from it.

Spillovers increase the social gains from cooperation. With high spillovers the *NCE* is more likely to be dominated by other *TOC*, whereas the *NCE* generally dominates (in terms of welfare, at least) without spillovers. Moreover, by analysing the gap between the *NCE* and the other TOC, we see that spillovers increase the value of cooperation, for they increase the inefficiency of the *NCE* compared with the social optimum (this is clear form figure 4).

The interactions between h and *HC* can be understood in terms of the business strategies taxonomy of Tirole (1989) (see table 3). When h is low and there is no *HC* or *GC*, firms adopt a *top dog* strategy: R&D investments make the investing firm look tough, by improving its competitive position. Moreover, in that case reaction functions between competitors are downward sloping,[31] and this increase in R&D by firm i reduces R&D by its competitors. When h is low and there is *HC* or *GC*, firms adopt a *puppy dog* strategy: each firm reduces its R&D investments, so as to be inoffensive, given that firms are cooperating.[32] In that case research efforts within industries are strategic complements, and this reduction in R&D reduces competitors' R&D as well. With high h and no *HC* or *GC*, firms adopt a *lean and hungry look*: because investments benefit competitors, firms underinvest to be tough. Given that in that case research efforts within industries are strategic complements, this underinvestment reduces competitors' R&D as well. Finally, with high h and *HC* or *GC*, firms adopt a *fat cat* strategy: they want to look inoffensive, given that they are cooperating; and the best way to achieve that is to invest heavily in R&D, which benefits competitors. And given that reaction functions are upward sloping in this case, this overinvestment is matched by overinvestment from competitors.

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[30] On the input side, Canada, for instance, devotes a relatively low proportion of its resources to R&D compared to most OECD countries. On the output side, studies typically find that the social rate of return on R&D is much higher than the private rate of return.

[31] It can be easily shown (when $m=n=2$) that in the *NCE* and the *HCE*, buyers' research expenditures are strategic substitutes iff $7>11h+4v$, and sellers' research expenditures are strategic substitutes iff $1>2h+v$. In the *GCE* and the *VCE*, buyers' research efforts are strategic substitutes iff $-71+182h-71h^2+40v+40hv+40v^2<0$ and sellers' research expenditures are strategic substitutes iff $-11+32h-11h^2+10v+10hv+10v^2<0$. These inequalities imply that horizontal and vertical spillovers induce strategic complementarity between competitors, and that buyers' research expenditures are more likely to be strategic substitutes than sellers' research expenditures. Moreover, research efforts between buyers and sellers are strategic complements in all *TOC*.

[32] As figure 4c shows, this result may be slightly altered by the presence of vertical spillovers.

Table 3- Business strategies, cooperation and spillovers

	HC or *GC*	*NC* or *VC*
Low *h*	puppy dog	top dog
High *h*	fat cat	lean and hungry look

6. Market Structure and innovation

The relation between competition and innovation can be affected by many factors. One such factor is the technological environment of the industry. In this model the technological environment is characterized by appropriability (horizontal and vertical spillovers) and R&D cooperation. We use the model to analyze how the technological environment affects the relation between competition and innovation. Moreover, by analysing the upstream and downstream simultaneously, one can assess how competition and technological opportunities in vertically related markets affect innovation. As Peters (2000:13) notes: "the conditions on vertically related markets also determine the innovative activities of firms".

For the sake of simplicity this analysis is performed for the four polar appropriability environments described in section 5: (0,0), (1,0), (0,1), (1,1). With four *TOC* and four appropriability environments, there are 16 different relations between market structure and R&D. These 16 different relations can be grouped under three types of relations, shown in figure 5. The vertical axis measures total R&D output, and the horizontal axes measure industry sizes.

Figure 5a depicts a positive relation between competition and R&D: both symmetric and asymmetric increases in competition increase R&D. I call this relationship the *Competitive model*, and refer to it as *C*. Figure 5b depicts a negative relationship between competition and R&D along the diagonal[33] as well as for asymmetric increases (except when at least one industry is highly concentrated, where the asymmetric effect may be positive). I call this relationship the *Schumpeterian model*, and refer to it as *S*. Figure 5c depicts a rather odd relationship between competition and R&D. A symmetric increase in the size of the two industries increases R&D; an asymmetric increase in *m* (holding *n* constant) increases R&D for low *n* and decreases R&D for high *n*; similarly, an asymmetric increase in *n* (holding *m* constant) increases R&D for low *m* and decreases R&D for high *m*. In this configuration, R&D

[33]Except from the move from a bilateral monopoly to a bilateral duopoly. This suggests that, even if it can be argued that competition may hinder innovation in some cases, any competition level less than a duopoly reduces innovation.

is maximized when the market structure is very asymmetric. I call this relationship the *Asymmetric model*, and refer to it as *A*.

Table 4 shows the correspondence between couples of cooperation and appropriability, and the relations described above. No row and no column gives uniformly the same result, implying that the effect of competition on R&D cannot be predicted without specifying *both* the appropriability conditions of the market and the prevailing type of cooperation. In the case of the *VCE*, the result is determined along the diagonal $m=n$, because asymmetric market structures are not allowed. Hence, for the *VCE*, an increasing R&D along this diagonal indicates either the relation *C* or the relation *A* (it is impossible to differentiate between the two), while a decreasing R&D indicates the relation *S*.

Note the following regularities. Comparing columns, we see that the *NCE* and the *VCE* yield the same results (subject to the impossibility of distinguishing between *C* and *A* under *VC*). Moreover, *GC* and *HC* yield closely related results, with the difference that *C* under *HC* is replaced by *A* under *GC*. Comparing rows, we see that the cases (1,1) and (1,0) yield similar results. Finally, note that *A* obtains only with *GC*.

Table 4 - Effect of competition on total R&D spending

	No cooperation	Generalized cooperation	Horizontal cooperation	Vertical cooperation
No spillovers (0,0)	C	S	S	C or A
Perfect horizontal spillovers No vertical spillovers (1,0)	S	A	C	S
Perfect vertical spillovers No horizontal spillovers (0,1)	C	A	C	C or A
Perfect spillovers (1,1)	S	A	C	S

C: Competitive; *S*: Schumpeterian; *A*: Asymmetric

The change in market structure can take two forms: a simultaneous increase in the number of firms in both industries, or an increase in the number of firms in one industry only. Consider first a simultaneous increase in the number of firms in the two industries. The result will be stated in terms of the horizontal competitive externality, *H*. Remember that *H* represents the sum of the marginal effects of a firm's R&D on the profits of its competitors; this externality is internalized in both the *HCE* and the *GCE*. *H* can be positive or negative, depending on whether an increase in R&D by a firm increases or decreases the profits of its competitors. In general, *H* is more likely to be positive the higher horizontal and vertical spillovers are.

Proposition 3. *Let $k=m=n>2$ (an increase in k is a north-east move along the diagonal in figure 5, and corresponds to a simultaneous and equal increase in the number of firms in the two industries). Let $h,v\in\{0,1\}$. Let $\lambda=1$ if there is intraindustry cooperation (HC or GC) and let $\lambda=0$ otherwise (NC or VC). Then*

$$sign(\partial X/\partial k) = sign(1+2v(1-h)-2|\lambda-h|).$$

This implies that:

3a. When $h=1$ or $v=0$ (the first, second, and fourth rows of table 4) $\partial X/\partial k$ is of the opposite sign of the horizontal competitive externality when that externality is not internalized, and is of the same sign as the horizontal competitive externality when that externality is internalized.

3b. When $h=0$ and $v=1$ (the third row of table 4), $\partial X/\partial k>0$.

The intuition is as follows. Consider first part *a* of proposition 3.[34] When a negative competitive horizontal externality is not internalized, R&D serves mainly as a competitive tool. Hence $\partial X/\partial k>0$: as competition intensifies, firms use more of this competitive tool (each firm's R&D declines, but total R&D increases). When the negative competitive horizontal externality is internalized, however, firms use R&D to increase the total size of the market, benefiting all from this expansion. However, they do not aim at hurting each other through R&D. Hence an increase in *k*, which increases the effects of the negative externality, reduces R&D. Similarly, when a positive competitive horizontal externality is not internalized, the main effect of R&D is to benefit competitors. Hence an increase in competition increases the effect of this positive externality on competitors, and R&D decreases. When this positive competitive externality is internalized, however, firms maximize the benefits from it as *k* increases, and total R&D increases.

Consider now part *b* of proposition 3. Because *v* is very large compared to *h*, its positive impact implies that $\partial X/\partial k>0$. Horizontal effects are still present, but small: when negative they are dominated by vertical effects; when positive they reinforce vertical effects.[35] It is specifically in this case that the effect of vertical spillovers on the relationship between competition and innovation is most explicit.

Note that whereas the effect of *h* depends on whether it is internalized or not, the effect

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[34]In these cases $sign(\partial X/\partial k)$ is determined solely by horizontal effects (which may be positive or negative); vertical effects (which are always positive) are always dominated by horizontal effects.

[35]The often positive effects of competition in this model should be qualified by the fact that the model does not incorporate fixed costs to R&D.

of v is independent of its internalization. This is because the internalization of h changes the sign of the externality, whereas the internalization of v merely reinforces its (always positive) effect, without changing its sign.

Proposition 3 dealt with the effects of symmetric increases in industry sizes. Consider now the effects of an asymmetric increase in industry size. The fourth column of table 4 is irrelevant here, because asymmetries are not allowed under *VC*. An asymmetric increase in competition has a positive effect on R&D under *C*, a generally negative effect under *S*, and an ambiguous effect under *A*. The asymmetric effects in the *C* and *S* model can be understood by using the same analysis as for symmetric increases in competition. With either $h=1$ or $v=0$, the effect of horizontal externalities dominates. Hence the effect of an asymmetric increase in industry size is of the same sign as the horizontal competitive externality if it is internalized, and is of inverse sign if that externality is not internalized. In the fourth case, (0,1), the result is determined by vertical effects, which are always positive.

The asymmetric effects under the *A* model can be understood in terms of the vertical and diagonal competitive externalities. As mentioned earlier, the asymmetric increase in industry size in this case has an ambiguous effect on R&D: it is positive when the other industry is highly concentrated, and negative when the other industry is highly competitive. This implies, as figure 5c shows, that R&D is maximized when one industry is highly concentrated, and the other is highly competitive. The reason for this asymmetric outcome is that in the *A* model, the fringe spends more on R&D relative to asymmetric market structures in the *C* or the *S* models. Indeed, in the *A* cases, when one industry becomes highly concentrated, the increase in total R&D comes mainly from the fringe, not from the concentrated industry. The intuition is as follows. The profits of firms in the concentrated industry are higher than profits of firms in the fringe. With *GC*, firms maximize joint profits. Firms in the concentrated industry benefit more from R&D by the fringe the higher spillovers are. With any type of spillovers present, and with *GC*, because of the large marginal profits of the concentrated industry, the fringe spends more on R&D, given that joint profits are maximized. Moreover, given diseconomies of scale in R&D, substantial collective benefits from R&D (high spillovers), and asymmetric market structures, total R&D costs are minimized when the fringe undertakes more R&D than the concentrated industry. In a sense, the fringe gets exploited by the concentrated industry, and it is happy to be so. Indeed, by comparing profits, we see that the ratio of profits of each firm in the concentrated industry to the profits of each firm in the fringe is highest with the Asymmetric model. With no spillovers, this effect does not arise, because the benefit of the concentrated industry from the fringe's R&D is more limited.[36] [37] The Asymmetric model obtains only with *GC*, because this is the only TOC internalizing simultaneously vertical and diagonal competitive externalities.

To summarize, the relation between competition and innovation can be understood in terms of the three competitive externalities. When *H* dominates, the effect of competition on innovation is of the same sign as that externality if it is internalized, and of the opposite sign if it is not internalized. When *V* dominates, the effect of competition is always positive. When *D* dominates (and that it is internalized), it is generally the Asymmetric model that prevails.

The effect of competition on innovation in a given industry cannot be fully understood without specifying the appropriability conditions and the cooperative relations in the industry as well as in adjacent industries. Teece (1992) suggests that "Discussions of the link between firm size and innovation are outmoded because the boundaries of the firm have become fuzzy", due to strategic alliances. Our model shows that strategic alliances can alter the relation between market structure and innovation, but in no way does the question become obsolete.

Changes in total R&D may hide important different sectoral effects. Upstream and downstream R&D expenditures may move in different directions. For instance, starting from a symmetric market structure, an equal increase in the size of the two industries increases the share of buyers in total R&D in the *NCE* and the *HCE*. With an asymmetric market structure each firm in the more concentrated industry spends more than each firm in the less concentrated industry.[38] A similar result is obtained by Peters (1995). The fruits of innovation by the (more) competitive industry accrue mainly to the oligopolistic industry, because of the

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[36]Peters (2000) finds that in the German automobile industry, a higher supplier concentration reduces (stimulates) R&D intensity if buyer markets are lowly (highly) concentrated. In the model studied here, the relation between competition and R&D intensity hinges on spillovers and R&D cooperation. An increase in the number of competitors of a firm increases (decreases) its R&D intensity when spillovers are high (low) in the *NCE* and the *VCE*. Spillovers have the opposite effect in the *GCE* and the *HCE*.

[37]Peters (2000) finds that in the German automobile industry, a small number of suppliers and a large stock of customers stimulate innovative activities. He interprets this outcome in terms of reduced risk for sellers from the opportunistic behaviour of buyers when the latter are in large number, and in terms of the positive effect of buyers' number on the potential utilization of the innovation and the speed of adoption of new technologies. The model proposes an alternative explanation: asymmetric market structures maximize innovative activities when there is generalized cooperation and there are spillovers.

[38]Poyago-Theotoky (1996) shows that the relation between firm size and cost reduction incentives hinges on the way R&D affects production costs. When costs are affected in an additive (multiplicative) way, large/low cost (small/high cost) firms spend more (these results were derived between competitors, with no vertical linkages).

limited market power of firms in the competitive industry.[39] This asymmetry in the distribution of the benefits of R&D is reinforced by, but does not require, vertical spillovers. Regarding the effect of spillovers, an increase in (either type of) spillovers increases the share of the more concentrated industry in the *NCE*, and reduces it in all other *TOC*.

7. Private incentives for cooperation

This section addresses the private incentives for cooperation.[40] The question is: under a decentralized negotiation mechanism, do firms, and under what circumstances, decide to cooperate? And when they do, do they choose the socially optimal type of cooperation? This question is important, because regulators need not provide incentives for R&D cooperation when cooperation arises from decentralized negotiations. Moreover, regulators need not prohibit cooperation when firms have no interest in cooperating. In some cases, however, incentives or prohibition may be necessary.

First firms' profits across different *TOC* are ranked based on numerical simulations. For the sake of simplicity, this analysis is performed in the case $m=n=2$. Tables 5 and 6 present the ranking of profits of buyers and sellers across *TOC* for different appropriability environments.

The comparison of profits shows that firms will always prefer to cooperate, even though they may have different preferences as to the choice of a *TOC*. Some forms of cooperation can cause losses to firms compared with the *NCE*. Buyers generally prefer the *HCE*, except when there are only vertical spillovers, in which case they prefer the *VCE*. Sellers always prefer the *GCE*. Buyers generally prefer *HC* to *VC*, whereas sellers, in contrast, always prefer *VC* to *HC*.

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[39] Terleckyj (1974) provides an illustration of this situation, where the productivity growth of the airline industry was mainly due to the introduction of quality aircraft by the (competitive) aircraft manufacturing industry. Vanderwerf (1992) finds that in the commodity materials-using production processes, more concentrated upstream firms are the source of more downstream innovations when upstream firms are more concentrated, and when downstream firms are less concentrated. This is consistent with the predictions of the model regarding the relation between concentration and R&D. Here, however, upstream firms cannot originate downstream innovations as such.

[40] Some studies endogenize the formation and the stability of research joint ventures (De Bondt et al., 1992; Poyago-Theotoky, 1995; Kamien and Zang, 1993; Eaton and Eswaran, 1997; Kesteloot and Veuglelers, 1995; Yi, 1998).

Table 5 - Ranking of buyers' profits (based on numerical simulations)

	No cooperation	Generalized cooperation	Horizontal cooperation	Vertical cooperation
No spillovers (0,0)	2	3	1	4
Perfect horizontal spillovers No vertical spillovers (1,0)	4	2	1	3
Perfect vertical spillovers No horizontal spillovers (0,1)	3	4	2	1
Perfect spillovers (1,1)	4	2	1	3

Table 6 - Ranking of sellers' profits (based on numerical simulations)

	No cooperation	Generalized cooperation	Horizontal cooperation	Vertical cooperation
No spillovers (0,0)	4	1	5	1
Perfect horizontal spillovers No vertical spillovers (1,0)	5	1	4	3
Perfect vertical spillovers No horizontal spillovers (0,1)	5	1	4	3
Perfect spillovers (1,1)	5	1	4	3

The explanation of these divergent preferences lies in the asymmetric distribution of R&D between the two industries. In this model there is a general tendency for buyers to spend less on R&D than sellers when there is no interindustry cooperation (i.e. under *NC* and *HC*). This tendency of upstream firms to do more R&D than downstream firms is rooted at the heart of the vertical market structure. It is a fundamental property of vertical structures with equal numbers of buyers and sellers that sellers' profits are always higher than buyers'. Moreover, the marginal effect of a dollar of R&D on profits is higher for sellers than for buyers. In a vertical market without R&D, with linear demand, constant marginal costs (but not necessarily equal between buyers and sellers), quantities as strategic variables, $m=n$, and $\alpha \equiv \pi_{bi}/\pi_{si}$, it is straightforward to verify that $\alpha=n/(n+1)$.[41] When R&D is added to the model the ratio becomes more complicated, but it remains true that $\alpha<1$ and $\lim_{n\to\infty}\alpha=1$. As $m=n$ grow the asymmetries in profits and in profits' sensitivity to changes in parameters become negligible, reducing the asymmetries in behaviour between buyers and sellers. Therefore, when taking their decisions independently from sellers (*NC* or *HC*), buyers spend less on R&D than sellers, because they

[41]The higher profitability of sellers does not hold for all strategic variables. For instance, when firms use a percentage mark-up rule for pricing, downstream firms make more profits (Irmen, 1997). Moreover, Choe (1998) shows that with a general demand, $\alpha=n/(n+1+\theta)$, where θ is the quantity elasticity of the slope of the retail demand function.

make less profits. With *VC* or *GC*, buyers are forced to take into account the effect of their R&D on sellers' profits, and this induces an increase in buyers' R&D, and a decrease in sellers' R&D.[42]

To illustrate this result consider the move from *HC* to *VC*. For all polar cases of spillovers, sellers gain from this move; and for all polar cases of spillovers except (0,1), buyers lose. The explanation is as follows. Consider first the case (0,0). In this case $x_{b\ i}^{HC}<x_{s\ i}^{HC}$, and $x_{b\ i}^{VC}=x_{s\ i}^{VC}$. Moreover, $x_{b\ i}^{HC}<x_{b\ i}^{VC}$ and $x_{s\ i}^{HC}<x_{s\ i}^{VC}$. These inequalities imply that R&D increases for all firms with the move from *HC* to *VC*, but increases more for buyers. This increase in total R&D triggers an output expansion. However, this output expansion is marginal, because the decline in the transfer price and in the final price are small. Moreover, the sellers' margin is higher, and they benefit more from this output expansion. Hence, buyers benefit less from this output expansion, and have to bear a larger increase in R&D costs than sellers. It turns out that the higher additional revenues of sellers are sufficient to cover their modest increase in R&D, but that the small increase in buyers' revenues is insufficient to cover their large increase in R&D. Therefore buyers' profits decline and sellers' profits increase in the passage from *HC* to *VC* with spillovers (0,0).

Consider next the cases (1,0) and (1,1). In these cases $x_{b\ i}^{HC}<x_{s\ i}^{HC}$, and $x_{b\ i}^{VC}=x_{s\ i}^{VC}$. However, $X^{VC}=X^{HC}$. Hence total R&D remains unchanged but buyers increase, and sellers decrease, their R&D. The size of the market is hardly affected, and buyers have to spend more on R&D. Naturally, their profits fall compared to *HC*, while sellers, who reduce their R&D, see their profits increase.

Finally, this result does not obtain in the case (0,1). In this case, the importance of v relative to h makes *VC* beneficial to all firms. And given that h is very low, *HC* is not particularly attractive.

Buyers' lower innovation is a consequence -not a cause- of their lower profitability, which is due to the structure of the output market. By cooperating on technology with sellers, buyers are attacking the symptom rather than the cause of their inferior position. Technological cooperation, while it increases buyers' innovation, reduces their profits, because it forces them to align their innovation rate on more innovative, more powerful, and more profitable firms. Total profits increase with cooperation, but the redistribution of profits is in favour of sellers

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[42]This explains also why in all cases where buyers prefer *HC* to *VC*, they prefer *GC* to *VC*: *GC*, while implying some form of vertical cooperation, also incorporates horizontal cooperation.

and at the expense of buyers. This result illustrates how firms seeking technological agreements to solve deeper problems may exasperate these problems instead of alleviating them.

