COLLABORATION IN RESEARCH

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DANSK RESUMÉ

Inden for de seneste årtier har der været en betydelig stigning i offentlig-privat samarbejde. Dette er gældende både i Danmark og internationalt. Samarbejde inkluderer både formelt samarbejde samt interaktioner af mere uformel karakter. Fordelene ved offentlig-privat samarbejde er bl.a. muligheden for videnoverførsel, læring og videnproduktion, som ikke vil have været muligt for parterne at opnå i isolation. Parallelt med udviklingen i offentlig-privat samarbejde har der været en betydelig stigning i antallet af politiske tiltag, som har til formål at promovere offentlig-privat samarbejde, da samarbejde vurderes som en væsentlig kilde til vidensprednings, der skal styrke effekten af forskningsindsatsen. Dette gælder både ift. forskningspolitik, som promoverer de såkaldte 'third mission' aktiviteter på universiteterne, kommercialisering og entreprenørskab generelt, og i form af innovationspolitik med det formål at tilskynde virksomheder til at interagere med offentlige forskningsinstitutioner.

Formålet med denne rapport er at undersøge sammenhængen i Danmark mellem omfanget af offentlig-privat samarbejde og performance hos forskere og virksomheder, der deltager i samarbejdet. Rapportens fokus er afgrænset til forskning i perioden 1995-2013, målt ved videnskabelige publikationer, samt forskningssamarbejde målt ved medforfatterskab af videnskabelige publikationer[1].

Forskningspublikationer kan bidrage positivt til virksomheders konkurrenceevne igennem flere kanaler. Samarbejdet om forskningspublikationer kan bidrage ved at forbedre virksomhedernes adgang og relationer til offentlig forskning, ved at forøge den interne forskningskapacitet, samt ved at have en strategisk indflydelse på udviklingen af relevante forskningsområder. Det kan lede til forbedrede resultater af virksomhedens forskningsindsats og dermed til bedre eller nye produkter og processer.

Forskningssamarbejder er en af flere mulige kanaler for vidensoverførsel. Forskningssamarbejder, som resulterer i videnskabelige publikationer, udgør kun en del af disse samarbejder. Netop forskningssamarbejder, som leder til videnskabelige publikationer, er dog af flere grunde særligt vigtige. For det første sætter forskningssamarbejde med videnskabelige publikationer fokus på forskning, der repræsenterer et langsigtet fokus på at skabe ny viden, som kan føre til innovationer. For det andet indikerer medforfatterskaber tæt interaktion mellem offentlige forskningsinstitutioner og det private. Samtidig har medforfatterskab den fordel, at det er muligt at undersøge effekten af forskningssamarbejder for begge parter af offentlig-privat samarbejde. Det gælder både videnskabelig citationimpact i form af citationshyppighed og den økonomiske effekt i form af virksomheders produktivitet. Ved at undersøge brugen af videnskabelige publikationer er det samtidig muligt at måle volumen af forskning produceret af danske forskningsinstitutioner, samt hvordan denne viden overføres til dansk erhvervsliv.

For at kunne sætte forskningssamarbejde, baseret på sampublikationer, i en bredere kontekst, sammenligner vi andelen af virksomheder engageret i forskning og udvikling samt innovationssamarbejde med offentlig forskning generelt. Det gør vi baseret på den danske FoU statistik. I 2013 havde 28,2 pct. af danske virksomheder med mindst 10 ansatte og med egne forskning-og udviklingsaktiviteter[2] samarbejdet med en offentlig forskningsinstitution om FoU og innovation inden for de seneste tre år. Til sammenligning har 18,3 pct. af virksomheder med FoU-aktiviteter udgivet mindst én videnskabelig artikel og 15,8 pct. af virksomhederne sampubliceret en videnskabelig artikel med en offentlig forskningsinstitution inden for de seneste tre år.

Målet med nærværende analyse er tredelt:
1) At kortlægge sampubliceringsmønsteret i dag og over tid,
2) At undersøge betydningen af sampublicering for videnskabelig citation impact (forskningsperspektivet) og
3) At undersøge betydningen af sampublicering for produktivitet i danske virksomheder (virksomhedsperspektivet).