Using firms' profits, the stability of cooperation is now analysed. We look for the *TOC* which firms would agree upon for each appropriability environment. This game can be seen as an initial stage being played before the three-stage game involving R&D, upstream output, and downstream output, is played. The strategies at this stage are *TOC*. Each industry chooses a *TOC*, given appropriability. If the two industries agree on a *TOC*, this setting is implemented. If no *TOC* constitutes a Nash equilibrium, the *NCE* is implemented.[43] There are four games, one for each appropriability environment. The payoffs are based on profit rankings as presented in tables 5 and 6. Table 7 indicates those *TOC* which form Nash equilibria in each game (each row represents a game). Only pure strategies are considered. In order to compare firms' preferences to social preferences, table 8 presents the ranking of welfare levels.

In the two games with (1,1) and (1,0), all *TOC* form Nash equilibria. Although optimal *TOC* could arise in a decentralised manner, there is no guarantee that they will. With no spillovers, the only Nash equilibrium is the *NCE*. As table 8 shows, in this case $W^{VC} > W^{NC}$: the optimal *TOC* cannot be decentralized. Finally, with vertical spillovers all *TOC* constitute Nash equilibria, except the *GC*. It happens that, as table 8 shows, this is the optimal *TOC* in this case.

Table 7- Nash equilibria

	No cooperation	Generalized cooperation	Horizontal cooperation	Vertical cooperation
No spillovers (0,0)	*			
Perfect horizontal spillovers No vertical spillovers (1,0)	*	*	*	*
Perfect vertical spillovers No horizontal spillovers (0,1)	*		*	*
Perfect spillovers (1,1)	*	*	*	*

* An asterisk indicates a Nash equilibrium

[43] A complete stability analysis would require the study of the incentives of each firm and each possible coalition of firms to deviate, in each situation. Given that there are four strategies (*TOC*), four games (appropriability environments), and two types of firms, this would be exhaustive. Instead, stability is studied at the industry level: firms within a given industry always play the same strategy. Moreover, in principle, it would be possible to have asymmetric strategies. For instance, one industry could choose horizontal cooperation whereas firms in the other industry prefer not to cooperate among themselves. However, the payoffs presented in tables 5 and 6 are based on symmetric choices of cooperation, and this case is therefore not considered.

Table 8- Ranking of welfare levels (based on numerical simulations) ($m=n=2$)

	No cooperation	Generalized cooperation	Horizontal cooperation	Vertical cooperation	Social optimum
No spillovers (0,0)	3	4	5	1	1
Perfect horizontal spillovers No vertical spillovers (1,0)	5	2	4	3	1
Perfect vertical spillovers No horizontal spillovers (0,1)	4	2	5	3	1
Perfect spillovers (1,1)	5	2	4	3	1

Many observations can be made based on the preceding strategic interaction analysis. First, multiple equilibria arise in all appropriability environments, except when there are no spillovers. Second, the *NCE* is always an equilibrium, even when there exist other equilibria which are more profitable to both buyers and sellers. By comparing the results of table 7 with those of table 8 (welfare ranking), we see that the decentralized equilibria may diverge largely from those *TOC* which are socially desirable. Firms are often caught in a prisoner's dilemma situation. Third, the divergence between sellers' and buyers' interests shows the importance of the bargaining process in R&D cooperation. Any form of asymmetry between firms can induce them to have different preferences with respect to cooperative settings. This negotiation dimension is often neglected in the theoretical study of R&D agreements.

Early studies of strategic R&D concluded from the social benefits of cooperation that R&D support by the government is desirable. Later, some authors argued that because cooperation is also privately beneficial to firms, public intervention is not necessary.[44] In the stability analysis it was shown how the profitability of some cooperative settings was not sufficient for them to arise as a result of decentralized negotiations. Conversely, cooperation settings benefiting firms do not always benefit society. Our analysis shows that the outcome of negotiation between asymmetric firms may result in something that is both socially and privately inferior. Government intervention on this dimension will be justified when private incentives (of both parties, or of the party capable of imposing its preferred *TOC*) diverge from the second-best alternative.

Table 7 shows that with no spillovers firms have no incentives to cooperate. Hence, not

[44]For instance, Steurs assumes that convergence between profitability and welfare is sufficient: "the type of cooperative agreement which is preferred by the firms because it results in the highest profitability, typically also results in the highest total welfare." (Steurs 1994:88). In the same spirit, Leahy and Neary (1997) argue that increased profitability to all firms from cooperation is sufficient to induce cooperation.

only does a strict patent policy reduce the diffusion of the innovation, but it also makes cooperative R&D less attractive to firms. The model is consistent with the high rate of R&D cooperation in Japan, since it predicts an inverse relation between appropriability and R&D cooperation.[45][46]

8. Conclusions

This paper focussed on vertical interindustry spillovers and vertical R&D cooperation between firms. Whereas horizontal spillovers may increase or decrease innovation and welfare depending on prevailing cooperation types, vertical spillovers always increase them. Cooperative settings were compared in terms of R&D. It was shown that no type of cooperation uniformly dominates the others. The type of cooperation yielding more R&D depends on horizontal spillovers, vertical spillovers, and market structure. The ranking of cooperative structures hinges on the signs and magnitudes of three competitive externalities (vertical, horizontal, and diagonal) which capture the effect of the R&D of a firm on the profits of other firms. The type of cooperation inducing firms to internalize a larger positive sum of competitive externalities yields more R&D. In particular, one of the basic results of the strategic investment literature is that cooperation between competitors increases (decreases) R&D when horizontal spillovers are high (low); the model showed that this result does not necessarily hold when vertical spillovers and vertical cooperation are taken into account.

A theory of innovation and market structure was proposed: it was shown that the effect of competition in one industry on total innovation depends on horizontal spillovers, vertical spillovers, cooperative settings, and competition in the other industry. The relation between competition and innovation can be understood in terms of the horizontal, vertical, and diagonal competitive externalities. When the horizontal competitive externality dominates, the effect of competition on innovation is of the same sign as that externality if it is internalized, and of the opposite sign if it is not internalized. When the vertical competitive externality dominates,

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[45] As Baumol notes: "with little protection available from the patent system, Japanese innovators appear to have been driven to create profitable technology-sharing agreements with competitors and others" (1997:19).

[46] A drawback to this analysis of the incentives for cooperation is its overlooking of the high transaction costs of R&D cooperation. R&D production, R&D cooperation and, more generally, knowledge, are characterised by high transaction costs. These are the costs of building and maintaining multi-firm cooperation, of leakage of information about technology and about strategies behind the technology, and of monitoring opportunistic behaviour (Fransman, 1990). For a discussion of the high transaction costs associated with knowledge and R&D, see Lee (1994). Moreover, different types of cooperation may have different transaction costs (I thank Michel Patry for this insight): one would expect that the hazards of horizontal cooperation are more important than the hazards of vertical cooperation.

the effect of competition is always positive. When the diagonal competitive externality dominates (and that it is internalized), it is generally the Asymmetric model that prevails.

Finally, the analysis of the private incentives for cooperation showed that buyers and sellers have different preferences over cooperative settings: sellers prefer vertical cooperation, whereas buyers (generally) prefer horizontal cooperation. Higher spillovers increase the likelihood of cooperation, but the multiplicity of equilibria makes the decentralized choice of socially optimal cooperative settings uncertain.

An important question that arises in the study of vertical vs. horizontal cooperation and spillovers is their relative importance for firms' innovation and production decisions. The model suggests that horizontal spillovers have more impact on firms' decisions than vertical spillovers. A corollary is that horizontal cooperation, which internalizes those horizontal externalities, has more impact than vertical cooperation. For instance, when both types of spillovers are present, the effects of horizontal spillovers tend to dominate those of vertical spillovers. Also, in general, a change in the level of vertical spillovers affects the results quantitatively, while a change in the level of horizontal spillovers can affect the results both qualitatively and quantitatively. Moreover, vertical cooperation is (almost) always beneficial, but it increases R&D only marginally relative to the non-cooperative equilibrium; whereas horizontal cooperation can increase or decrease R&D, but always significantly relative to the non-cooperative equilibrium. These observations are (generally) verified in figure 4 (comparison of types of cooperation), table 4 (market structure effects), tables 5 and 6 (buyers' and sellers' profits), and table 8 (Nash equilibria). This difference can be explained by the fact that the vertical competitive externality, even when it is not internalized, benefits the innovating firm because of the reduction in the total production cost of the final product. In contrast, the horizontal competitive externality does not always benefit the innovating firm: this depends on its sign, and its internalisation.

The identification of different types of interindustry spillovers is important for the empirical study of technology flows. Empirical studies have typically classified R&D spillovers into two types: interindustry and intraindustry spillovers. The contrast of some of our results with Steurs (1994,1995) -who studies spillovers between demand unrelated industries- shows the necessity to distinguish between spillovers between vertically related industries and those between demand unrelated industries, in addition to the classical distinction of intraindustry/interindustry spillovers.

The study of R&D cooperation and of the protection of innovation inevitably raises important science and technology policy issues. Carefulness is required in drawing policy recommendations from this model because it abstracts from many real world issues, especially asymmetric information between policymakers and firms. Nonetheless the model provides some reflections on R&D policy from the point of view of the incentives for cooperation, mergers, and vertical integration.

The model argues for a customized policy toward R&D, as opposed to across the board standardized R&D policies. The optimal R&D policy varies according to horizontal spillovers, vertical spillovers, and the prevailing type of R&D cooperation. Levin et al. (1987:816) reached a similar conclusion when they noted that "the incremental effects of policy changes should be assessed at the industry level". They further note that the impact of innovation protection depends on the extent of other appropriability mechanisms, which are industry specific.

Beyond traditional R&D policy tools, the model suggests that the choice of cooperative settings and of incentives to cooperation, taking appropriability into account, is crucial for the determination of R&D levels and distribution. This approach should be seen as a complement, rather than as a substitute, to traditional policy leverages.

The model predicts that spillovers increase the gains -to firms and to society- from cooperation, so it can be argued that higher spillovers should induce more R&D incentives. However, spillovers also increase the likelihood that firms will cooperate: when spillovers are high, many or all *TOC* constitute Nash equilibria, and one could hence argue that firms would cooperate because it is profitable for them to do so. On the other hand, with multiple equilibria, there is no guarantee that firms will choose cooperation over no cooperation, or that they will choose the socially optimal type of cooperation.

The interpretation of the choice of *TOC* should be broader than the special cooperative settings studied here. In the model different combinations of vertical and horizontal cooperation were considered. However, cooperation has many other dimensions. The same basic problem arising here with respect to the choice of the -privately or socially- preferred types of cooperation is expected to arise, at a much larger scale, when all the richness of cooperative settings is considered: choice of research projects, extent of cooperation, information sharing, enforcement mechanisms, intellectual property rights, etc. This gives the government a larger scope for intervention.

The model emphasized the vertical dimension of innovation, in terms of vertical R&D

spillovers and vertical R&D cooperation. Geroski (1992) has made a clear call for more focus on the role of vertical relations, and perhaps less on horizontal relations, which can lead to collusion on the output market. Vertical cooperation does not bring with it all the potentially anti-competitive effects of horizontal research joint ventures.[47] Moreover, vertical cooperation may require less incentives than horizontal cooperation, for it is easier to induce firms into cooperating with suppliers/distributors than into cooperating with competitors.

The results have implications for merger analysis. Mergers usually entail the use of R&D -in addition to output- to maximize joint profits. Economists have tended to focus on the output effects of mergers; more attention needs to be drawn to the innovation effects of mergers. The results show that the innovation effects of horizontal mergers, apart from any output distortions, depend on the level of horizontal spillovers. Depending on the appropriability conditions and the type of R&D cooperation prevailing before the merger, the merger may reinforce or mitigate the negative effect of output reduction by increases or reductions in innovation. For instance, regulators should be severe regarding mergers where output decisions are joint but where R&D decisions remain separate. The innovation effects of vertical mergers also need to be considered: vertical integration makes vertical R&D cooperation intrinsic to the structure of the firm, thus increasing R&D.

The model has many possible extensions. An important type of vertical cooperation that has not been addressed by the paper is vertical cooperation when the upstream sector is the developer of the innovation and the downstream sector is the user of the innovation. It was assumed that upstream and downstream firms conducted the same type of research. In real markets, downstream firms are closer to the final user, and may be engaged in more applied research, whereas upstream levels may be conducting more fundamental research. Insofar as appropriability problems are thought to be more severe in basic research than in applied research (Arrow, 1962), spillovers between suppliers may be higher than spillovers between buyers. This in turn may affect the symmetry of vertical spillovers assumed in this paper. Finally, when the levels of concentration in the upstream and downstream industries are very different, vertical cooperation takes place between firms of different sizes, and therefore of

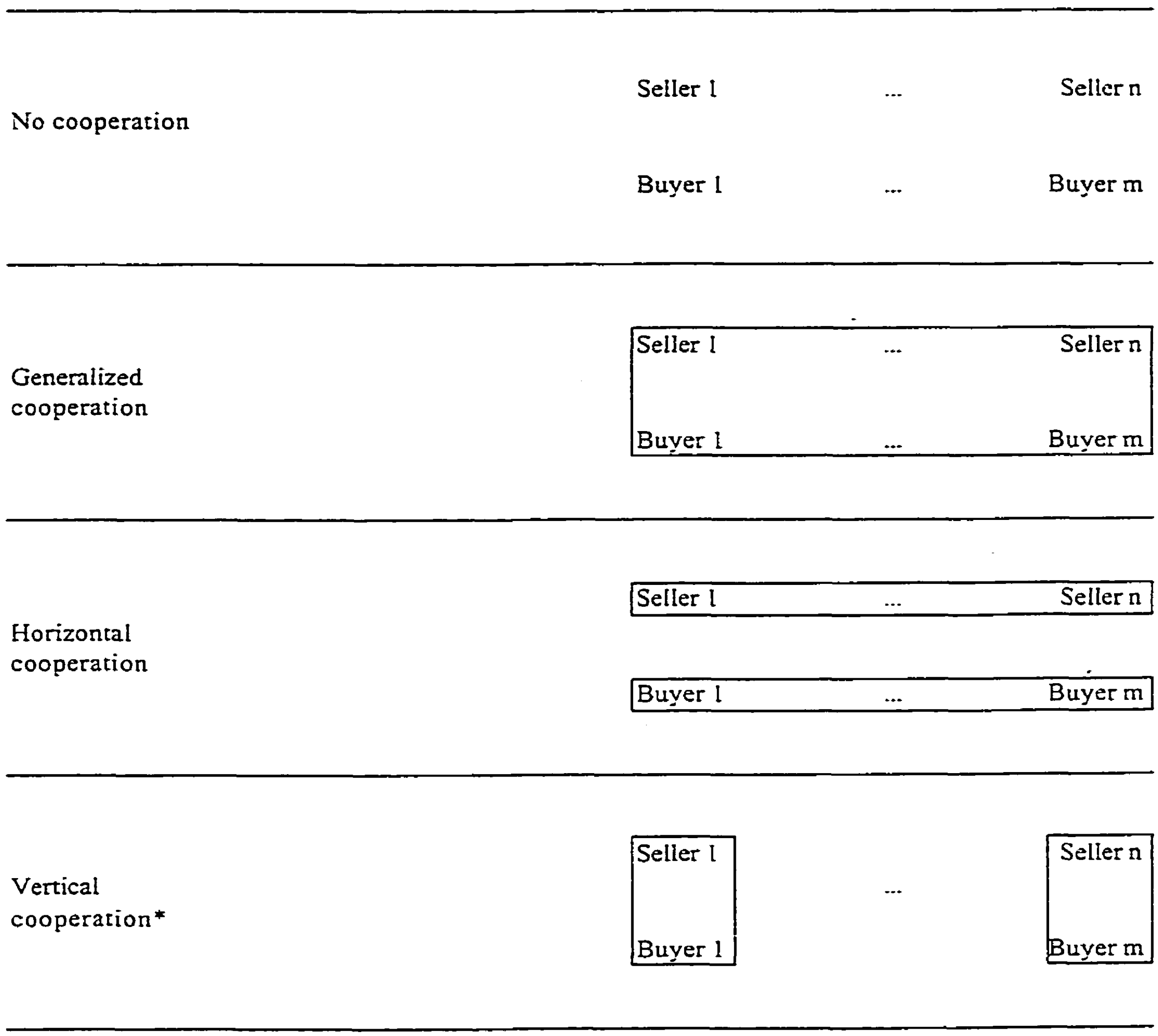
[47] Examples are production of a technology of the lower common denominator (Dodgson, 1994), reduction in the diversification of research paths, barriers to entry, elimination of competitors, output collusion, and collusion to control the technological cycle.

different technological, financial, and managerial capabilities.[48]

[48]This is the case, for instance, within SEMATECH (the Semiconductor Manufacturing Technology Consortium), where large semiconductor firms cooperate with small semiconductor materials and equipment suppliers.

Figure 1

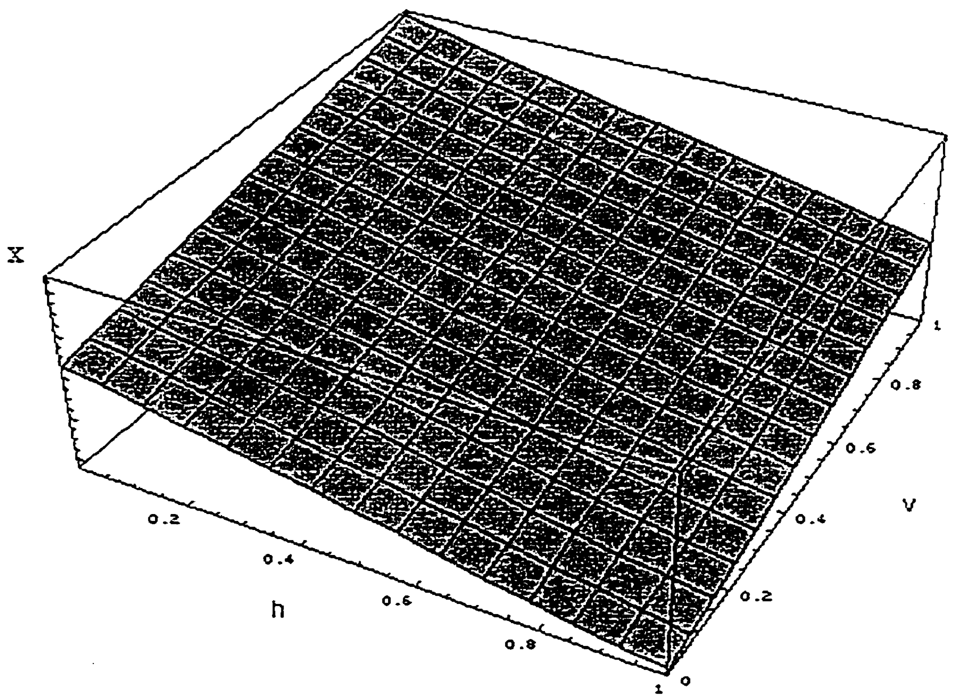
Types of cooperation (TOC)



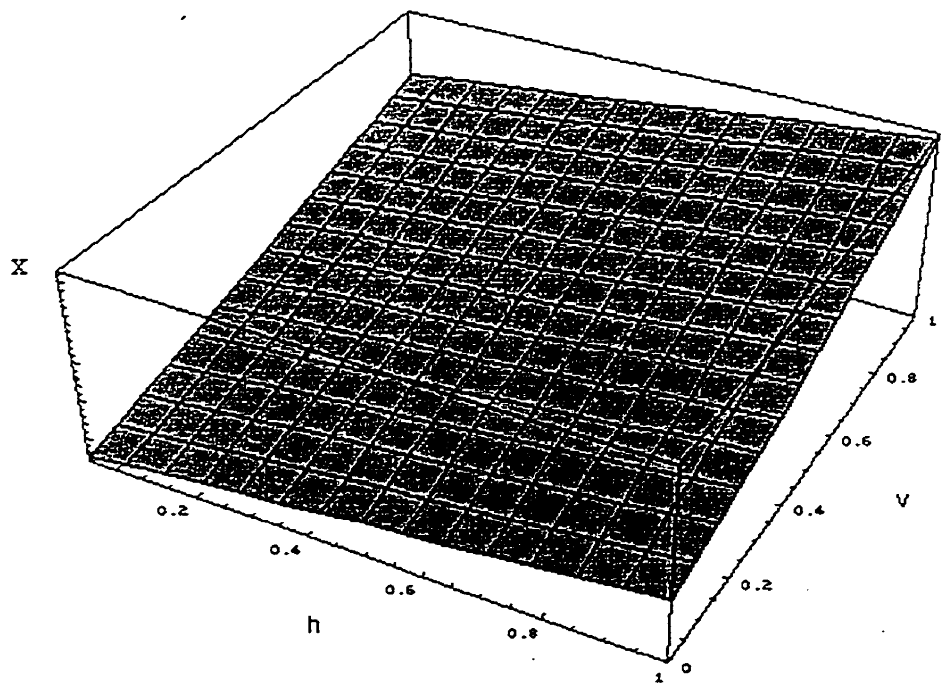
A block represents a group of cooperating firms

* With vertical cooperation, where each buyer cooperates with one seller, symmetric strategies require imposing the restriction m=n.

Figure 2
Effects of spillovers on R&D

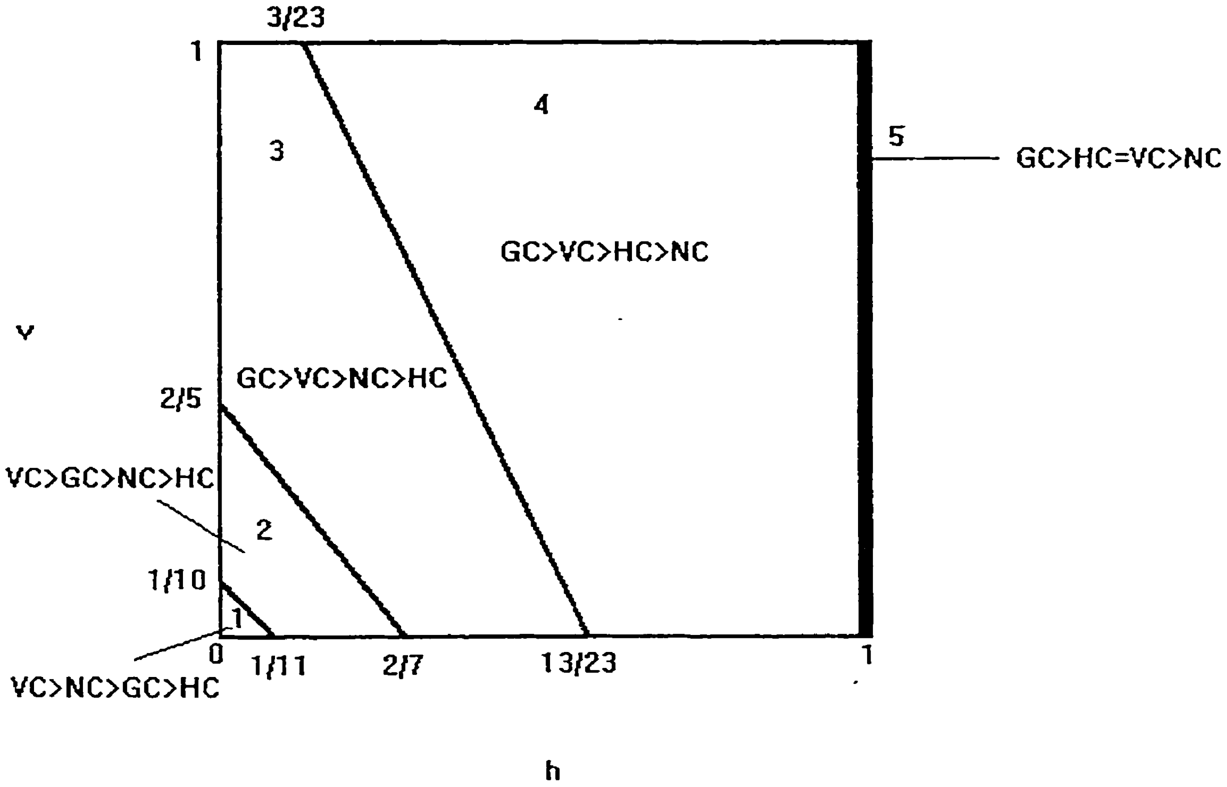


2a
No cooperation
and
Vertical cooperation



2b
Horizontal Cooperation
and
Generalized Cooperation

Figure 3
Effect of cooperation on R&D (m=n=2)



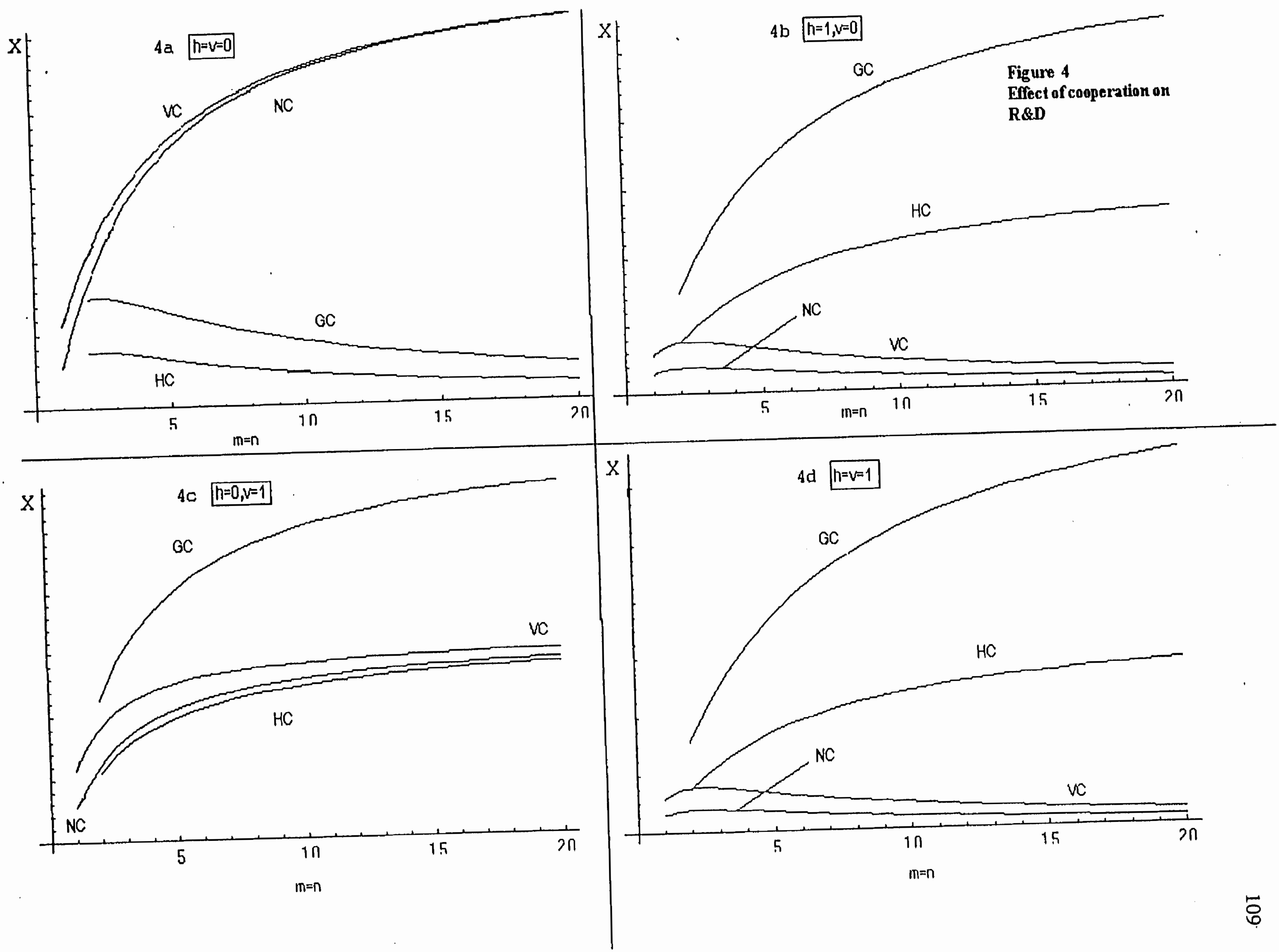
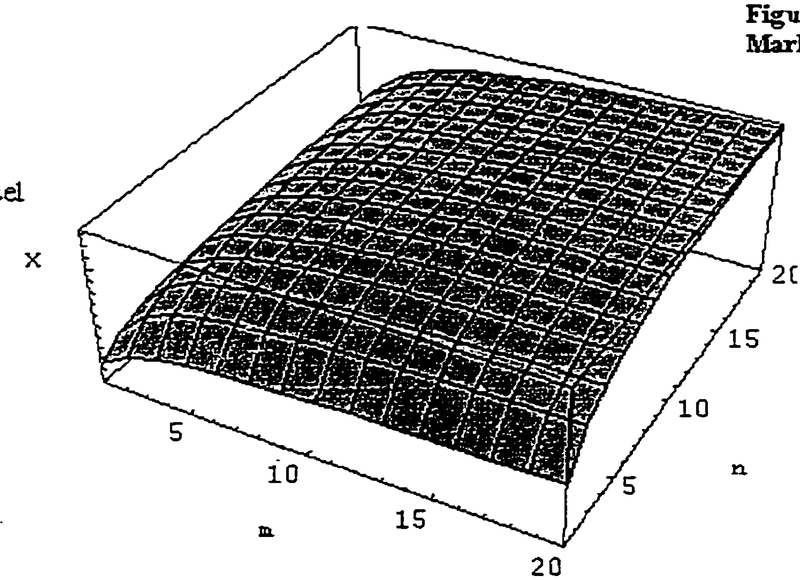


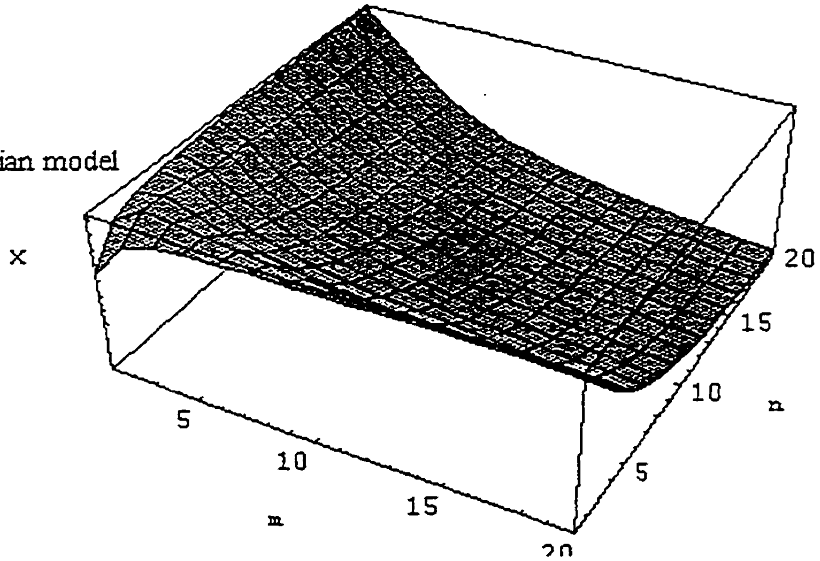
Figure 4
Effect of cooperation on R&D

Figure 5
Market Structure and Innovation

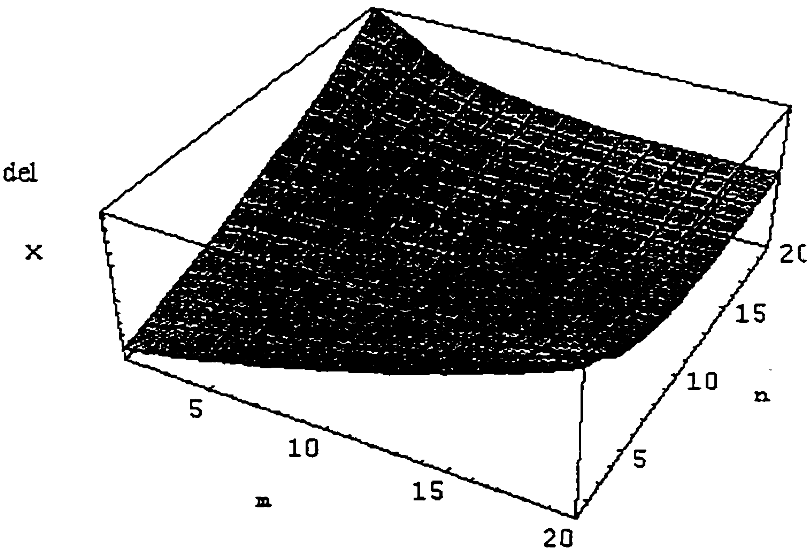
5a
The Competitive model



5b
The Schumpeterian model



5c
The Asymmetric model



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INFORMATION SHARING AND THE STABILITY OF COOPERATION IN RESEARCH JOINT VENTURES

1. Introduction

R&D cooperation incorporates three dimensions: the coordination of R&D expenditures, information sharing, and the stability of the cooperative venture. The coordination of R&D expenditures induces firms to internalize innovation externalities. Information sharing increases R&D spillovers between cooperating firms. The instability of cooperation arises because cartels are vulnerable to individual and coalitional deviations.

A large theoretical literature on R&D cooperation and competition now exists, starting with the seminal paper of d'Aspremont and Jacquemin (1988). Most of this literature has focussed on the coordination of R&D spending, with little attention being devoted to the information sharing dimension, or to the stability of cooperation. Generally, information sharing and Research Joint Venture (RJV) formation have been analysed separately. Typically, the extent of information sharing has been assumed exogenously, and cooperation has been assumed to be industry-wide. However, important interactions between information sharing and RJV formation arise. The level of information sharing affects the attractiveness of the cooperative venture to outsiders, and also affects the willingness of cooperating firms to admit additional members. A thorough understanding of R&D cooperation requires the study of the interactions between information sharing and RJV formation. This paper attempts to remedy this gap by studying the endogenous determination of information sharing, together with endogenous RJV formation.

Two approaches coexist in the literature regarding information sharing. The first assumes that information sharing is not affected by cooperation, in which case cooperating firms simply coordinate R&D expenditures (De Bondt et al., 1992; Kamien et al., 1992). The second assumes that cooperating firms share all of their research results (Kamien et al., 1992; Poyago-Theotoky, 1995). Both assumptions are arbitrary, and lack theoretical as well as empirical foundations. While it is reasonable to assume that information sharing is improved by cooperation, there is no foundation for the assumption of perfect information sharing.

Spillovers can be endogenous in two (non-exclusive) ways. First, by investing in learning and improving their absorptive capabilities (Cohen and Levinthal, 1989; Adams, 2000), firms can increase the effective information they receive from other agents. Second, by affecting how much information leaks out, firms can impact the level of outgoing spillovers. Ultimately, therefore, a flow of information is affected by the behaviour of both the source and the destination of the information. This paper focusses on the control of firms over outgoing spillovers.

Consider next the question of industry-wide cooperation. Studies have typically assumed that all industry members participate in the RJV. Among the few studies that have endogenized the cooperation decision are De Bondt et al. (1992), Poyago-Theotoky (1995), Kamien and Zang (1993), Eaton and Eswaran (1997), Kesteloot and Veuglelers (1995), and Yi (1998). However, in all of these studies, while the size of the cooperative venture(s) is endogenous, information sharing is exogenous.

Only De Bondt and Wu (1997) and Katz (1986) have addressed jointly RJV stability and information sharing. De Bondt and Wu (1997) study an R&D cooperation model with insiders/outsiders. The effect of different levels of information sharing is addressed, although information sharing remains exogenous. They find that an industry-wide RJV quickly becomes stable for relatively low levels of information sharing.

Katz (1986) is the only paper that simultaneously endogenizes information sharing and RJV formation. In his model, firms decide on their RJV membership, R&D cost sharing and information sharing rules, R&D expenditures, and output. The model shows that cooperation is beneficial when product market competition is low, when spillovers are important, and when cooperation improves information sharing. With industry-wide cooperation, full information sharing is adopted. The conditions for the emergence of industry-wide cooperation are characterized. However, the model focuses on polar cases: no exogenous spillovers, and either industry-wide or no cooperation.

In the model studied here both information sharing and participation in the RJV are endogenous. In a four-stage game-theoretic model, firms decide on participation in a RJV, information sharing, R&D expenditures, and output. There are two types of exogenous spillovers: those affecting all firms, and those from the RJV to outsiders. Moreover, RJV members may decide to share information among themselves. An important feature of the model is that voluntary information sharing between cooperating firms increases information leakage from the RJV to outsiders. The underlying argument is that sharing information increases the likelihood that this information leaks out to third parties.

It is found that it is the spillover from the RJV to outsiders that determines the decision of insiders whether to share information or not, while it is the spillover affecting all firms that determines the level of information sharing within the RJV. Larger RJVs are more likely to share information. This result shows the importance of the interaction between RJV size and information sharing. It is also found that when sharing information is costless firms never choose intermediate levels of information sharing: they share all the information or none at all. The model predicts that the absence of information sharing is due to competitive impediments (leakage of information to non-RJV members), while intermediate levels of information sharing would arise as a result of other considerations: costs of sharing information, or limited compatibility of firms' technologies. The size of the RJV is found to depend on three effects: a coordination effect, an information sharing effect, and a competition effect. Depending on the relative magnitudes of these effects, the size of the RJV may increase or decrease with spillovers. Paradoxically, the size of the RJV may increase with the leakage from the RJV to outsiders. The effect of information sharing on the profitability of firms as well as on welfare is studied.

It is useful to review some empirical evidence showing that the assumptions of exogenous information sharing and of industry-wide cooperation are unsatisfactory. Some theoretical studies which have attempted to address these issues -albeit separately- are also briefly discussed.

Consider information sharing. R&D cooperation with and without information sharing is observed.[1] Branstetter and Sakakibara (1997) find evidence of increased knowledge spillovers within Japanese research consortia. They report that access to complementary knowledge of other RJV members is the most highly cited motive behind participation in research consortia by R&D managers. Mariti and Smiley (1983) studied 70 cooperative agreements between European firms that took place in 1980, and found that one way flows of information were behind 41% of agreements, while information sharing (two-ways flows of information) were behind 29% of agreements. Cassiman and Veugelers (1998), from the study of a sample of firms from the Belgian manufacturing industry, find that spillovers received by a firm tend to be higher when the firm engages in cooperative R&D, which is consistent with improved information sharing between cooperating firms. Adams (2000), from the study of a sample of R&D laboratories in the chemicals, machinery, electrical equipment, and transportation equipment industries, finds that learning expenditures increase in response to spillovers, which is an indication that spillovers are endogenous.

Imperfect information sharing may arise because of technical difficulties, differences

1.See Cassier and Foray (1999) for a discussion of the rules governing the sharing of research results in eight biotechnology research consortia.

in organizational culture, and strategic factors (De Bondt and Wu, 1997). The distinctive nature of the technologies of some firms may impose constraints on the extent of cooperation and information sharing with other firms (Uenhora, 1985). Firms also have discretion over how much information they effectively disclose. A firm can affect the spillover rate through the choice of the location of its laboratories, or by controlling the participation of its researchers in scientific conferences (De Fraja, 1990). Bhattacharya et al. (1992) report reluctancy on the part of some firms to send their best researchers to the RJV.

The regulation of information sharing can be found in the cooperative agreement itself. The US Department of Commerce estimates that one year is the minimum length of time required to reach agreement on the research agenda between cooperating firms (Link and Tancy, 1989). This shows the complexity of the negotiation mechanism behind research output sharing contracts. The European cooperative research programs Esprit and Race require cooperation and information sharing, while the program Eureka requires cooperation but not information sharing (Fölster, 1993).

Fransman (1990) addresses the issue of information sharing in terms of research facilities. He distinguishes between cooperative research where firms keep distinct research facilities -in which case the level of information sharing is low- and cooperative research where firms use joint research facilities -in which case we can expect higher levels of information sharing. Naturally, firms may want to maintain both types of cooperative agreements in parallel. In some cases, they may wish to share information more thoroughly with suppliers/distributors, and less with competitors. In Japan, separate research facilities between cooperating firms seem the norm, not the exception. There is evidence that the propensity to share knowledge is lower for commercializable devices, and when inter-firm competition is important (Fransman, 1990).

A number of studies have addressed the issue of technology sharing between competitors, without taking into consideration the interactions between information sharing and the stability of cooperation, however. d'Aspremont et al. (1996) consider the problem of bargaining over the disclosure of interim research knowledge in a R&D race for a patentable innovation between two firms. Katsoulacos and Ulph (1998a, 1998b) endogenize R&D spillovers taking into account distinctions such as whether firms are in the same industry or not, product versus process innovations, technical substitutability or complementarity, and information sharing versus research coordination. Poyago-Theotoky (1999) allows firms to choose the spillover level after R&D investments are undertaken in a duopoly; she finds that cooperating (non-cooperating) firms choose maximal (minimal) spillovers. Kamien and Zang (1998) allow firms to choose an "R&D approach" which determines how much the firm can benefit from other firms' R&D. Combs (1993) develops a model where R&D cooperation increases the probability of innovation by sharing information about research strategies and outcomes. De Fraja (1990, 1993) investigates whether firms have an incentive to disclose their research results or not. Rosenkranz (1998) studies firms' incentives to form RJVs in an incomplete information framework when technological know-how is private information; two firms first decide on cooperation and information revelation and then compete for a patent. Finally, Bhattacharya et al. (1990) develop a two-stage model where researchers may share endowments of productive knowledge in the first stage and choose R&D efforts independently in the second stage.