[1] Samarbejde er defineret som forskningsartikler med mere end en forfatter. Dette inkluderer også de publikationer, hvor alle forfatterne kommer fra samme institution.
[2] Danske virksomheder udvalgt af Danmarks Statistik, da de på grund af størrelse, branche m.m. formodes at kunne være FoU aktive.

Rapporten adresserer følgende spørgsmål:

- Hvad er den totale forskningsproduktion i Danmark, og hvilken andel indebærer offentlig-privat og/eller internationalt samarbejde? Og hvordan har disse typer af samarbejde udviklet sig over tid?
- Hvor vigtig er den danske offentlige forskning for dansk industri sammenlignet med den internationale offentlige forskning? Nærværende rapport undersøger distinktionen mellem national og international vidensoverførsel til dansk erhvervsliv ved at se på samarbejdsmønstre for tidsskriftsartikler sampubliceret af danske virksomheder.
- Hvor stort er omfanget af publikationsaktiviteten i danske virksomheder? Vores mål er at karakterisere forskningssamarbejde og publikationsaktivitet generelt for Danmark i forhold til antallet af publicerings-aktive virksomheder, og i hvilke brancher det gør sig gældende.
- Hvad er citation impact for ren akademisk forskning i forhold til offentlig-privat forskning?
- Hvad er effekten på citation impact af forskningssamarbejde for den enkelte forsker? For at tjekke dette udvælger vi en fast gruppe af forskere, som både har sampubliceret med det private og i rent offentligt regi og sammenligner citation impact for denne gruppes offentlige forskningspublikationer med citation impact for deres offentlig-private forskningspublikationer.
- Hvor tæt er forskning, baseret på samarbejde, på forskningsfronten sammenlignet med andre typer af forskning?
- Er offentlig-private samarbejde mere tværdisciplinært end anden forskning?
- Hvordan er offentlig-privat samarbejde og videnskabelig produktion relateret til danske virksomheders produktivitet?
- Varierer sammenhængen mellem publikationsaktivitet, forskningssamarbejde og produktivitet mellem industrier?