Some studies have focussed on the moral hazard dimension of technology sharing. Pérez-Castrillo and Sandonís (1997) study a model in which the disclosure of information makes the expected cost of the project lower. An RJV may fail to form because of the moral hazard problem arising from the difficulty of contracting upon the transfer of information. They find that penalties can alleviate the incentive problem and the individual rationality constraints. Bhattacharya et al. (1992) consider a three-stage model of R&D where firms can share knowledge prior to choosing unobservable R&D levels and competing in the product market. d'Aspremont et al. (1998) consider RJVs with adverse selection in knowledge sharing and moral hazard in private development efforts.

Consider now the second dimension, the stability of cooperation. The assumption of industry-wide cooperation (common in the literature) is at odds with empirical evidence. Most RJVs comprise only a subset of firms of a given industry. From the examination of 27 cooperative research agreements, Combs (1986) finds that in no case did the agreement include an entire industry. Industry-wide RJVs are generally directed at industry regulatory problems (Peck, 1986). Snyder and Vonortas (2000) find that many RJVs are constituted of a large number of firms; The MCC (Microelectronics and Computer Technology Corporation) research consortium included 21 participating firms. This makes the standard duopoly framework even less appropriate for the study of RJVs.

There are many reasons why one or more firms may decide not to participate in a RJV. Firms in an industry may take different technological paths, and may hence have more technological affinities with some firms than with others. Moreover, asymmetries between firms may lead some firms to opt out of the RJV. It may also be the case that the RJV is composed of more advanced firms in the industry, and that less advanced firms are not allowed in. In the same token, the RJV may be formed by technologically backward firms that are trying to catch up with the leaders, in which case the latter have no interest in participating in the RJV.[2] Firms may have different objectives and priorities with respect to the technological developments of their products. Some firms may prefer to stay out of the RJV and benefit from the research results of the RJV without sharing in the costs or providing information about its technology.[3] Antitrust authorities may pay more attention to cooperation between a large number of firms: an industry-wide RJV eliminates competition along the R&D dimension, which may lead to complacency in research efforts (Kamien and Zang, 1993). Finally, some firms may be more secretive about their R&D results, and refuse to participate in RJVs. It is then not surprising that in the real world, most RJVs involve only a subset of firms in a given industry.

De Bondt et al. (1992) study the stability of a RJV assuming that information sharing is not improved by cooperation, and that spillovers between the RJV and outsiders are symmetric. Poyago-Theotoky (1995) analyzes a model with spillovers where one RJV forms endogenously, assuming that cooperation entails maximal information sharing. Kamien and Zang (1993) study an industry where several competing RJVs form endogenously. Yi and Shin (2000) examine the endogenous formation of RJVs when many RJVs can form, and study the effects of exclusive membership versus open membership rules. Yi (1998) studies the stability of cost reducing joint ventures with exogenous cost reduction. Greenlee (1998) studies the stability of RJVs that share information but do not coordinate R&D expenditures; while information sharing in RJVs is imperfect, it remains exogenous. Kesteloot and Veuglelers (1995) study the stability of R&D cooperation in a two-firms repeated game model. Eaton and Eswaran (1997) study the formation of technology-trading coalitions with an infinite horizon.

The paper is organized as follows. The four-stage model is presented in section 2. The results are taken up in section 3 in terms of output and R&D, information sharing, cartel stability, technological diffusion, and profits and welfare. Section 4 concludes.

2.Branstetter and Sakakibara (1997) report that in Japan technology leaders are more reluctant to participate in some research consortia.

3.For instance, the research results of SEMATECH (the Semiconductor Manufacturing Technology Consortium) benefited members as well as non-members of the research consortium (Grindley et al., 1994).

2. The model

There are T identical firms selling a homogeneous output, whose inverse demand is given by $p=a\text{-}wY$, $Y=\sum_{i=1}^{T} y_i$, where Y is total output and y_i is firm i's output. The unit cost of firm i is

$$c_i(\Gamma_i) = r - x_i - f\sum_{j\neq i}^{T} x_j - \Gamma_i \tag{1}$$

The parameter r is the production cost per unit before cost reductions attributable to R&D spending. The variable x_i is the R&D output of firm i. One unit of R&D reduces the production cost to its producer by one dollar and reduces the production cost of each of the other firms by f dollars, $f\in[0,1]$ being an (involuntary) exogenous spillover level. Γ_i represents the effect of voluntary information sharing on the cost of firm i. Note that Γ_i represents information received by, not information divulgated by, firm i. The parameters are assumed to be such that costs are strictly positive, that is,

$$r > x_i + f\sum_{j\neq i}^{T} x_j + \Gamma_i \tag{2}$$

The profit of firm i is

$$\pi_i = [p(Y) - c_i(\Gamma_i)]y_i - ux_i^2 \tag{3}$$

where the dollar cost of x units of R&D is ux^2, $u>0$.

The game has four stages. In the first stage the size of the RJV, M, is determined endogenously. The number of firms outside the RJV is $N=T\text{-}M$. Only one RJV is allowed to form. In the second stage insiders decide on g, the level of information sharing within the RJV. In the third stage each firm decides on its R&D output, x_i. RJV members coordinate R&D expenditures to maximize their joint profits, while outsiders act noncooperatively. In the final stage firms compete noncooperatively à la Cournot.

The sequence of decisions is linked to the logical sequence of the formation of a real RJV. Before participating in the RJV, firms decide on its structure. Two important elements of this structure are the size of the RJV and the level of information sharing within the RJV. The former is likely to be agreed upon before the latter, for it will be only participants that decide on the level of information sharing.

The first stage is the determination of the size of the RJV. For simplicity's sake, the total size of the industry, T, is given. Players are ranked according to an exogenous rule of order. Because firms are identical, the profitability of the RJV depends only on its size, and not on the identity of its members. This is equivalent to an anonymity condition: each player's payoff depends only on the number of players who choose each strategy (insider/outsider).[4] It is assumed that insiders can block the entry of an additional firm if it reduces their profits.[5] An outsider will join the RJV only if this increases its profits, and is allowed by insiders. I define stability of the RJV as follows:

Definition. Let $\pi_i^m(z)$ represent the profit of an insider, and $\pi_i^n(z)$ represent the profit of an outsider when the RJV is of size z. Then a RJV of size M is stable iff, for $M \geq 2$,

$$\begin{aligned} &i)\ \pi_i^m(M) \geq \pi_i^m(M-1) \text{ and} \\ &ii)\ \pi_i^m(M) \geq \pi_i^n(M-1) \text{ and} \\ &iii)\ \pi_i^m(M) \geq \pi_i^m(M+1), \text{ or } \pi_i^n(M) \geq \pi_i^m(M+1), \text{ or both.} \end{aligned} \tag{4}$$

Condition *i* states that RJV members would not gain by eliminating a firm from the RJV. Condition *ii* states that no member wants to drop unilaterally from the RJV (internal stability). Condition *iii* states that either no outsider wants to join the RJV (external stability), or insiders would lose by allowing an additional firm into the RJV, or both. When more than one RJV size satisfy (4), (4) is re-applied to those RJV sizes, except that profits are compared between stable coalitions, not by considering individual deviations (since these have already been taken care off in (4)). When more than one RJV size yield exactly the same profits for insiders and the same profits for outsiders (and that both satisfy (4)), the largest of these RJV sizes is assumed to prevail.

The stability conditions used here are different from those usually adopted in the cartel stability literature. De Bondt et al. (1992) and De Bondt and Wu (1997) use a Nash stability concept, based on d'Aspremont et al. (1983), which relies exclusively on internal and external stability, allowing for free entry into the cartel. Shaffer (1995) addresses the entry-blocking capacity of the cartel, but her stability concept incorporates only conditions *i* and *ii*. Poyago-Theotoky (1995) uses an entry-blocking cartel, but considers the condition $\pi_i^m(M) \geq \pi_i^m(M+1)$ as necessary, while here it is not. The concept used here incorporates internal and external

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4. A common weakness of this approach to cartel stability is that, while it informs us about the stability of the cartel, it tells us very little about the process behind the formation of the cartel, or about the identity of its members.

5. For instance, Combs (1993) reports that members of the Microelectronics and Computer Technology Corporation vote to allow a firm to purchase shares in the venture.

stability, and goes further by allowing for entry-blocking by the cartel.[6]

We now turn to the second stage of the game, where insiders decide on information sharing. Cooperating firms may decide to share information beyond the basic spillover level, f. The cause to effect relationship between cooperation and spillovers is bidirectional: not only do spillovers affect the decision to cooperate, but also the decision to cooperate affects spillovers.[7] Let $g \in [0, 1-f]$ represent the level of voluntary information sharing within the RJV. The total (involuntary+ voluntary) information sharing level within the RJV is $f+g$.

There is an information leakage from the RJV to outsiders on voluntary information sharing within the RJV. It is the same information that is affected by voluntary information sharing and by exogenous spillovers, and the voluntary sharing in the first case is likely to affect the (involuntary) leakages in the second case. From the moment a firm decides to share some of its private information with one or more other firms , the firm takes the risk that this information may leak to third parties.[8] By transmitting the information to other RJV members, the probability of leakage increases.[9] While an in-house research project may be run in total secrecy, the very formation of a RJV and the type of research being performed is common knowledge, for it usually requires the government's approval. When RJV members know that their information sharing will increase spillovers to outsiders, they may wish to choose less than perfect information sharing. And outsiders, knowing this, will act strategically so as to benefit from this link.[10] The dependence of spillovers from the RJV to outsiders on information sharing, which is endogenous, makes those spillovers themselves endogenous to the model.

Let $k \in [0,1]$ represent the leakage factor from the RJV to outsiders on voluntary

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6.RJVs are generally short-lived. Kogut (1989) shows that joint ventures are highly unstable. This instability is often due, in his words, to "business failure or a fundamental instability in governance." He finds that the stability of a joint venture increases with its R&D intensity. Bureth et al. (1997) note that the knowledge produced by pre-competitive research agreements (such as the one studied here) is highly generic and abstract, which reduces the cost of breaking with the cartel, thereby increasing instability.

7.Colombo and Garrone (1996), in their study of R&D and cooperation behaviour of 95 US, European, and Japanese firms, find that feedbacks between internal R&D and the participation in cooperative R&D agreements exist, and hence neither dimension can be considered exogenous with respect to the other.

8.For instance, Mansfield (1985) finds that information on a new product or process is divulgated on average one year after its discovery.

9.Cassiman and Veugelers (1998) find that cooperating firms have lower outgoing spillovers. However, that result is weakened by the fact that the data used gives information only on whether a given firm cooperates in R&D or not, without evidence on the extent of cooperation or on the nature of the cooperative agreement. Moreover, the data does not allow the separation of spillovers to and from partners versus non-partners. Also, they do not explain what mechanisms cooperating firms use to reduce outgoing spillovers, or why such mechanisms are not used by noncooperating firms.

10.Even if the spillover on voluntary information sharing is high, outsiders may still suffer because of the lead time advantage of insiders. This advantage seems important, for instance, in the Microelectronics and Computer Technology Corporation RJV (Peck, 1986).

information sharing. The total spillover level from the RJV to outsiders is $f+kg$. Hence there are three types of spillovers: an exogenous spillover level applicable to all firms (f), an endogenous spillover level applicable within the RJV (g), and an exogenous spillover level from the RJV to outsiders (k). Figure 1 shows information flows. The following inequalities must hold: $0 \leq f \leq f+kg \leq f+g \leq 1$.

Let M be the number of RJV members (to be determined endogenously in the first stage), and let N be the number of outsiders, $M+N=T$. Without loss of generality assume that the first M firms join the RJV, while the other N firms remain outsiders. The following notation will be used to represent R&D output:

$X^m \equiv \sum_{i=1}^{M} x_i^m$ (Total R&D output of the RJV)

$X_{-i}^m \equiv X^m - x_i^m$

$X^n \equiv \sum_{i=M+1}^{T} x_i^n$ (Total R&D output of outsiders)

$X_{-i}^n \equiv X^n - x_i^n$

$X \equiv X^m + X^n$ (Total R&D output)

$X_{-i} \equiv X - x_i$

We now define Γ_i. The information received by firm i, Γ_i, can take two values, depending on whether the firm is an insider or an outsider.

$$\Gamma_i^m \equiv gX_{-i}^m, \qquad i=1,\dots,M$$

$$\Gamma_j^n \equiv kgX^m, \qquad j=M+1,\dots,T$$

Insiders benefit the most from voluntary information sharing if they receive more information than outsiders, that is, if $\Gamma_i^m > \Gamma_j^n$. It is useful to examine under what circumstances this inequality holds. Assume for this purpose that $x_{M+1}^n = \dots = x_T^n$, $x_1^m = \dots = x_M^m$ (this will be shown to hold in equilibrium). Then it is immediate that $\Gamma_i^m > \Gamma_j^n$ if and only if

$$M > \frac{1}{1-k} \tag{5}$$

We see that insiders are more likely to benefit from information sharing (by insiders) more than outsiders the larger the RJV, and the lower k is. The relation does not depend on g. Also, it is neither sufficient nor necessary for insiders to spend more on R&D in order to benefit more from voluntary information sharing.

On substituting Γ_i^m and Γ_j^n into (1) we obtain the unit costs of outsiders and insiders

$$c_i^m = r - x_i^m - (f+g)X_{-i}^m - f X^n, \qquad i=1,...,M$$
$$c_j^n = r - x_j^n - f X_{-j}^n - (f+kg)X^m, \qquad j=M+1,...,T \tag{6}$$

In the second stage insiders choose g to solve the following problem (outsiders do not take any decision at this stage):

$$max_g \quad \Sigma_{i=1}^M \quad \pi_i^m = [p(Y(\Gamma)) - c_i^m(\Gamma_i^m)]y_i^m(\Gamma) - u[x_i^m(\Gamma)]^2 \tag{7}$$

where $\Gamma = \{\Gamma_1^m,...,\Gamma_M^m, \Gamma_{M+1}^n, ..., \Gamma_T^n\}$.

In the third stage firms decide on R&D expenditures. Insiders choose their R&D expenditures to maximize their joint profits, while each outsider chooses its R&D to maximize its own profits. Let $x^n \equiv \{x_{M+1}^n,...,x_T^n\}$, and $x^m \equiv \{x_1^m,...,x_M^m\}$. Outsider i solves the following problem

$$max_{x_i^n} \quad \pi_i^n = [p(Y(x^n,x^m)) - c_i^n(x^n,x^m)]y_i^n(x^n,x^m) - u[x_i^n]^2 \qquad i=M+1,...,T \tag{8}$$

and insiders solve, jointly

$$max_{x_1^m,...,x_M^m} \quad \Sigma_{i=1}^M \quad \pi_i^m = [p(Y(x^n,x^m)) - c_i^m(x^n,x^m)]y_i^m(x^n,x^m) - u[x_i^m]^2 \tag{9}$$

In the final stage (the output stage) firm i solves the following problem

$$max_{y_i} \quad \pi_i = [p(Y) - c_i(\Gamma_i)]y_i - ux_i^2 \qquad i=1,...,T \tag{10}$$

Note that output is chosen noncooperatively.

3. Results

We solve the model starting from the last stage to ensure subgame perfectness.

3.1 Output and R&D

Solving the output stage (10) yields each firm's output as a function of R&D expenditures of all firms and of spillovers:

$$y_i = \frac{a - r + (f + T(1-f))x_i + T\Gamma_i + (2f-1)X_{-i} - \Sigma_{j \neq i}^T \Gamma_j}{w(T+1)} \qquad i=1,...,T \tag{11}$$

Substituting Γ_i^m and Γ_i^n into (11) yields each outsider's output y_i^n and each insider's output y_i^m

$$y_i^n = \frac{a-r+(f+T(1-f))x_i^n+(2f-1)X_{-i}^n+[2f-1+g(1+k-M(1-k))]X^m}{(T+1)w} \qquad i=M+1,...,T$$

$$y_i^m = \frac{a-r+(f+g+M(1-f-g)+N(1-f-kg))x_i^m+(2f-1+g(2+N(1-k)))X_{-i}^m+(2f-1)X^n}{(T+1)w} \qquad i=1,...,M \tag{12}$$

We now turn to the third stage, the determination of R&D expenditures. The simultaneous solving of the T first-order conditions resulting from (8) and (9) yields each insider's R&D, $x_i^m(a,w,M,N,r,u,f,g,k)$, $i=1,...,M$, and each outsider's R&D, $x_i^n(a,w,M,N,r,u,f,g,k)$, $i=M+1,...,T$.[11] The ex ante symmetry of firms implies that $x_{M+1}^n=...=x_T^n$, $x_1^m=...=x_M^m$.[12] From (12) it can be seen that this symmetry in R&D expenditures implies symmetry in output, that is, $y_{M+1}^n=...=y_T^n$, $y_1^m=...=y_M^m$.

3.2 Information sharing

The second stage is the determination of information sharing within the RJV. This requires solving (7). It turns out that even with the relatively simple functional forms used here no closed form solution exists for g, hence numerical simulations are used. The following numerical parametrization is adopted: $a=1000$, $r=50$, $u=60$, $w=1$, and $T=10$. Note that f and k have not been fixed, because we want to study their effect on the equilibrium. For that, in the remainder of this paper the solution is studied at $f=\{0,0.1,...,1\}$, $k=\{0,0.1,...,1\}$.

To derive the result we proceed as follows. We first fix M. Then, we consider all possible combinations of f and k. For every couple (f,k), we search, numerically, for g that maximizes insiders' profits. This exercise is repeated for all $M\in\{2,3,...,T\}$. We obtain g for all couples (f,k), for all $M\in\{2,3,...,T\}$.

Proposition 1. *For a given RJV size $M\in\{2,...,T\}$, there exists a critical leakage level $k_c\in(0,1]$ such that for all $k\le k_c$, maximal information sharing is chosen ($g=1-f$), and for all $k>k_c$, no information is shared ($g=0$). Moreover, k_c is nondecreasing in M.*

Proposition 1 says that for a given RJV size, firms will choose maximal information

11. See Appendix.

12. The Salant and Shaffer (1998) critique of the use of symmetric R&D strategies does not apply here, because there are no side payments and there is only one output market. Moreover, the very idea of side payments goes counter to the pre-competitive nature of R&D collaboration.

sharing if k is smaller than a certain threshold, and will choose zero information sharing if k is higher than that threshold. The threshold k_c is nondecreasing in M. Information sharing is found to be either maximal or minimal, it never takes intermediate values. This implies that, everything else being equal, the relationship between insiders' profits and g is either positive or negative, it never changes sign with g. It is positive when $g=1-f$, and negative when $g=0$.

When $k=0$, voluntary information sharing within the RJV reinforces its competitive position relative to outsiders, without yielding any advantage to outsiders; hence insiders always choose maximal information sharing in this case. With $k>0$, some information leaks out, hence information sharing by insiders benefits both insiders and outsiders. Insiders choose maximal information sharing when k is sufficiently low so that the benefits leaking to outsiders are not too important. For large k, insiders do not share information, since outsiders benefit from it significantly at no cost. Clearly, for a given level of R&D, it is socially optimal that firms share all their research results. Hence a weak protection of cooperative research (i.e. a high k) will lead to suboptimal information sharing.

The leakage on voluntary information sharing represents a competitive impediment to information sharing. It is shown that this competitive impediment leads to extreme levels of information sharing. There exist other factors which may also affect information sharing. Technological impediments represent one such factor: the cost of sharing information, or imperfect compatibility of firms' technologies, can lead to intermediate levels of information sharing. The model predicts that the absence of information sharing is due to competitive impediments, while intermediate levels of information sharing are due to technological impediments.

The finding that firms choose extreme levels of information sharing (in the absence of technological impediments) is recurrent in the literature. Amir and Wooders (1999) analyse a research consortium composed of two firms which choose R&D and the spillover rate. However the spillover is one-directional: it flows only from one firm to the other firm. They find that firms choose extreme levels of information sharing. The rationale is that firms choose maximal information sharing when the efficiency effect -which pushes for cost minimization- dominates, while they choose no spillovers when the asymmetry effect -which pushes for maximum cost differentiation in order to maximize joint profits- dominates. Poyago-Theotoky (1999) allows firms to choose the spillover level after R&D investments are undertaken in a duopoly; she finds that cooperating (non-cooperating) firms choose maximal (minimal) spillovers.

Figure 2 depicts the relationship between the leakage factor on voluntary information sharing and RJV size. This figure reads as follows. For each RJV size, values of k lower or equal to the corresponding k_c entail maximal information sharing (g=1-f), and values of k higher than the corresponding k_c entail minimal information sharing (g=0). Hence, maximal information sharing is chosen below the curve $k_c(M)$, while minimal information sharing is chosen above that curve. For $M \geq 6$ firms always choose maximal information sharing. For $M \leq 6$, they minimize or maximize information sharing, depending on k. Moreover, f does not appear on this graph because it does not affect the decision of whether to share information or not.

The threshold k_c increases with M because as M increases the impact of information leakage on outsiders is less important (because there are less outsiders to benefit from it), and the benefits of internal information sharing increase (because there are more insiders). As k increases, a larger RJV becomes necessary to make information sharing in the RJV beneficial to insiders. This suggests that RJVs constrained in size (by regulation, for instance) are less likely to share information, or are likely to share less information, than non constrained RJVs, because of the benefits such sharing provides to outsiders.

Because small RJVs are less likely to share information, they need more protection than larger RJVs. Moreover, RJVs in markets where appropriability problems are important need more protection. Hence, it is sufficient to induce either a low k or a large M: either cooperative research is protected, which will induce larger RJVs, or incentives for larger RJVs are provided, in which case less protection is needed. This recommendation underlines a paradox when viewed from a dynamic point of view, however. Small RJVs need more protection. As this protection is provided, the size of the RJV is likely to increase. As the RJV becomes larger, the level of protection of the RJV necessary to induce its members to share information decreases. However, the temporary nature of most R&D agreements mitigates the importance of this dynamic inconsistency problem.

Also drawn on figure 2 is the curve k=1-1/M, which is derived from equation (5). On this curve $\Gamma_i^m=\Gamma_j^n$: insiders and outsiders receive exactly the same amount of cost reduction in dollars coming from voluntary information sharing (for insiders) and from the leakage on that voluntary information sharing (for outsiders). Below (above) the curve, insiders receive more (less) information than outsiders. For k sufficiently high, outsiders always receive more information, independently from M.

Note that this curve lies below the function $k_c(M)$. This means that there is a parameter space (region B) where outsiders receive more cost reduction from voluntary information sharing (between insiders) than insiders, but where insiders still choose to share that information. In that case, even though outsiders benefit more (in terms of technological flows), insiders still increase their profits by sharing information.

In region A, the information outsiders receive is so much higher than what insiders receive that information sharing would reduce insiders' profits, therefore insiders refrain from sharing information. In region C, insiders receive more information from voluntary information sharing, therefore they share the information.

The fact that the function $k=1-1/M$, which is derived from the cost functions, has the same shape as $k_c(M)$, which is derived from numerical simulations, reinforces the results obtained from numerical simulations, and show the robustness of the general shape obtained for the function $k_c(M)$.

Corollary 1. *The decision of whether to share information or not depends on k, but is independent of f. The level of information sharing depends on f, but is independent of k.*

Corollary 1 states that the determinants of the decision to share information and the determinants of the level of information sharing are different. While the decision of whether to share information or not does not depend on f, the level of information sharing depends on f, because $g \leq 1-f$. At the same time, the decision to share information or not depends on k, but the level of information sharing is independent of k. However, while the level of information sharing is independent of k, the amount of information effectively shared is affected by k, since k affects R&D.

Information sharing within the RJV is socially desirable. Firms may in some circumstances choose suboptimal levels of information sharing. There is a well-known tradeoff between increasing the pace of innovation and inducing a high diffusion of the innovation.[13] The model points to a related effect of the lack of protection of cooperative innovations (high k): it may prevent firms from sharing information, hence reducing the diffusion of existing

13.This result does not always hold empirically, however. As Baumol (1997) notes, innovation spillovers are higher in the Japanese economy than in the American economy, with no observable negative effects on Japanese innovation.

innovations. There is a tradeoff between the (voluntary) diffusion of the innovation to the immediate partners of the firm, and the (involuntary) diffusion of the innovation to other agents in the economy.

3.3 RJV size

Consider now the first stage of the game, the determination of the RJV size according to (4). The size of the RJV is determined by three effects: a coordination effect, an information sharing effect, and a competition effect. The coordination effect comes from the fact that an additional member increases the externalities internalized by the RJV. The information sharing effect comes from the possibility of improved information sharing among RJV members, discounted by any leakage of part or all of this information to outsiders. The competition effect comes from the fact that the newcomer is now a fiercer competitor on the output market.

From the point of view of insiders, the first two effects encourage an increase in the size of the RJV, while the third effect discourages increases in the size of the RJV. Moreover, there is an indirect link between the information sharing effect and the competition effect: because information sharing reinforces the competitive position of RJV members relative to outsiders, it reinforces the competition effect. From the point of view of an outsider considering whether to join the RJV or not, all three effects reinforce the profitability of joining the RJV.

The importance of each of these effects varies with f, k, and M. Consider first the effect of f. The coordination effect becomes more important as f increases, because more externalities are internalized. The information sharing effect becomes less important as f increases, because there is less scope for additional information sharing. The competition effect becomes less important as f increases because the advantage of the RJV over outsiders tends to diminish with spillovers; hence as f increases the scope for an improved competitive position of the newcomer is reduced.

Consider next the effect of k. With information sharing, the coordination effect declines with k: in that case coordination increases R&D, and the benefits of this increase decline with k. Without information sharing, the coordination effect increases with k when f is low (in that case coordination reduces R&D; the ensuing reduction in leakage to outsiders is more important when k is high), and declines with k when f is high (in that case coordination increases R&D). The information sharing effect becomes less important with k because higher leakage on voluntary information sharing reduces the value of additional information sharing to the RJV. The competition effect becomes less important with k, because the relative disadvantage of outsiders diminishes with k.

The importance of the three effects also varies with the size of the RJV. The coordination effect and the information sharing effect become negligible as M increases, because the marginal gain compared to existing coordination and information levels decreases. Regarding the competition effect, Bloch (1995) notes that it becomes more important as the size of the RJV increases: the cost reduction advantage of the RJV tends to increase with its size. The larger the RJV, the more inefficient is the newcomer, the more it gains from joining the RJV, and hence the stronger is the competition effect. On the other hand, when M is small, the RJV is only marginally more efficient than outsiders, hence the competition effect is less important.

We now determine the endogenous size of the RJV, M^*, which has to satisfy (4). For each couple (f,k) we determine M^* given that g is chosen according to proposition 1.

Proposition 2. *Generally, the size of the RJV (M^*) increases and then decreases with f, and increases and then decreases with k (see table 1 for exact results).*

The result of this algorithm is shown in table 1. In most cases, the RJV comprises more than half the industry, and in some few cases $M^*=T$. Overall there is an inverted U relationship between M^* and f: M^* increases and then decreases with f.[14] M^* first increases with f because the coordination effect increases, and the competition effect decreases, with f. M^* is low for high f because, as explained above, the information sharing effect (which encourages the formation of a larger RJV) becomes less important with f. Given that M^* is very small with high spillovers, it can be said that firms refrain from cooperation when it is most highly socially valued.

Consider next the effect of k. Overall there is an inverted U relationship between M^* and k: M^* increases and then decreases with k.[15] The size of the RJV may increase with the extent of the leakage from the RJV to outsiders (this is counterintuitive, since a higher k

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14.Poyago-Theotoky (1995) finds that M^* increases steadily with f. This monotonous relation does not obtain here, because of the leakage on voluntary information sharing.

15.For $f=1$ the result is invariant to k, because $f=1 \rightarrow g=0$. This invariance will be true in all subsequent tables.

decreases the attractiveness of the RJV for both insiders and outsiders)[16] because the competition effect, which induces a smaller RJV, becomes less important as k increases. M^* decreases with k when k is high because the information sharing effect becomes negligible.

The size of the RJV can be less than the whole industry for two reasons: external stability, or blocking by insiders. Table 1 distinguishes between these two cases. When either f or k are low, the size of the RJV is constrained by blocking by insiders. In these cases, the coordination effect, which encourages larger RJVs, is small; and the competition effect, which encourages smaller RJVs, is large. On the other hand, when either f or k are high, the size of the RJV is constrained by external stability: outsiders are not interested in joining the RJV. This is because, as explained earlier, the attractiveness of the RJV to outsiders decreases with f and k.

There is a strong link between the curve k=1-1/M of figure 2 and table 1. It is almost always when $\Gamma_i^m<\Gamma_j^n$ (regions A and B of figure 2, above the curve k=1-1/M) -i.e. when voluntary information sharing benefits outsiders more than insiders- that the size of the RJV is limited by external stability rather than by blockage by the RJV.

Table 2 shows M_w, the socially optimal size of the RJV, taking into account endogenous (and decentralized) information sharing decisions by firms. For a given k, M_w is nondecreasing in f. Similarly, for a given f, M_w is nondecreasing in k. M_w is nondecreasing in f and k because the benefit of the internalization of externalities increases with these externalities. By comparing tables 1 and 2 we see that in most cases the RJV is too small compared with the social optimum.[17] $M^*=M_w$ only in very special cases.

Table 2 shows that in some cases $M_w<T$ (remember that T=10). This is true for low f and/or low k (the fact that with high spillovers a RJV encompassing all firms in the industry is socially optimal is well understood. It is consistent with other findings in the literature, e.g. Poyago-Theotoky, 1995). This means that welfare increases, and then decreases, with the size of the RJV, when f and/or k are low. This reduction in welfare is linked to R&D spending. When spillovers are low, R&D by each insider increases, and then decreases, with the size of

16.For insiders, the value of sharing information -and therefore the attractiveness of the RJV- is reduced by k because a larger portion of the information proprietary to the RJV leaks out. For outsiders, the attractiveness of the RJV decreases with k because they obtain a larger portion of the information shared by insiders without having to join the RJV.

17.While the model suggests that in many cases industry-wide RJVs are socially optimal, the potential for output collusion qualifies this result. The presence of outsiders limits the benefit to insiders from output collusion, and maintains a competitive pressure in the industry.

the RJV. This can be seen on figure 3, which shows the R&D output of insiders for different values of M: x_i^m increases, and then decreases, with M when spillovers are low.

The explanation is as follows. An increase in the size of the RJV induces two effects on R&D spending by insiders: an R&D-coordination effect, and an R&D-information sharing effect.[18] The R&D-coordination effect comes from the internalization of more externalities. It is negative when spillovers are low, and positive when spillovers are high (this is a standard result in the literature; see De Bondt, 1996). The R&D-information sharing effect comes from the increased value of R&D to insiders, given that they can share more information. The R&D-information sharing effect encourages R&D, for all levels of spillovers. With low spillovers the R&D-coordination effect induces less R&D, while the R&D-information sharing effect induces more R&D spending. As the size of the RJV increases, the (negative) R&D-coordination effect becomes more important (because more externalities are being internalized) relative to the R&D-information sharing effect, and R&D decreases. On the other hand, with high spillovers the two effects have a positive impact on R&D, x_i^m increases steadily with M, hence an industry-wide RJV is desirable. The benefits of information sharing explain why a RJV is socially desirable even when spillovers are low. The reduction in R&D when spillovers are low explains why the socially optimal size of the RJV is smaller than the industry.[19]

3.4 Technological diffusion

Proposition 1 and corollary 1 in section 3.2 explained how information sharing is determined for a given RJV size. Now that the size of the RJV has been endogenized in section 3.3, we analyze information sharing in equilibrium. Table 3 shows g for all couples (f,k), given that $M=M^*$. Maximal information sharing is chosen except for some high levels of f and k. There is a dynamic interaction between the choices of M and g: the level of g to be chosen in the second stage has a direct impact on the choice of M in the first stage. Because the likelihood of information sharing increases with M, firms tend to choose the size of the RJV so as to make maximal information sharing an equilibrium. This explains why firms almost always choose

18. We use the prefix R&D to distinguish these effects from those affecting the size of the RJV.

19. De Bondt and Wu (1997) obtain a similar result. They find that, when information sharing is allowed, with high spillovers full cooperation is desirable, while with low spillovers welfare increases, and then decreases, with the size of the RJV. And they note: "As the size of the RJV increases, the tendency for research cartel members to restrict output begins to dominate incentives to expand resulting from better information-sharing". Poyago-Theotoky (1995), in a model with $g=1-f$, finds that an industry-wide RJV is always socially optimal. However, she defines social welfare as industry profits, while here I consider the sum of industry profits and consumer surplus.

maximal information sharing. A higher level of information sharing increases the benefits from cooperation to insiders, and increases the attractiveness of the RJV to outsiders, thereby increasing the size of the RJV. And a larger RJV is more likely to share information. Hence information sharing and the endogenization of M reinforce each other and lead to larger RJVs and more information sharing.[20] The information sharing problem, and the leakage of information to outsiders, are partly resolved when firms can adjust the size of the RJV.[21]

Figure 4 shows voluntary and total diffusion when $k=f$ and $T=10$. The size of the RJV is not constant on this figure, it is determined endogenously. Note the gradual and then abrupt decline in g as k increases. Total diffusion in the RJV is first invariant to k, and then decreases and increases with k. Diffusion decreases and then increases with f. Hence higher legal diffusion can lead to less effective diffusion. Total spillovers from the RJV to outsiders ($f+kg$) increase with $f=k$ at a decreasing rate, until the point where $g=0$, where the slope becomes constant.

Whereas for a given M, only f affects the level of information sharing, and only k affects the decision whether to share information or not (corollary 1), both k and f affect the choice of g when M is endogenized through their effect on the choice of M, which in turn affects the choice of g. Through that effect, both k and f can be said to affect the level of information sharing and the decision whether to share information or not, indirectly.

Table 4 shows total effective cost reduction, which is the sum of cost reductions accruing from different sources, to all firms. Total effective cost reduction, Q, is given by $Q = X[1+f(M^*+N-1)]+X^m[g(M^*+kN-1)]$. In general Q decreases with f and k: the disincentives of diffusion on innovators dominate the positive effects of diffusion on receivers. Figure 5 shows the decomposition of Q according to its sources in the case $f=k$. The decomposition is as follows:

Own cost effect $= X$

Involuntary spillovers $= f(M^*+N-1)X$

Voluntary information sharing $= g(M^*-1)X^m$

Leakage from the RJV on voluntary information sharing $= kgNX^m$

Involuntary spillovers and voluntary sharing are the most important sources of cost reduction,

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20.Kesteloot and Veuglelers (1995) obtain a similar result in a two-firms repeated game model.

21.De Bondt et al. (1992) conjecture that "If cooperation on R&D is accompanied with perfect spillovers, ... one would expect stability to be less problematic". Here it is shown that stability problems do not vanish when information sharing is allowed.

with voluntary sharing dominating for low f=k and involuntary spillovers dominating for high f=k. The own cost effect is less important, and diminishes further with spillovers. However, the own cost effect is the only source of cost reduction that is strictly positive for all levels of spillovers. Nonetheless, most cost reduction is due to diffusion, rather than to the use of the technology by the innovating firm. Finally, the cost reduction accruing to outsiders from the leakage from the RJV is negligible, even (and especially) when k is high. However, this negligible leakage has the non-negligible effect of reducing voluntary information sharing (as well as the own cost effect for insiders). Moreover, involuntary leakage (kg) is generally more important than what figure 5 suggests. This is because involuntary leakage is highest when f is low and k is high (but not high enough to stop insiders from sharing information). This case is not depicted on figure 5. Looking at total effective cost reduction (the upper bound of the graph), we see that even when accounting for diffusion, spillovers reduce total cost reduction (this is not necessarily true when $k \neq f$, however).

The possibility of improved information sharing affects total R&D mostly when spillovers are low. This is due to three factors. First, the scope for additional information sharing is large with low spillovers, but is much reduced when spillovers are already high. Second, with high spillovers, firms are more likely to choose not to share any information, because of leakage to outsiders. Third, for very high spillovers, the endogenous decline in the RJV size induces firms to choose not to share any additional information.

It is useful to separate the effects of R&D coordination and the effects of information sharing on welfare. Whereas the (social) benefits of R&D coordination are positively related to f, the (social and private) benefits of information sharing are negatively related to f. The intuition is as follows. R&D coordination internalizes an externality. When this externality is negative (f is low), firms reduce R&D. When this externality is positive (f is high), firms increase R&D. Hence society benefits from R&D coordination only when f is high. A different pattern emerges regarding the relation between the benefits of information sharing and f. The maximum amount of information firms can share voluntarily is that amount that does not leak out involuntarily, and this amount is inversely related to f.[22]

This result has implications for the regulation of R&D cooperation. Baumol (1992)

22.Consistent with that result, Hinloopen (1994) and Greenlee (1998) find that RJVs which share information but do not coordinate R&D expenditures are welfare reducing when spillovers are high. This is due to the disincentives information sharing has on R&D when it is not coupled with R&D coordination.

argues that "The use of a technology cartel to collude on ... total R&D expenditures is likely to be damaging to public welfare." He is more open to technology cooperative agreements involving improved information sharing. A similar position is held by De Fraja (1990).[23] The model gives mixed recommendations regarding the regulation of R&D cooperation. Contrarily to RJVs that coordinate R&D expenditures only, which are beneficial only when spillovers are high, and RJVs that share information only, which are beneficial only when spillovers are low (Hinloopen, 1994; Greenlee, 1998), RJVs that coordinate R&D expenditures and (may) share information improve welfare for all levels of spillovers. When spillovers are low, R&D coordination by itself reduces R&D, but this is more than compensated for by the increase in R&D due to information sharing. When spillovers are high, there is little scope for information sharing, but R&D coordination increases R&D. R&D coordination is beneficial if spillovers are high and/or firms share information. Also, combined with the results of Hinloopen (1994) and Greenlee (1998), the model suggests that information sharing is beneficial when spillovers are low (when spillovers are high information sharing is only marginally beneficial) and/or firms coordinate R&D expenditures.

3.5 R&D, profits, and welfare

Having determined RJV size and information sharing, we now analyze R&D and profits. Table 5 shows insiders' R&D. Again, *M* and *g* are not constant across this table: they are determined endogenously by firms for every level of *f* and *k*. As expected, x_i^m generally decreases with *k* and *f*, reaching a maximum at (0,0). Outsiders behave differently (table 6): x_i^n is decreasing in *f*, but increasing in *k*. A higher *k* increases the value of cost reduction to outsiders, increasing their R&D.

Tables 5 and 6 cannot be compared directly because the results are normalized so that $x_{i|(0,0)}=1$. Table 7 shows the ratio x_i^m/x_j^n. When *k* is low or moderate, $x_i^m>x_j^n$: insiders value R&D more, because they enjoy (the possibility of) improved information sharing, and internalize the

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23.Fölster (1995) studies the effects of different types of R&D subsidies on R&D cooperation and spending for a sample of Swedish industrial firms. Some R&D subsidies require cooperation but allow firms to choose the mode and extent of information sharing (e.g. Eureka). Other R&D subsidies require cooperation and information sharing between participating firms (e.g. Esprit, Race). Fölster finds that subsidy programs requiring only cooperation have no effect on the likelihood of cooperation but have a positive effect on R&D incentives. On the other hand, subsidy programs requiring both cooperation and information sharing increase the likelihood of cooperation, but decrease R&D incentives. He interprets the potential negative effect on R&D as a socially desirable elimination of duplication in research. Our model shows that this decline in R&D following cooperation can be due to at least two other factors: collusion between firms, and the desire to limit the amount of information leaking to competitors.

externalities of their R&D on other insiders.[24] Outsiders free ride on insiders' R&D. When k is high, it is possible that $x^m_i < x^n_j$. The ratio decreases with k, but may increase or decrease with f.

The fact that information sharing within the RJV increases insiders' R&D implies that outsiders benefit from information sharing even when k=0, as long as f>0: when f is positive, outsiders obtain more spillovers from insiders through fx^m_i, because of the increase in x^m_i (which is due to information sharing). However, the net competitive effect of information sharing on outsiders may still be negative.

Table 8 shows insiders' profits. They generally decrease with f and k. In terms of technological flows (abstracting from R&D expenditures and RJV size, the effect of which is considered elsewhere in the paper), the information insiders receive from voluntary sharing is g, and the leakage to outsiders is kg. We saw that in equilibrium in most cases insiders choose maximal information sharing: g=1-f. Substituting g=1-f into the technological flows each group receives, and subtracting the second from the first to obtain the advantage of the RJV (when it shares information) over outsiders, we find that the advantage of the RJV is (1-f)(1-k). This advantage diminishes with both f and k. This explains why insiders' profits diminish with both the general spillover and the leakage on voluntary information sharing. In particular, spillovers hurt the RJV more than they hurt outsiders, because they reduce the possibility of information sharing. Even by adjusting their size and their information sharing to spillovers, insiders lose from f *and* k: π^m_i reaches a maximum at (0,0). Outsiders' profits (table 9) tend to increase with f when k is low and to decrease with f when k is high. They tend to increase, although not always, with k.