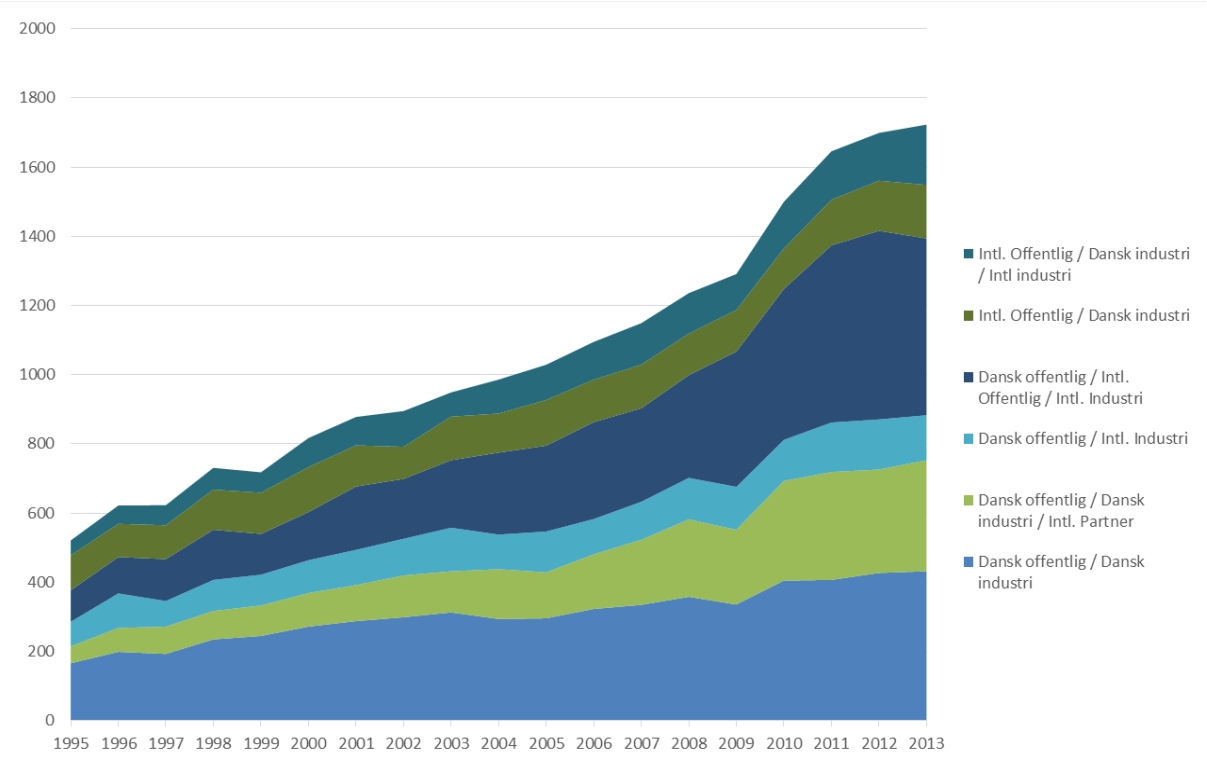
Hovedresultater af analysen

- Der har været store stigninger i både den offentlige og virksomhedernes samlede publikationsaktivitet samt i den offentlig-privat sampublicering. Nationale offentlig-private samarbejder er fordoblet i perioden 1995-2013, mens internationale samarbejder er mere end firedobbelt.[1]
- Et stigende antal danske virksomheder engagerer sig i videnskabelig publikation, og en stor del af disse involverer forskningsarbejde. Antallet af virksomheder, som har sampubliceret mindst én tidsskriftsartikel, er steget fra 104 i 1995 til 313 i 2013.
- Virksomhedernes nationale og internationale forskningssamarbejder involverer ofte dansk offentlig forskning. Andelen af artikler publiceret af danske virksomheder, som er publiceret i samarbejde med danske forskningsinstitutioner, er steget fra 36 pct. til 61 pct. fra 1995 til 2013.
- Citationsimpacten for forskningssamarbejder (dvs. artikler forfattet af to eller flere forskellige forfattere[1]) samlet set er over 50 pct. højere end for artikler med en enkelt forfatter. Effekten er endnu højere blandt offentlig-private samarbejder.
- For rene nationale samarbejder finder analysen ikke nogen klar forskel i citationseffekt mellem offentlig-privat samarbejde og rene offentlige samarbejder. Forskellen i citations-effekt mellem offentlig-privat samarbejde og rene offentlige publikationer er derfor primært drevet af internationale samarbejder. Det gælder især for de højst citerede artikler (blandt de top 1 pct. mest citerede), hvor andelen for internationale, offentlig-private samarbejder er mere end 300 pct. højere end verdensgennemsnittet.
- Der er ingen indikation at offentlig-privat samarbejde er mindre tvær-disciplinært end rent offentlig forskning
- Blandt en udvalgt gruppe af forskere, som har både rene offentlige publikationer og offentlig-privat samarbejder, er den gennemsnitlige citationseffekt signifikant højere for offentlig-privat samarbejder.
- Produktiviteten er 12-13 pct. højere i virksomheder med videnskabelige publikationer, uanset om det er med eller uden offentlig-privat samarbejde.

Vidensflows til danske virksomheder

Det totale antal tidsskriftsartikler er steget fra 6.738 i 1995 til 16.351 i 2013 (se figur 0.1). Dette dækker i et vist omfang over stigninger i dækningsgraden i de internationale databaser, men stigningen er væsentlige større end det der kan forklares med udviklingen i databasernes dækningsgrad. Det er især internationalt samarbejde med andre offentlige forskere, som er steget med 400 pct. i perioden, og som nu udgør halvdelen af alle publikationer. Antallet af både nationale såvel som internationale offentlig-private samarbejder er steget. De nationale samarbejder er fordoblet i perioden, mens de internationale samarbejder er mere end firedobbelt. Offentlig-privat samarbejde udgjorde 10,5 pct. af det samlede publikationsaktivitet i 2013.