Table 10 compares insiders and outsiders' profits.[25] In most cases $\pi^m_i > \pi^n_j$. Insiders' profits are highest relative to outsiders' with (0,0). With low spillovers, insiders spend more on R&D, and a small portion of this R&D leaks out to competitors. Moreover, they may choose to increase information sharing, and only a small portion of this additional information sharing leaks out to outsiders. Hence insiders make more profits with low spillovers. When both f and k are high, $\pi^m_i < \pi^n_i$. This is also true when f=1. Even though insiders spend more on R&D than

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24.Empirical evidence suggests that participation in research consortia has a positive impact on R&D expenditures (e.g. Branstetter and Sakakibara, 1997).

25.There is some empirical evidence that firms which cooperate on R&D obtain a higher rate of return on their research expenditures. For instance, Link and Bauer (1989), in the study of 92 US firms, found that the rate of return on R&D for firms engaging in cooperative R&D was 150 percent larger than for those that do not.

outsiders, the high level of spillovers, the small size of the RJV, and the limited scope for improving information sharing (remember that $g \leq 1-f$), result in a situation where outsiders benefit from this higher R&D output more than insiders.

Reading tables 1 and 10 together shows that, when the size of the RJV is limited by external stability, $\pi_i^m < \pi_i^n$. In contrast, when the size of the *RJV* is limited because of blockage by insiders, $\pi_i^m > \pi_j^n$. Also, there is a strong association between the curve k=1-1/M of figure 2 and table 10. It is almost always when $\Gamma_i^m < \Gamma_j^n$ (regions A and B of figure 2, above the curve k=1-1/M) -i.e. when voluntary information sharing benefits outsiders more than insiders- that insiders' profits are lower than outsiders'.

Table 11 shows the effect of f and k on total welfare. Overall welfare decreases with f, except with low k where it increases and then decreases with f. No clear trend can be detected for the effect of k on welfare. By reading this table jointly with table 1, we see that welfare is highest for those combinations of (f,k) that induce all firms to participate in the RJV. Those combinations yield the same level of total welfare even though k and f are different: k is irrelevant, because there are no outsiders; and f is irrelevant because firms choose maximal information sharing.

4. Conclusions

At the outset of the strategic investment literature the question was whether R&D cooperation is socially beneficial or not. Empirical and theoretical studies show that R&D cooperation is generally beneficial. Thus the question has now shifted to: what types of cooperation are superior, and which are likely to arise in a decentralized market? R&D cooperative ventures are complex multidimensional agreements. In this paper the focus was on RJV stability, information sharing, and leakage on voluntary information sharing.

The model studied information sharing and the stability of cooperation in cost reducing Research Joint Ventures (RJVs). In a four-stage game-theoretic framework, firms decided on participation in a RJV, information sharing, R&D expenditures, and output. An important feature of the model was that voluntary information sharing between cooperating firms increased information leakage from the RJV to outsiders. It was found that it is the spillover from the RJV to outsiders that determines the decision of insiders whether to share information or not, while it is the spillover affecting all firms that determines the level of information sharing within the RJV. RJVs representing a larger portion of the industry are more likely to share information. It was also found that firms never choose intermediate levels of information sharing: they share all the information or none at all. The model predicts that the absence of information sharing is due to competitive impediments (leakage of information to non-RJV members), while intermediate levels of information sharing would arise because of other considerations: costs of sharing information, or limited compatibility of firms' technologies. The size of the RJV was found to depend on three effects: a coordination effect, an information sharing effect, and a competition effect. Depending on the relative magnitudes of these effects, the size of the RJV may increase or decrease with spillovers. The effect of information sharing on the profitability of firms as well as on welfare was studied.

The sharpness of many of the results (e.g. no intermediary levels of information sharing; inverted U relationships between M and f on the one hand, and M and k on the other hand; different determinants of sharing information and of how much information to share) suggests that they are robust to changes in the numerical parametrization of the model. Numerical parametrization generally affects the magnitude of the results, not their qualitative nature.

The model focussed on the effect of leakage on voluntary information sharing on the level of information sharing. It was shown that this effect is most important when the RJV is small: large RJVs suffer less from leakages, and are less likely to stop sharing information because of them. The effect is also less important when spillovers are small. Because the maximum amount of information firms can share is the amount that is not already available through spillovers, information sharing is marginally beneficial when spillovers are high. Therefore leakages are less socially costly (even if they stop firms from sharing information) when spillovers are high.

The finding that firms share information when leakages are low and may not share it when leakages are high indicates that the imposition of no or maximal information sharing - both approaches are common in the literature- hides important assumptions. Studies that assume that cooperation firms do not share information implicitly assume that k is high, making information sharing unprofitable. Studies that assume maximal information sharing between firms implicitly assume that k is low.

By using a lax patent policy, the government gives firms the incentives to cooperate in order to internalize innovation externalities. And this formation of cooperative agreements may lead to information sharing. However, a problem with a lax patent policy aiming at inducing firms to cooperate is that firms may get the wrong message: instead of cooperating on R&D to internalize externalities and share information, firms may find it easier to move their research facilities to legislations (in a context where competition between legislations for R&D activities exists) providing a stricter protection for innovations, albeit with less R&D cooperation.

The scope for information sharing may be higher with newer technologies. Cooperation in industries with older, more mature technologies is likely to rely mainly on the coordination of R&D expenditures. This suggests that governments should favour RJVs in high-tech sectors. MITI (the Japanese Ministry of International Trade and Industry) seems to be following this path, with its focus on emerging technologies. In contrast, the British government funds cooperative research in mature declining industries.[26]

In this paper k was interpreted as a leakage parameter on information sharing. The mechanism behind this leakage was not specified. k can also be seen as a moral hazard parameter: once a firm has received information from other RJV members, it may have an incentive to trade part or all of that information with outsiders. While insiders may benefit from committing not to give information to third parties, such a commitment would not be credible. k can therefore represent the degree to which firms violate the secrecy of the RJV. In that respect, the results of the model suggest that firms may share information even in the presence of substantial moral hazard problems.

The model has many possible extensions. An interesting issue to explore is how information sharing is affected by product differentiation. Firms selling differentiated goods face less fierce competition on the product market, and may be more willing to share information. This intuition is confirmed by the observation that industry-wide joint ventures are observed more in countries where exports have a relatively greater importance than the domestic market (De Fraja, 1990). However, as product differentiation increases the information each firm possesses (or develops) may become less relevant to other firms.

The role of information leakage, k, could be explored further. k can depend on the size of the RJV: a larger RJV may leak out more information to outsiders than a smaller one. For instance, Link and Bauer (1989) find an inverse relation between appropriability of research results and the number of participants in research cooperative agreements.

26.The reference for this insight is unfortunately lost.

In this paper firms were found to choose relatively high levels of information sharing. Many factors can make it difficult for firms to achieve such a high rate of diffusion of innovations. Information sharing may require the use of common research facilities, which brings into play diseconomies of scale. Increasing production costs would reduce the value of output expansion and hence of cost reduction. The high transaction costs of innovation may imply that RJVs are smaller than the model suggests, or that less information is shared because of opportunism. There may be a cost to sharing information, and that cost may rise with the size of the RJV; this would limit both RJV size and information sharing. When discoveries are made at different points in time, information exchange becomes more difficult; information sharing between firms could be made dependent on past experiences of information sharing. Differences in compatibility and communication, absorptive capacities, and organizational culture impose further limits on the levels (De Bondt et al., 1992) and the symmetry of information sharing.

Perhaps the main limit of this study is that firms can form only one RJV. Kamien and Zang study multiple RJV formation, with RJVs of identical sizes, although in their model information sharing is imposed upon firms. A more complete model of R&D cooperation would consider both endogenous information sharing and multiple RJV (of different sizes) formation. The socially optimal number of RJVs with endogenous information sharing is likely to be smaller than the socially optimal number of RJVs with exogenous perfect information sharing because, as our model shows, smaller RJVs are less likely to share information.

Figure 1 - R&D spillovers

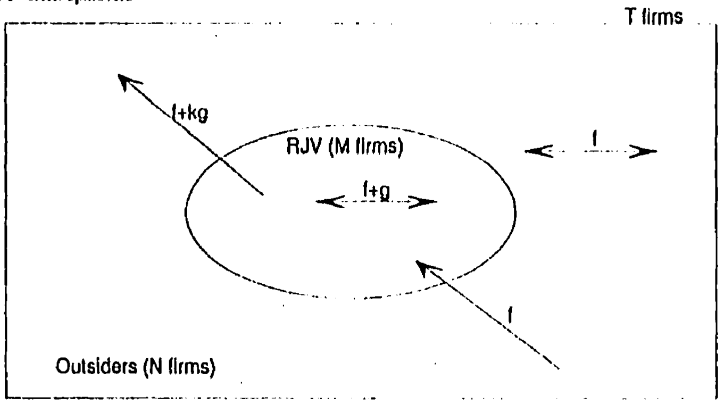

Figure 2 - Information sharing as a function of k and M

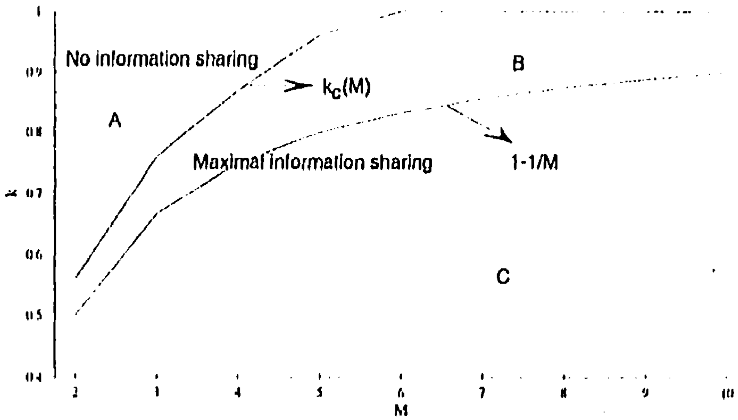

Figure 3 - Effect of M on insiders' R&D

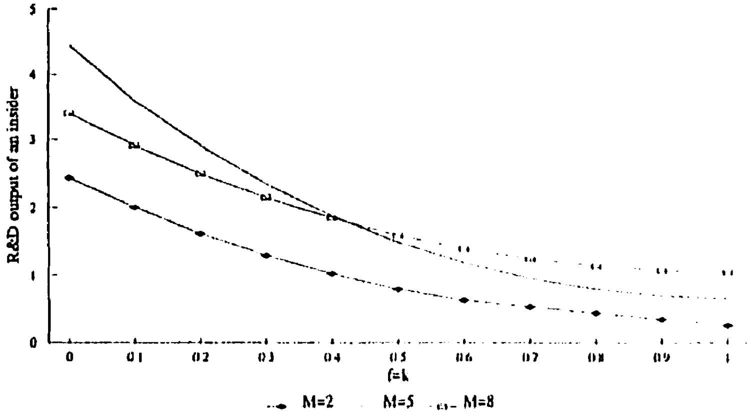

Figure 4 - Information sharing

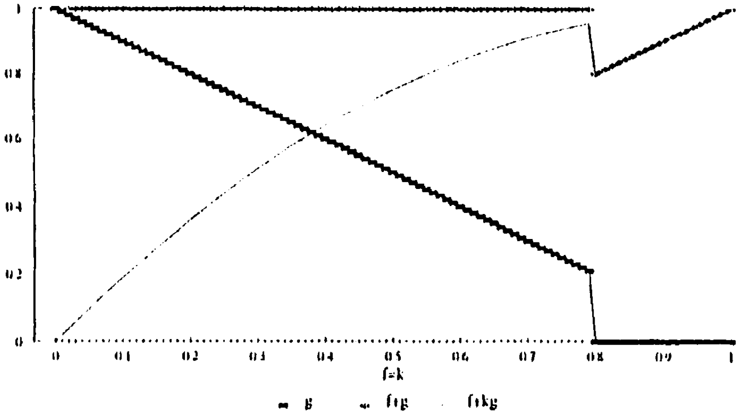

Figure 5 - Decomposition of cost reduction

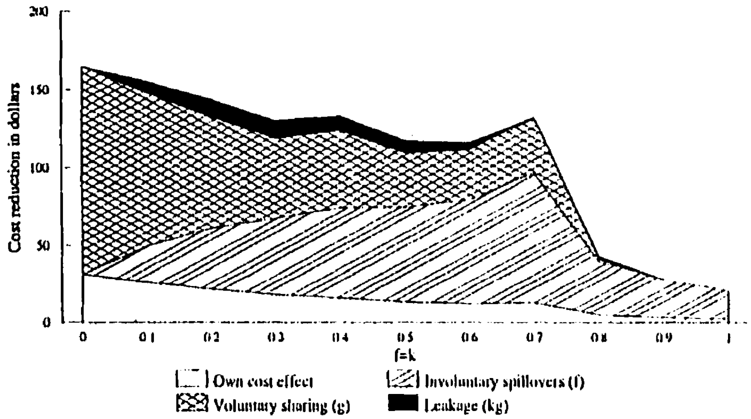

Table 1- Endogenous RJV size

f \ k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	6	6	6	6	6	7	7	8	10	10	2
0.1	6	6	6	6	6	7	7	8	10	5	2
0.2	6	6	6	6	6	7	7	8	10	5	6
0.3	6	6	6	6	6	7	7	8	10	5	6
0.4	6	6	6	6	7	7	7	8	10	5	6
0.5	6	6	6	6	7	7	8	8	10	5	6
0.6	6	6	6	7	7	7	8	9	10	5	6
0.7	6	7	7	7	7	8	9	10	10	5	6
0.8	7	7	8	8	8	9	10	10	4	5	3
0.9	9	10	10	10	10	10	5	3	3	3	3
1	3	3	3	3	3	3	3	3	3	3	3

m: Blockage by RJV

m: external stability

Table 2- Socially optimal RJV size

f \ k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	8	8	8	9	9	9	9	9	10	10	10
0.1	8	8	8	8	9	9	9	10	10	10	10
0.2	8	8	8	9	9	9	9	10	10	10	10
0.3	8	8	8	9	9	9	9	10	10	10	10
0.4	8	8	9	9	9	9	10	10	10	10	10
0.5	8	9	9	9	9	9	10	10	10	10	10
0.6	9	9	9	9	9	10	10	10	10	10	10
0.7	9	9	10	10	10	10	10	10	10	10	10
0.8	10	10	10	10	10	10	10	10	10	10	10
0.9	10	10	10	10	10	10	10	10	10	10	10
1	10	10	10	10	10	10	10	10	10	10	10

Table 3- Information sharing

f \ k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	1	1	1	1	1	1	1	1	1	1	0
0.1	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0
0.2	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
0.3	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
0.4	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.6	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
0.7	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
0.8	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0
0.9	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0

Table 4- Total effective cost reduction

f \ k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	164.97	158.77	151.43	142.98	133.43	145.45	131.64	131.10	132.68	132.68	12.84
0.1	162.30	155.85	148.48	140.20	131.02	141.55	128.85	128.85	132.68	56.82	22.28
0.2	157.91	151.37	144.11	136.13	127.42	136.85	125.29	126.12	132.68	59.27	59.38
0.3	151.72	145.28	138.27	130.71	122.59	131.33	120.97	122.93	132.68	60.62	61.56
0.4	143.64	137.48	130.91	123.92	133.78	124.97	115.87	119.26	132.68	60.87	62.87
0.5	133.62	127.94	121.97	115.71	125.33	117.76	122.40	115.12	132.68	60.02	63.32
0.6	121.59	116.60	111.42	122.05	115.94	109.68	116.39	122.82	132.68	58.08	62.90
0.7	107.52	119.60	115.00	110.32	105.57	114.30	122.51	132.68	132.68	55.04	61.62
0.8	107.17	103.98	114.71	111.77	108.81	120.04	132.68	132.68	43.57	50.92	34.03
0.9	119.29	132.68	132.68	132.68	132.68	132.68	50.07	29.88	28.43	28.43	28.43
1	20.98	20.98	20.98	20.98	20.98	20.98	20.98	20.98	20.98	20.98	20.98

Table 5- Insiders' R&D

f \ k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.00	0.90	0.81	0.72	0.63	0.53	0.47	0.38	0.30	0.30	0.26
0.1	0.25	0.00	0.74	0.66	0.58	0.50	0.44	0.37	0.30	0.21	0.24
0.2	0.23	0.24	0.00	0.60	0.54	0.47	0.41	0.35	0.30	0.21	0.18
0.3	0.22	0.22	0.23	0.00	0.49	0.43	0.39	0.34	0.30	0.20	0.18
0.4	0.20	0.20	0.20	0.21	0.00	0.40	0.36	0.32	0.30	0.19	0.18
0.5	0.18	0.18	0.18	0.18	0.18	0.00	0.33	0.31	0.30	0.18	0.18
0.6	0.16	0.16	0.16	0.16	0.16	0.16	0.00	0.30	0.30	0.18	0.18
0.7	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.00	0.30	0.17	0.18
0.8	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.30	0.00	0.16	0.12
0.9	0.08	0.08	0.08	0.08	0.08	0.08	0.30	0.30	0.08	0.00	0.10
1	0.06	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09

Table 6- Outsiders' R&D

f \ k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	28.38	1.04	1.08	1.11	1.13	1.14	1.16	1.18			1.19
0.1	25.76	23.81	1.00	1.02	1.04	1.05	1.07	1.07		1.10	1.09
0.2	23.22	21.55	19.94	0.94	0.95	0.95	0.96	0.97		0.99	0.99
0.3	20.76	19.35	17.97	16.63	0.85	0.85	0.86	0.87		0.88	0.88
0.4	18.36	17.18	16.03	14.90	14.74	0.75	0.76	0.76		0.77	0.77
0.5	16.00	15.05	14.11	13.19	13.31	12.39	0.65	0.66		0.66	0.66
0.6	13.70	12.95	12.21	12.62	11.88	11.15	11.32	0.55		0.55	0.55
0.7	11.43	12.12	11.57	11.01	10.47	10.95	11.41			0.44	0.44
0.8	10.51	10.14	10.89	10.58	10.26	11.10			4.39	0.34	0.33
0.9	10.99						4.73	2.89	2.85	2.85	0.23
1	1.91	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12

Table 7- Insiders' R&D over outsiders' R&D *k*

		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	0	4.06	3.51	3.04	2.63	2.26	1.90	1.62	1.32			0.90
	0.1	3.87	3.40	2.98	2.61	2.27	1.94	1.67	1.39		0.79	0.91
	0.2	3.73	3.32	2.94	2.60	2.29	1.99	1.74	1.48		0.85	0.72
	0.3	3.63	3.27	2.93	2.62	2.33	2.06	1.82	1.59		0.92	0.82
	0.4	3.57	3.25	2.95	2.66	2.39	2.16	1.93	1.73		1.01	0.93
f	0.5	3.55	3.27	2.99	2.73	2.51	2.29	2.08	1.92		1.13	1.09
	0.6	3.59	3.33	3.09	2.90	2.69	2.49	2.34	2.22		1.30	1.30
	0.7	3.69	3.55	3.35	3.16	2.97	2.86	2.77			1.55	1.62
	0.8	4.09	3.93	3.85	3.72	3.59	3.58			1.77	1.96	1.43
	0.9	5.28						3.16	1.91	1.84	1.84	1.84
	1	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00

Table 8- Insiders' profits *k*

		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	0	1.0000	0.9783	0.9593	0.9426	0.9281	0.9158	0.9067	0.8997	0.8965	0.8965	0.8745
	0.1	0.9809	0.9637	0.9484	0.9349	0.9231	0.9131	0.9054	0.8995	0.8965	0.8816	0.8784
	0.2	0.9642	0.9507	0.9387	0.9279	0.9184	0.9104	0.9041	0.8992	0.8965	0.8841	0.8837
	0.3	0.9495	0.9392	0.9299	0.9215	0.9140	0.9078	0.9027	0.8987	0.8965	0.8862	0.8857
	0.4	0.9367	0.9290	0.9220	0.9156	0.9098	0.9053	0.9013	0.8982	0.8965	0.8878	0.8873
f	0.5	0.9255	0.9200	0.9149	0.9102	0.9063	0.9029	0.8997	0.8976	0.8965	0.8890	0.8886
	0.6	0.9158	0.9120	0.9085	0.9055	0.9029	0.9004	0.8984	0.8970	0.8965	0.8897	0.8895
	0.7	0.9074	0.9053	0.9033	0.9014	0.8997	0.8983	0.8971	0.8965	0.8965	0.8901	0.8901
	0.8	0.9010	0.8998	0.8988	0.8980	0.8972	0.8967	0.8965	0.8965	0.8897	0.8900	0.8890
	0.9	0.8967	0.8965	0.8965	0.8965	0.8965	0.8965	0.8905	0.8884	0.8883	0.8883	0.8883
	1	0.8870	0.8870	0.8870	0.8870	0.8870	0.8870	0.8870	0.8870	0.8870	0.8870	0.8870