Figur 0.1. Tidsskriftsartikler med offentlig-privat samarbejde, efter samarbejdstype, 1995-2013



Ud over forøgelsen af offentlig-private samarbejder, har et stigende antal danske virksomheder engageret sig i videnskabelig produktion. Antallet af virksomheder, som har sampubliceret mindst én tidsskriftsartikel, er steget fra 104 i 1995 til 313 i 2013. I 2013 publicerede eller sampublicerede danske virksomheder 1.163 tidskriftsartikler. En stor del af disse virksomheder har kun publiceret en enkelt publikation, mens en lille gruppe virksomheder har publiceret en stor del af artiklerne.

I alt er andelen af artikler med internationale medforfattere steget fra 39 pct. i 1995 til 61 pct. i 2013. Det påvirker dog ikke inddragelsen af offentlig dansk forskning negativt. Selvom danske virksomheder i stigende grad engagerer sig i internationale samarbejder, involverer de i stigende grad også dansk offentlig forskning.

Måling af forskningsproduktion og vidensflows til danske virksomheder

Som vores primære mål for forskningsviden definerer vi forskningsviden produceret i Danmark i et givent år, som antallet af publikationer med mindst en medforfatter fra en dansk adresse. Dette inkluderer derfor både private virksomheder, universiteter og andre offentlige organisationer, som har adresse i Danmark. Samarbejde er målt i forhold til samforfatterskab af publikationer. Dette studie fokuserer hovedsageligt på tidsskriftsartikler dækket af Web of Science, men inkluderer også i begrænset omfang konferencepapirer, som ofte anvendes inden for ingeniørvidenskab og IT. Dækningen af forskningspublikationer skrevet af danske offentlige forskningsinstitutioner og den private sektor er meget omfangsrig.

Samarbejdstyper er klassificeret i forhold til, hvorvidt danske offentlige forskningsinstitutioner og/eller dansk erhvervsliv er involveret, og hvorvidt der er samarbejde med internationale partnere (både offentlig forskning og den private sektor.).

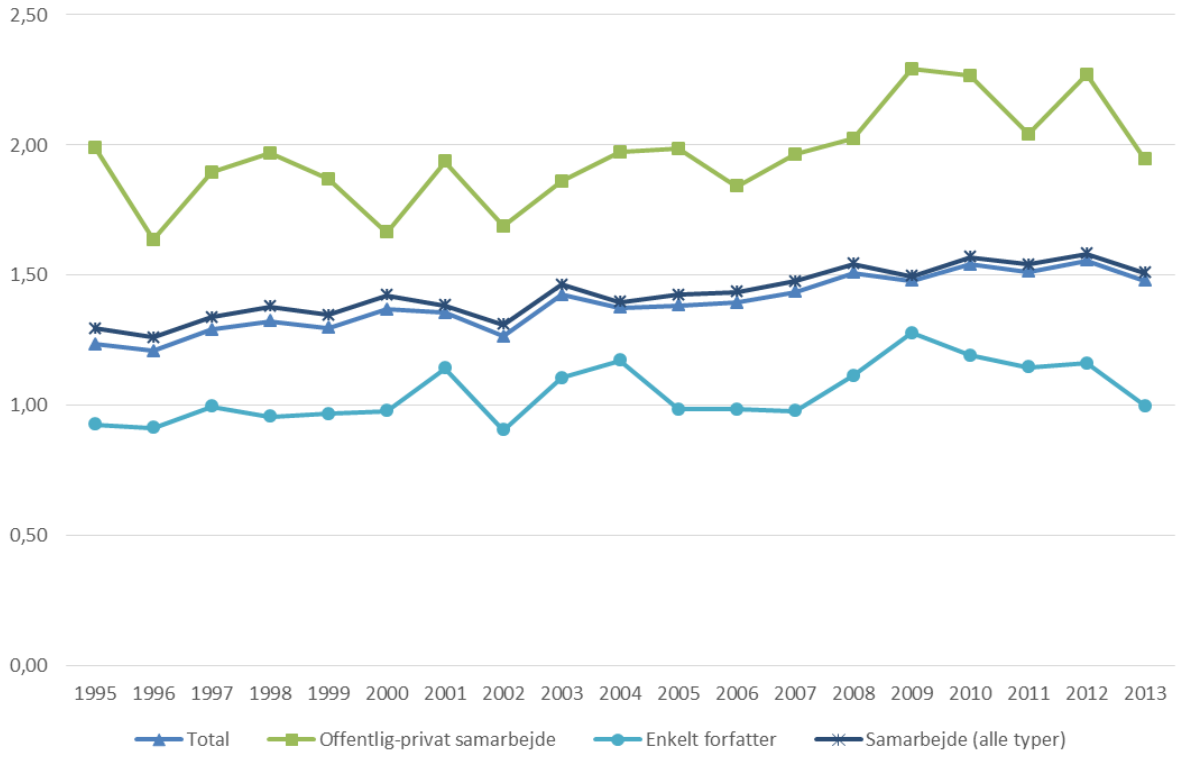
I 1996 var 36 pct. af danske industriartikler[3] publiceret i samarbejde med danske forskningsinstitutioner. Denne andel er steget og har ligget stabilt på 60-61pct. i perioden 2010-2013.