Table 9- Outsiders' profits *k*

		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	0	1.0000	1.0850	1.1614	1.2291	1.2880	1.3034	1.3562	1.3859			1.4251
	0.1	1.0845	1.1537	1.2158	1.2708	1.3188	1.3297	1.3734	1.3969		1.4518	1.4311
	0.2	1.1604	1.2153	1.2646	1.3084	1.3465	1.3537	1.3891	1.4073		1.4531	1.4622
	0.3	1.2276	1.2699	1.3079	1.3416	1.3711	1.3753	1.4033	1.4170		1.4540	1.4618
	0.4	1.2861	1.3174	1.3455	1.3706	1.3698	1.3946	1.4160	1.4261		1.4547	1.4613
f	0.5	1.3359	1.3578	1.3776	1.3953	1.3935	1.4116	1.4173	1.4345		1.4550	1.4607
	0.6	1.3769	1.3913	1.4042	1.4000	1.4138	1.4262	1.4298	1.4371		1.4551	1.4600
	0.7	1.4094	1.4026	1.4128	1.4222	1.4307	1.4318	1.4356			1.4548	1.4592
	0.8	1.4241	1.4297	1.4275	1.4339	1.4399	1.4418			1.4515	1.4542	1.4487
	0.9	1.4410						1.4525	1.4484	1.4479	1.4479	1.4479
	1	1.4464	1.4464	1.4464	1.4464	1.4464	1.4464	1.4464	1.4464	1.4464	1.4464	1.4464

Table 10- Insiders' profits over outsiders' profits *k*

		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	0	1.6289	1.4687	1.3454	1.2493	1.1738	1.1446	1.0890	1.0574			0.9996
	0.1	1.4734	1.3607	1.2707	1.1983	1.1401	1.1186	1.0739	1.0488		0.9892	0.9997
	0.2	1.3535	1.2743	1.2090	1.1552	1.1109	1.0955	1.0602	1.0407		0.9911	0.9845
	0.3	1.2599	1.2047	1.1581	1.1188	1.0858	1.0752	1.0478	1.0331		0.9927	0.9869
	0.4	1.1864	1.1487	1.1161	1.0881	1.0819	1.0574	1.0367	1.0259		0.9941	0.9891
f	0.5	1.1285	1.1036	1.0817	1.0625	1.0593	1.0418	1.0340	1.0192		0.9952	0.9909
	0.6	1.0833	1.0678	1.0538	1.0536	1.0402	1.0284	1.0235	1.0166		0.9960	0.9924
	0.7	1.0487	1.0514	1.0414	1.0324	1.0243	1.0219	1.0178			0.9966	0.9936
	0.8	1.0305	1.0251	1.0256	1.0201	1.0149	1.0131			0.9984	0.9969	0.9996
	0.9	1.0136						0.9986	0.9991	0.9993	0.9993	0.9993
	1	0.9989	0.9989	0.9989	0.9989	0.9989	0.9989	0.9989	0.9989	0.9989	0.9989	0.9989

Table 11- Welfare *k*

		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	0	1.0000	1.0004	1.0004	1.0002	0.9996	1.0032	1.0014	1.0023	1.0038	1.0038	0.9790
	0.1	1.0013	1.0014	1.0012	1.0007	1.0000	1.0030	1.0013	1.0021	1.0038	0.9888	0.9813
	0.2	1.0021	1.0019	1.0016	1.0010	1.0001	1.0027	1.0010	1.0018	1.0038	0.9895	0.9897
	0.3	1.0024	1.0021	1.0015	1.0008	0.9999	1.0021	1.0006	1.0014	1.0038	0.9900	0.9903
	0.4	1.0022	1.0017	1.0011	1.0003	1.0026	1.0013	1.0000	1.0009	1.0038	0.9902	0.9907
f	0.5	1.0015	1.0009	1.0002	0.9994	1.0015	1.0003	1.0015	1.0003	1.0038	0.9902	0.9909
	0.6	1.0002	0.9996	0.9989	1.0010	1.0001	0.9991	1.0005	1.0019	1.0038	0.9899	0.9909
	0.7	0.9983	1.0007	1.0000	0.9992	0.9985	1.0002	1.0018	1.0038	1.0038	0.9894	0.9907
	0.8	0.9987	0.9982	1.0002	0.9997	0.9993	1.0014	1.0038	1.0038	0.9872	0.9886	0.9853
	0.9	1.0012	1.0038	1.0038	1.0038	1.0038	1.0038	0.9884	0.9846	0.9843	0.9843	0.9843
	1	0.9828	0.9828	0.9828	0.9828	0.9828	0.9828	0.9828	0.9828	0.9828	0.9828	0.9828

Appendix

R&D output

Let

$$
\begin{aligned}
q = \; & -f+3f^2-3f^3+f^4+2fg-4f^2g+2f^3g-fg^2+f^2g^2-M+4fM-8f^2M+8f^3M-3f^4M+2gM-8fgM+12f^2gM-6f^3gM-g^2M+4fg^2M \\
& -3f^2g^2M-2fM^2+6f^2M^2-7f^3M^2+3f^4M^2-2gM^2+8fgM^2-12f^2gM^2+6f^3gM^2+2g^2M^2-5fg^2M^2+3f^2g^2M^2-f^2M^3+2f^3M^3 \\
& -f^4M^3-2fgM^3+4f^2gM^3-2f^3gM^3-g^2M^3+2fg^2M^3-f^2g^2M^3-N+3fN-4f^2N+3f^3N-f^4N+2gN-4fgN+4f^2gN-2f^3gN-g^2N+fg^2N \\
& -f^2g^2N-MN+fMN+2f^2MN-4f^3MN+2f^4MN+2fgMN-5f^2gMN+4f^3gMN+g^2MN-fg^2MN+2f^2g^2MN+fgkMN-f^2gkMN \\
& -fg^2kMN-fM^2N+f^2M^2N+f^3M^2N-f^4M^2N-2gM^2N+3fgM^2N-2f^3gM^2N+g^2M^2N-fg^2M^2N-f^2g^2M^2N+gkM^2N-2fgkM^2N \\
& +2f^2gkM^2N-g^2kM^2N+2fg^2kM^2N-fgM^3N+f^2gM^3N-g^2M^3N+fg^2M^3N+fgkM^3N-f^2gkM^3N+g^2kM^3N-fg^2kM^3N-N^2+3fN^2 \\
& -4f^2N^2+3f^3N^2-f^4N^2+2gN^2-4fgN^2+4f^2gN^2-2f^3gN^2-g^2N^2+fg^2N^2-f^2g^2N^2-2fMN^2+5f^2MN^2-4f^3MN^2+f^4MN^2 \\
& -2gMN^2+7fgMN^2-9f^2gMN^2+4f^3gMN^2+2g^2MN^2-3fg^2MN^2+3f^2g^2MN^2+gkMN^2-2fgkMN^2+3f^2gkMN^2-2f^3gkMN^2 \\
& -g^2kMN^2+fg^2kMN^2-2f^2g^2kMN^2-3fgM^2N^2+5f^2gM^2N^2-2f^3gM^2N^2-g^2M^2N^2+3fg^2M^2N^2-3f^2g^2M^2N^2+3fgkM^2N^2 \\
& -5f^2gkM^2N^2+2f^3gkM^2N^2+g^2kM^2N^2-3fg^2kM^2N^2+4f^2g^2kM^2N^2-f^2g^2k^2M^2N^2-fg^2M^3N^2+f^2g^2M^3N^2+2fg^2kM^3N^2 \\
& -2f^2g^2kM^3N^2-fg^2k^2M^3N^2+f^2g^2k^2M^3N^2-fN^3+3f^2N^3-3f^3N^3+f^4N^3+2fgN^3-4f^2gN^3+2f^3gN^3-fg^2N^3+f^2g^2N^3-2fgMN^3 \\
& +4f^2gMN^3-2f^3gMN^3+2fg^2MN^3-2f^2g^2MN^3+2fgkMN^3-4f^2gkMN^3+2f^3gkMN^3-2fg^2kMN^3+2f^2g^2kMN^3-fg^2M^2N^3 \\
& +f^2g^2M^2N^3+2fg^2kM^2N^3-2f^2g^2kM^2N^3-fg^2k^2M^2N^3+f^2g^2k^2M^2N^3+uw-ufw-2ugw+2ufgw+ug^2w+2uMw-2uf^2Mw \\
& -2ufgMw-ug^2Mw+2uM^2w-ufM^2w+2ugM^2w-2ufgM^2w-ug^2M^2w+uM^3w-2ufM^3w+2uf^2M^3w+2ufgM^3w+ug^2M^3w \\
& +4uNw-7ufNw+4uf^2Nw-6ugNw+6ufgNw+3ug^2Nw+5uMNw-4ufMNw+2ugMNw-6ufgMNw-4ug^2MNw \\
& -2ugkMNw+2ufgkMNw+2ug^2kMNw+2uM^2Nw-ufM^2Nw+4ugM^2Nw-2ufgM^2Nw-ug^2M^2Nw-2ugkM^2Nw+2ufgM^3Nw \\
& +2ug^2M^3Nw-2ufgkM^3Nw-2ug^2kM^3Nw+4uN^2w-7ufN^2w+4uf^2N^2w-6ugN^2w+6ufgN^2w+3ug^2N^2w+2uMN^2w \\
& -2uf^2MN^2w+4ugMN^2w-6ufgMN^2w-5ug^2MN^2w-4ugkMN^2w+4ufgkMN^2w+4ug^2kMN^2w+2ugM^2N^2w+ug^2M^2N^2w \\
& -2ugkM^2N^2w-2ug^2kM^2N^2w+ug^2k^2M^2N^2w+ug^2M^3N^2w-2ug^2kM^3N^2w+ug^2k^2M^3N^2w+uN^3w-ufN^3w-2ugN^3w+2ufgN^3w \\
& +ug^2N^3w+2ugMN^3w-2ufgMN^3w-2ug^2MN^3w-2ugkMN^3w+2ufgkMN^3w+2ug^2kMN^3w+ug^2M^2N^3w-2ug^2kM^2N^3w \\
& +ug^2k^2M^2N^3w-u^2w^2-3u^2Mw^2-3u^2M^2w^2-u^2M^3w^2-3u^2Nw^2-6u^2MNw^2-3u^2M^2Nw^2-3u^2N^2w^2-3u^2MN^2w^2-u^2N^3w^2
\end{aligned}
$$

Then

$$
x_i^n = \frac{\begin{aligned}&[1+N+f^2(1-M+N)+g^2(1-M+kM)(1-M+N-MN+kMN)-g(2-2M+kM+2N-2MN+2kMN) \\ &+f(-2+M-2N+g(2-3M+kM+M^2-kM^2+2N-2MN+2kMN))-uw-uMw-uNw](-M-N+f(-1+M+N))(r-a)\end{aligned}}{q}
$$

for $i=M+1,\ldots,T$, and

$$
x_i^m = \frac{(1+f(-1+M-N)+N+g(-1+M-N+MN-kMN))(a-r)(M+f(1-2M-2N)+N+f^2(-1+M+N)-uw-uMw-uNw)}{q}
$$

for $i=1,\ldots,M$.

Strategic interaction of research efforts

The study of A the strategic interaction of research efforts helps to illustrate the basic structure of the model, and will show how it compares with existing work.[27] As Becker and Peters (1995) note, "the incentives to create knowledge spillovers are always larger for strategic complements than for strategic substitutes". A standard result in the literature is that research efforts are strategic complements (substitutes) when spillovers are higher (lower) than a certain threshold. The basic intuition is that when spillovers are low, the externality on other firms is

27.Following Bulow et al. (1985) actions *a* and *b* are strategic complements if $\partial^2\pi/\partial a\, \partial b>0$, and are strategic substitutes if $\partial^2\pi/\partial a\, \partial b<0$.

negative: an increase in research by firm i hurts firm j, which reduces its R&D. When spillovers are high, the externality is positive: an increase in research by firm i benefits firm j, which increases its R&D. This intuition applies for a homogeneous good industry with linear demand and (exogenous) industry-wide cooperation,[28] when firms produce in demand-unrelated industries (Steurs, 1995), and when the size of the RJV is endogenous (Poyago-Theotoky, 1995). While the threshold may change across market settings, the intuition remains the same.

In the model studied here, where the size of the RJV is endogenous and where spillovers between the RJV and outsiders are asymmetric and endogenous, the same intuition applies, but the result is more complex. There are four thresholds, determining the strategic interaction between outsiders and insiders, between insiders, and between outsiders.

Proposition 3.

i) $sign(\partial^2\pi_i^m/\partial x_i^m\, \partial x_j^n) = sign(f-\frac{1}{2})$.

ii) $sign(\partial^2\pi_j^n/\partial x_j^n\, \partial x_i^m) = sign(-1+2f+g(1+k-M(1-k)))$.

iii) $sign(\partial^2\pi_j^m/\partial x_j^m\, \partial x_i^m) = sign(-1+2f+g(2+N(1-k)))$.

iv) $sign(\partial^2\pi_j^n/\partial x_j^n\, \partial x_i^n) = sign(f-\frac{1}{2})$.

Proof. On substituting (12), Γ_i^m, and Γ_i^n into (3) and differentiating, we find that

i.

$$\frac{\partial^2\pi_i^m}{\partial x_i^m \partial x_j^n} = -\frac{2(-1+2f)[-T+f(T-1)+g(M+kN-1)]}{w(T+1)^2}$$

Since the term in brackets is negative, this expression takes the sign of $f-\frac{1}{2}$.

ii.

$$\frac{\partial^2\pi_j^n}{\partial x_j^n \partial x_i^m} = \frac{2(-1+2f+g(1+k-M(1-k)))[T-f(T-1)]}{w(T+1)^2}$$

Since the term in brackets is positive, this expression takes the sign of $-1+2f+g(1+k-M(1-k))$.

28.See De Bondt, 1996.

iii.

$$\frac{\partial^2 \pi_j^m}{\partial x_j^m \partial x_i^m} = -\frac{2(-1+2f+g(2+N(1-k)))[-T+f(T-1)+g(M+kN-1)]}{w(T+1)^2}$$

Since the term in brackets is negative, this expression takes the sign of $-1+2f+g(2+N(1-k))$.

iv.

$$\frac{\partial^2 \pi_j^n}{\partial x_j^n \partial x_i^n} = \frac{2(-1+2f)[-T+f(T-1)]}{w(T+1)^2}$$

Since the term in brackets is negative, this expression takes the sign of $f-\frac{1}{2}$. ■

Parts *i* and *iv* of proposition 3 state that an increase in R&D expenditures by an outsider will increase R&D by other outsiders, and by insiders, if $f>\frac{1}{2}$, and will reduce it if $f<\frac{1}{2}$. A higher f means that the increase in x_i^n benefits all other firms substantially, which increases the value of cost reduction for them, and induces them to increase R&D. Note that the threshold obtained for these two cases is the same as that obtained in most studies.

Part *ii* states the condition which must be satisfied for an outsider to respond positively to an increase in R&D by an insider. The result depends on f, k, g, and M. The response is more likely to be positive when f is higher; the explanation is the same as above. It is also more likely to be positive when k is higher. This is because a higher k means that outsiders benefit more from the increase in R&D by an insider. The effect of g is positive when k is high, and negative when k is low. This is because a higher g benefits outsiders insofar as information leakage (k) on this additional information sharing is important. Finally, the effect of M is negative: the higher M, the lower is the benefit of outsiders relative to the benefit of insiders. M has an effect only insofar as $g>0$.[29] Numerical simulations (taking into account the optimization by firms with respect to M and g) show that in most cases insiders' and outsiders' R&D expenditures are strategic substitutes, except when f or k are high.

Part *iii* of proposition 3 states the condition that must be satisfied for an insider to respond positively to an increase in R&D by another insider. This response is more likely to be positive the higher f, g, N, and the lower k. The role of f is well understood. A higher g means that the externality is positive. The lower k, the greater is the benefit of insiders relative

29.By setting $k=0$ and $g=1-f$ we obtain the special case studied by Poyago-Theotoky (1995) who finds that outsiders respond positively to an insider's increase in R&D if $f>M/(M+1)$.

to the benefit of outsiders, and the more likely is the response to be positive. A larger N increases the likelihood that x_i^m and x_j^m are strategic complements. N has an effect only insofar as $g>0$. Numerical simulations show that in most cases insiders' R&D expenditures are strategic complements, except when f is low and k is very high.

Note that because of information sharing, insiders' R&D expenditures are more likely to be strategic complements than outsiders'. This can be seen from the fact that the term in part *iii* of proposition 3 is more likely to be positive than the term in part *iv*. This is due specifically to information sharing, *not* to R&D coordination: when $g=0$ the two conditions are equivalent.

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CONCLUSION GÉNÉRALE

La thèse est constituée de trois essais sur l'analyse microéconomique du changement technologique. Le premier essai a étudié l'effet du changement technologique sur les frontières de la firme, en se basant sur la théorie des coûts de transaction et la théorie de l'agence. Dans le deuxième essai, on a examiné les externalités de recherche entre acheteurs et vendeurs, en incorporant différentes structures de marché, conditions d'appropriabilité et types de coopération. Le partage d'information et la stabilité de la coopération dans les consortiums de recherche ont été le sujet du troisième essai.

Dans le premier essai on a analysé l'effet du changement technologique sur les frontières de la firme en se basant sur la théorie des coûts de transaction et la théorie de l'agence. Le modèle incorpore quatre types de coûts: coûts de production, de coordination, de management et de transaction. L'analyse a été effectuée dans un cadre principal-deux agents, avec sélection adverse et risque moral. L'effet du changement technique dépend des magnitudes de l'effet d'efficience, qui est dû au différentiel de coûts et de niveaux d'efforts entre la firme et le marché, et de l'effet de contrôle, qui représente l'impact du changement technologique sur les rentes informationnelles des agents.

Un changement technique induisant une baisse des coûts de production se traduit par davantage d'intégration verticale lorsque les coûts de production du fournisseur sont faibles (dans ce cas l'effet d'efficience domine) et par davantage d'impartition lorsque les coûts de production du fournisseur sont élevés (l'effet de contrôle domine). Lorsque les coûts de production sont suffisamment plus élevés que les coûts de coordination, l'effet d'efficience tend à dominer toujours. Inversement, un changement technique induisant une baisse des coûts de coordination se traduit par davantage d'impartition lorsque les coûts de coordination de la firme sont faibles (l'effet d'efficience domine) et par davantage d'intégration verticale lorsque les coûts de coordination de la firme sont élevés (l'effet de contrôle domine). Donc, l'effet d'un changement technologique affectant les niveaux des coûts de production ou de coordination dépend du différentiel de coûts entre la firme et le marché et de l'importance relative des coûts de production et de coordination.

Un changement technique induisant une baisse de la désutilité de l'effort de réduction des coûts de production, ou une hausse de l'impact de cet effort, se traduit par davantage d'intégration verticale (l'effet d'efficience domine). Inversement, un changement technique induisant une baisse de la désutilité de l'effort de réduction des coûts de coordination, ou une hausse de l'impact de cet effort, se traduit par davantage d'impartition (l'effet d'efficience domine).

Un changement technique affectant à la fois le niveau des coûts de production, ainsi que l'impact et la désutilité de l'effort de réduction des coûts de production, induit un effet d'efficience, mais pas d'effet de contrôle: on observe donc davantage d'intégration verticale (impartition) lorsque les coûts de production du fournisseur sont faibles (élevés). De plus, ce changement réduit l'importance relative des coûts de production dans la détermination du mode d'approvisionnement. Une analyse similaire est effectuée pour les coûts de coordination.

L'effet d'introduire la concurrence entre fournisseurs a été analysé informellement. D'un point de vue statique, la concurrence augmente le recours à l'impartition, car elle réduit le coût de production espéré du fournisseur choisi en plus de réduire sa rente. Toutefois, d'un point de vue dynamique, suite à un changement technologique affectant les coûts de production, la concurrence tend à augmenter l'effet d'efficience (en augmentant le différentiel de coûts de production entre la firme et les fournisseurs) et à réduire l'effet de contrôle (en réduisant la rente des fournisseurs), ce qui peut se traduire par davantage d'intégration verticale. On voit que les effets statiques et dynamiques de la concurrence sur les frontières de la firme diffèrent.

On a examiné aussi l'effet de la supervision sur la règle de décision. Une meilleure supervision réduit les rentes reliées aux coûts de production externes et aux coûts de coordination internes, qui sont les coûts les plus difficiles à observer. Lorsque les coûts de production sont quantitativement plus importants que les coûts de coordination, l'effet net est d'induire davantage d'impartition. Toutefois, d'un point de vue dynamique, suite à un changement technique concernant les coûts de production, une meilleure supervision réduit les effets de contrôle (en réduisant l'importance des rentes), augmentant du même coup l'importance des effets d'efficience. Or, on sait que l'effet d'efficience associé à un changement technique concernant les coûts de production induit davantage d'intégration verticale (car la firme a des coûts de production plus élevés, et ces coûts sont plus faciles à observer que ceux du fournisseur). On voit que les effets statiques et dynamiques de la supervision sur les frontières de la firme diffèrent.

Ces résultats complètent ceux obtenus par Lewis et Sappington (1991) concernant les technologies de production et ceux obtenus par Reddi (1994)[26] concernant les TI. Lewis et Sappington (1991) trouvent que le changement technique sur les coûts de production augmente le degré d'intégration verticale, une prédiction qui n'est pas corroborée par l'évidence empirique. Par exemple, Empey (1988)[27] trouve que l'impartition augmente plus rapidement dans les industries où le changement technologique et les gains de productivité sont les plus importants. Le modèle étudié ici montre comment le changement technique sur les coûts de production et de coordination peut induire davantage d'intégration tout comme il peut induire davantage d'impartition. En comparant nos résultats à ceux de Lewis et Sappington, on constate que ne pas tenir compte des coûts de coordination produit des prédictions erronées quant à l'impact du changement technique affectant les coûts de production sur les frontières de la firme.

Durant les dernières décennies les investissements dans les TI ont crû à un rythme plus rapide que les investissements dans les technologies de production, d'où l'on peut conclure que les gains de productivité ont été plus importants pour les premières. Le modèle prédit que le changement technique sur les coûts de coordination augmente le plus souvent le degré d'impartition, alors que le changement technique sur les coûts de production augmente le plus souvent le degré d'intégration. Or, c'est ce qu'on observe empiriquement: une relation inverse entre les investissements en TI et le degré d'intégration des entreprises (Kambil, 1991;[28] Komninos, 1994;[29] Carlsson, 1988;[30] Brynjolfsson et al., 1994;[31] Shin, 1996).[32] Le modèle peut expliquer pourquoi davantage d'activités sont imparties dans les industries où les investissements en TI sont importants.

Toutefois, le modèle indique l'existence de situations où le contraire peut arriver. Empiriquement, il y a des instances où les TI ont augmenté le degré d'intégration. Par exemple,

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[26]Reddi, S.P., 1994, *The Impact Of Information Technology On The Organization Of Economic Activity (Outsourcing)*, Ph.D. Thesis, University Of Pennsylvania.
[27]Empey, W.F., 1988, *Contracting out of services by manufacturing industries*, Institut de Recherche en Politiques Publiques.
[28]Kambil, A., 1991, 'Information Technology and Vertical Integration: Evidence from the Manufacturing Sector', dans Guerin, C., Margaret E., et Wildman, S.S. (eds.), *Electronic services networks: A business and public policy challenge*, Greenwood, Praeger, London.
[29]Komninos, N.E., 1994, *The Effect of Information Technology on the Degree of Vertical Integration and Average Firm Size in the Manufacturing Sector*, Ph.D. Thesis, American University.
[30]Carlsson, B., 1988, *The Evolution of Manufacturing Technology and its Impact on Industrial Structure: An International Study*, The Industrial Institute for Economic and Social Research, Stockholm, Sweden.
[31]Brynjolfsson, E., Malone, T.W., Gurbaxani, V., et Kambil, A., 1994, 'Does Information Technology Lead to Smaller Firms?', *Management Science*, 40(12):1628-44.
[32]Shin, N., 1996, *The Impact of Information Technology on Vertical Integration: An Empirical Analysis*, http://hsb.baylor.edu/ramsower/ais.ac.96/papers/SHIN2.HTM, University of California, Irvine.

les chaînes d'hôtels centralisent la gestion des réservations (Gurbaxani et Whang, 1991).[33] Beede et Montes (1997)[34] analysent 46 industries américaines et n'identifient aucune relation agrégée entre les investissements dans les TI et l'emploi auxiliaire. Bröchner (1990)[35] prédit que, dans l'industrie de la construction, une des conséquences des TI sera l'émergence de contracteurs plus spécialisés qui voudront s'intégrer en amont dans la fourniture de matériaux et d'équipements spécialisés.

Ce premier essai constitue un mariage entre les explications contractuelles et les explications technologiques de l'existence et des frontières de la firme. Alors que les anciennes explications des frontières de la firme étaient caractérisées par un déterminisme technologique, les nouvelles explications sont caractérisées par ce que Englander (1988)[36] appelle un "déterminisme transactionnel". Williamson affirme que les coûts de transaction sont suffisants pour expliquer les frontières de la firme et que la technologie joue au mieux un rôle secondaire. Toutefois, comme le note Englander, les solutions technologiques aux problèmes de coûts de transaction sont implicites dans les arguments de Williamson. Des éléments tels que l'apprentissage et la coordination sont fondamentalement des phénomènes technologiques. De plus, la spécificité des actifs, qui est au coeur de la théorie des coûts de transaction, est fortement liée à des considérations technologiques.

Chandler a mis l'emphase sur le rôle de la technologie dans la théorie de la firme. North a critiqué Williamson et Chandler pour leur emphase sur une des deux dimensions aux dépens de l'autre. Les résultats de ce modèle donnent raison à la position de North, qui valorise l'interaction entre la technologie et les coûts de transaction. Lorsque le changement technologique et les asymétries informationnelles sont importants, l'effet du changement technologique sur l'approvisionnement ne peut être analysé sans tenir compte des asymétries informationnelles dans la firme et sur le marché. Les résultats obtenus ici vont même plus loin que Englander suggère, puisque son focus est -principalement- sur les interactions entre la technologie organisationnelle et les coûts de transaction, alors qu'ici il est montré que même la technologie liée au capital physique peut affecter les coûts de transaction. Dans un cadre

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[33]Gurbaxani, V., et Whang, S., 1991, 'The Impact of Information Systems on Organizations and Markets', *Communications of the ACM*, 34(1):59-73.

[34]Beede, D.N., et Montes, S.L., 1997, *Information Technology's Impact on Firm Structure: A Cross-Industry Analysis*, Working Paper ESA/OPD 97-2, Office of Business and Industrial Analysis.

[35]Bröchner, J., 1990, 'Impacts of information technology on the structure of construction', *Construction Management and Economics*, 8:205-18.

[36]Englander, E.J., 1988, 'Technology and Oliver Williamson's Transaction Cost Economics', *Journal of Economic Behavior and Organization*, 10(3):339-53.

dynamique, la firme choisira la technologie et la forme organisationnelle afin de minimiser (entre autres) ses coûts de management et de transaction, ce qui rend l'interaction entre les coûts de transaction et la technologie encore plus importante.

Les deuxième et troisième essais sont des contributions à la littérature sur l'investissement stratégique. Au départ la question posée par cette littérature était de savoir si la coopération en R&D est bénéfique. Cette question ayant été répondue par l'affirmative par nombre d'études théoriques et empiriques, la question maintenant est: quels types de coopération sont supérieurs, et lesquels vont émerger de manière décentralisée. Le deuxième essai a étudié la dimension verticale de la coopération en R&D. Dans le troisième essai l'emphase était sur la stabilité des consortiums de recherche, le partage d'information et les fuites causées par le partage volontaire d'information.

L'objectif du deuxième essai était d'analyser les externalités de recherche verticales entre des firmes en amont et des firmes en aval. On a modélisé deux industries verticalement reliées, avec des externalités horizontales au sein de chaque industrie et des externalités verticales entre les deux industries. On a analysé d'abord l'effet des externalités de recherche sur la R&D et le bien-être. Les externalités verticales augmentent toujours la R&D et le bien-être, alors que les externalités horizontales augmentent la R&D en contextes de coopération horizontale et de coopération généralisée et la diminuent en contextes de non-coopération et de coopération verticale. Une baisse de la R&D due aux externalités horizontales ne diminue pas nécessairement le bien-être, puisque la diffusion des innovations est améliorée. En contexte de non-coopération et de coopération verticale, les externalités verticales renforcent l'effet négatif des externalités horizontales sur la R&D, alors que les externalités horizontales mitigent l'effet positif des externalités verticales sur la R&D.

La comparaison des différents types de coopération en R&D a révélé qu'aucune structure coopérative ne domine uniformément les autres. Toutes les formes de coopération n'augmentent pas nécessairement la R&D par rapport à l'équilibre non-coopératif; mais, pour n'importe quel environnement d'appropriabilité, au moins un type de coopération augmente la R&D. Pour certains environnements d'appropriabilité, le classement de la coopération horizontale et de la coopération verticale dépend du niveau de concurrence: la coopération horizontale domine surtout lorsque la concurrence est forte; cela parce que l'internalisation des externalités horizontales devient plus importante à mesure que la concurrence augmente. Le classement général dépend des externalités horizontales, des externalités verticales et de la structure de marché. Ce classement dépend des signes et de l'importance relative de trois effets concurrentiels (vertical, horizontal et diagonal) captant l'effet de la R&D d'une firme sur les profits de toutes les autres firmes. Un des résultats de base de la littérature sur l'investissement stratégique est que la coopération entre concurrents augmente (réduit) la R&D lorsque les externalités horizontales sont élevées (faibles); or, le modèle a démontré que ce résultat n'est pas nécessairement vérifié lorsqu'on tient compte des externalités verticales et de la coopération verticale.

Le modèle fournit une théorie expliquant l'effet de la structure de marché sur l'innovation. Le modèle propose trois types de relations possibles entre la concurrence et l'innovation: a) une relation concurrentielle, où une intensification de la concurrence augmente l'innovation; b) une relation Schumpeterienne, où une augmentation de la concurrence diminue l'innovation; et c) une relation asymétrique, où l'innovation est maximisée lorsqu'une industrie est très concurrentielle alors que l'autre est très concentrée. Le modèle a montré comment le type de coopération et les niveaux des externalités horizontales et verticales déterminent laquelle de ces trois relations prévaut. La relation peut être comprise en termes des externalités concurrentielles horizontale, verticale et diagonale. Lorsque l'externalité concurrentielle horizontale domine, l'effet de la concurrence sur l'innovation est du même signe que cette externalité si elle est internalisée et du signe inverse si elle n'est pas internalisée. Lorsque l'externalité concurrentielle verticale domine, l'effet de la concurrence tend à être positif. Finalement, dans les cas où l'externalité concurrentielle diagonale domine (et qu'elle est internalisée), c'est généralement le modèle asymétrique qui prévaut.

Les incitations privées à la coopération en R&D ont été examinées. Les vendeurs et les acheteurs ont des préférences différentes quant au choix de la structure de coopération: entre la coopération horizontale et la coopération verticale, les vendeurs préfèrent la coopération verticale, alors que les acheteurs préfèrent la coopération horizontale. Cela est dû au fait que les vendeurs, à cause de leurs profits plus élevés, préfèrent dépenser plus en R&D que les acheteurs. Avec la coopération verticale, les acheteurs sont obligés d'augmenter leurs dépenses de R&D, augmentation qui bénéficie surtout aux vendeurs. On a analysé la stabilité de la coopération à l'aide des équilibres de Nash. En général il existe des équilibres multiples -sauf en l'absence d'externalités de recherche-; rien ne garantit donc que les firmes vont choisir le type de coopération socialement optimal (qui dépend des niveaux des externalités). La non-coopération est toujours un équilibre, même lorsqu'il existe des types de coopération préférés par toutes les firmes. Ces résultats montrent l'importance des problèmes de coordination et de négociation dans la coopération en R&D.

Une question importante dans l'étude des externalités et de la coopération verticales vs. horizontales est leur importance relative pour les décisions d'innovation par les entreprises. Le modèle suggère que les externalités horizontales ont plus d'impact sur les décisions des firmes que les externalités verticales. Le corollaire est que la coopération horizontale, qui internalise ces externalités horizontales, a plus d'impact sur la R&D que la coopération verticale. Par exemple, lorsque les deux externalités ont des effets opposés, l'effet des externalités horizontales tend à dominer. De même, en général, une variation dans le niveau des externalités verticales affecte les résultats quantitativement, alors qu'une variation dans le niveau des externalités horizontales peut causer des changements qualitatifs dans les résultats. Aussi, la coopération verticale est (presque) toujours bénéfique, mais elle augmente la R&D marginalement par rapport à la non-coopération; tandis que la coopération horizontale peut augmenter ou diminuer la R&D, mais toujours de manière significative par rapport à la non-coopération. Cette primauté des effets horizontaux s'explique par le fait que les externalités concurrentielles verticales, même si elles ne sont pas internalisées, bénéficient à la firme à cause de la réduction du coût total de production du produit final. En contraste, l'externalité concurrentielle horizontale ne bénéficie pas toujours à la firme: cela dépend de son signe et de son internalisation.

Par rapport à la politique d'innovation, le modèle préconise une politique de R&D "sur mesure", ou adaptée aux conditions spécifiques de chaque industrie, en opposition aux politiques standardisées. La politique optimale varie selon le niveau des externalités horizontales, des externalités verticales et des structures coopératives. Levin et al. (1987:816)[37] atteignaient une conclusion similaire lorsqu'ils notaient que "the incremental effects of policy changes should be assessed at the industry level". Ils ont aussi observé que l'impact de la protection de l'innovation dépend des autres mécanismes d'appropriabilité, qui sont spécifiques aux industries.

Au-delà des outils traditionnels de la politique d'innovation, le modèle suggère que le

[37]Levin, R.C., Klevorick, A.K., Nelson, R.R., et Winter, S.G., 1987, 'Appropriating the Returns from Industrial Research and Development', *Brookings Papers on Economic Activity*, pp.783-820.

choix de la structure coopérative et des incitations à la coopération, en tenant compte des conditions d'appropriabilité, est crucial pour la détermination des niveaux de R&D et de sa distribution entre les entreprises. Ces éléments devraient être vus comme des compléments, plutôt que des substituts, aux approches traditionnelles à la politique d'innovation.

Cet essai a mis l'emphase sur la dimension verticale de l'innovation, en termes d'externalités de recherche verticales et de coopération verticale. Geroski (1992)[38] a souligné l'importance des relations verticales, qui ont moins de chance d'induire la collusion entre firmes que les relations horizontales. La coopération verticale pose moins de problèmes anticoncurrentiels que la coopération horizontale. De plus, il peut être plus facile d'induire les firmes à coopérer avec leurs clients/fournisseurs qu'avec leurs concurrents.

La contribution principale du troisième essai est d'endogéniser le partage d'information entre des concurrents coopérant en R&D, et d'étudier sa relation avec la taille et la stabilité du consortium de recherche (RJV). Jusqu'ici, les études se sont concentrées sur la coordination des dépenses de R&D par les firmes qui coopèrent, et ont imposé le partage (ou le non partage) d'information aux firmes, sans aucuns fondements théoriques ou empiriques. Or, l'évidence empirique suggère que les RJVs varient en termes des règles de partage d'information.

On a modélisé une industrie de taille fixe où les firmes se concurrencent à la Cournot. Les firmes peuvent investir en R&D en vue de réduire leurs coûts. Il existe deux types d'externalités de recherche: une externalité générale, s'appliquant à toutes les firmes, et une externalité spécifique, s'appliquant au partage volontaire d'information entre les membres de la RJV. L'externalité spécifique constitue une fuite d'information de la RJV aux non membres. L'idée est que partager l'information augmente les chances qu'une partie de cette information soit transmise à d'autres firmes.

On a d'abord étudié le partage d'information par les membres de la RJV, pour une taille donnée de la RJV. Il a été montré qu'il existe un seuil critique de l'externalité spécifique au-delà duquel les firmes ne partagent pas d'information, et en deçà duquel les firmes partagent toute l'information. En l'absence de coûts de partage de l'information, les firmes ne choisissent jamais des niveaux intermédiaires de partage d'information. Donc, les niveaux intermédiaires seraient dus à des considérations technologiques ou à des considérations d'opportunisme, mais

[38]Geroski, P.A., 1992, 'Vertical Relations between Firms and Industrial Policy', *Economic Journal*, 102(410):138-47.

non pas à des considérations concurrentielles. Plus l'externalité spécifique est élevée, moins le partage volontaire d'information par les membres est rentable. Il se peut que les membres partagent de l'information même lorsque ce partage bénéficie davantage aux non membres qu'aux membres eux-mêmes (en termes de flux technologiques, à cause de l'externalité spécifique).

Le seuil critique de l'externalité spécifique augmente avec la taille de la RJV, indiquant que les RJVs plus larges tendront à partager l'information plus souvent que les petites RJV. Il existe une interaction entre la taille de la RJV et le partage d'information: une grande taille encourage le partage d'information (car l'externalité spécifique nuit moins à la RJV), et en même temps le partage d'information augmente l'intérêt d'augmenter la taille de la RJV, autant pour les membres que pour le non membre qui considère joindre la RJV.

Les déterminants de la décision de partager de l'information et de la quantité d'information à partager sont différents: c'est l'externalité spécifique qui détermine si les membres de la RJV partagent de l'information, alors que c'est l'externalité générale qui détermine le niveau du partage. Cela parce que l'externalité spécifique détermine l'effet du partage sur la position concurrentielle des membres, alors que l'externalité générale détermine la quantité d'information qu'il est possible de partager (qui n'est pas divulguée automatiquement à toutes les firmes de manière involontaire).

On a ensuite analysé la taille et la stabilité de la RJV. Cette taille est déterminée par trois effets: un effet de coordination, qui est relié à la coordination des dépenses de R&D par les membres; un effet de partage d'information, qui est relié à la possibilité qu'ont les membres de partager l'information; et un effet concurrentiel, qui est relié au fait qu'accepter un membre additionnel dans la RJV en fait un concurrent plus féroce. Du point de vue des membres, les deux premiers effets augmentent la taille profitable de la RJV, alors que le troisième la diminue. Du point de vue d'un non membre, les trois effets augmentent l'intérêt de joindre la RJV. L'importance de chacun des trois effets varie aussi avec la taille de la RJV, avec l'externalité générale et avec l'externalité spécifique.

La RJV est stable si aucun membre ne veut la quitter, que les membres n'ont pas intérêt à se débarrasser d'un membre et que l'une des deux conditions suivantes est satisfaite: soit qu'aucun non membre ne voudrait joindre la RJV, ou que les membres s'opposeraient à l'addition d'un membre. On a montré que la taille stable de la RJV a une relation en forme de U inversé avec l'externalité générale et avec l'externalité spécifique. On a distingué les cas où la taille de la RJV est limitée par la stabilité externe, de ceux où elle est limitée par le blocage par les membres. En général, la RJV est trop petite par rapport à l'optimum social.

Sur la base des résultats précédents on a analysé la diffusion technologique. La diffusion totale tend à diminuer avec l'externalité générale et aussi avec l'externalité spécifique: l'amélioration dans la diffusion due aux externalités ne compense donc pas les baisses dans les investissements en R&D. La décomposition de la diffusion totale en ses différentes composantes (effet propre, externalité générale, externalité spécifique, partage volontaire d'information) montre que l'externalité générale et le partage volontaire d'information sont les sources les plus importantes de réduction des coûts. L'effet propre représente une faible part de la réduction totale des coûts, et diminue avec les externalités, même s'il représente la seule source de réduction des coûts qui est strictement positive pour tous les niveaux des externalités. De manière générale, la plus grande partie de la réduction des coûts est due à la diffusion et au partage d'information, plutôt qu'à l'usage de la technologie par la firme innovatrice.

Les deux aspects fondamentaux de la RJV sont la coordination des dépenses de R&D et le partage volontaire d'information. Il s'avère que les gains de ces deux décisions ne varient pas de la même manière avec l'externalité générale. La coordination des dépenses diminue la R&D lorsque l'externalité générale est faible et l'augmente lorsque l'externalité est élevée. Il s'ensuit que les gains de la coordination des dépenses de R&D augmentent avec l'externalité générale. Inversement, la quantité maximale d'information que les membres de la RJV peuvent partager est celle qui n'est pas déjà divulguée par l'externalité générale. Cette quantité étant inversement reliée à l'externalité générale, on peut dire que les gains du partage volontaire d'information diminuent avec l'externalité générale.

Le résultat que les firmes partagent l'information lorsque la fuite sur le partage d'information est suffisamment faible suggère que les études existantes font d'importantes hypothèses implicites. Les études ne permettant pas aux firmes de partager l'information supposent implicitement que l'externalité spécifique est importante, alors que les études imposant le partage maximal d'information supposent implicitement que cette externalité est négligeable.