Citationsanalyse of forskningssamarbejde

Samlet set er citation impact for forskningssamarbejder med to eller flere forfattere over 50 pct. højere end for artikler med en enkelt forfatter, og den er endnu højere blandt offentlig-private samarbejder. Mean normalized citation score (MNCS; se forklaring i boksen nedenfor) for publikationerne med enten dansk eller international offentlig-privat samarbejde var på 1,95 i 2013, hvilket er 95 pct. højere end verdensgennemsnittet (se figur 0.2). Til sammenligning var MNCS for alle danske artikler 1,48 i 2013, og den var 1,00 for artikler med en enkelt forfatter. Forskellen er dog primært drevet af internationale samarbejder, hvor internationale offentlig-private samarbejder havde en MNCS på 2,13 i perioden 2010-2013, mens rent danske offentlige private samarbejder havde en MNCS på 1,12 i samme periode. Der findes ikke en klar forskel i citation impact mellem nationale offentlig-private samarbejder og rene offentlige forskningssamarbejder, med kun nationale samarbejdspartnere.

Citationsanalyse of forskningssamarbejde
Mean normalized citation score (MNCS) er et normaliseret mål for citation impact på tværs af forskningsområde, år og publikationstype. Hvis en enhed har en MNCS på 1, er de tilhørende publikationer blevet citeret i gennemsnit lige så meget, som verdensgennemsnittet for lignende publikationer i forhold til forskningsområde, år og publikationstype.

Figur 0.2. Citation impact over tid for samtlige publikationer og offentlig-private samarbejder, 1995-2013



Blandt samarbejdspublikationer er citation impact generelt lavest for publikationer, som kun indeholder dansk offentlig forskning. Hvis man ser på hele perioden har danske offentlig-private publikationer typisk haft en marginalt højere citation impact end rene danske offentlige publikationer. Forskellene er dog ikke særlig store, og faktisk har danske offentlige forskningspublikationer haft et højere MNCS i perioden 2010-2013, hvor den var 1,2 sammenlignet med 1,12 for offentlig-private publikationer.

[3] Danske industriartikler er artikler med en dansk privat virksomhed (uanset branche) som forfatter eller medforfatter.

Internationale samarbejder, som kun indeholder offentlig forskning, har højere citation impact end nationale samarbejder. I perioden 2010-2013 er citation impacten omkring 40 procentpoint højere for internationale offentlige forskningssamarbejder end for nationale samarbejdspublikationer.

I analysen finder vi ikke en signifikant forskel i citation impact mellem offentlig forskningspublikationer og offentlig-privat forskningspublikationer, når der ses på ren dansk forskning. Ydermere er MNCS faldet over tid for rent danske offentlig-private samarbejder (se figur 3.2 nedenfor). Dette til trods for, at andelen af publikationer uden citationer er faldet. Det tyder på, at faldet i MNCS hovedsageligt er grundet en international orientering, hvor de bedste forskere i højere grad søger internationalt samarbejde.

Det højeste citation impact finder vi blandt internationale offentlig-private samarbejder, som inddrager både danske og internationale forskningsinstitutioner samt international industri. De har en MNCS på 3,05 i perioden 2010-2013. Det betyder, at disse publikationer er 205 pct. mere citeret end verdensgennemsnittet. Disse resultater viser, at publikationer, som inkluderer internationalt offentlig-privat samarbejde, i gennemsnit har en meget højere citation impact end internationale samarbejder, som kun indeholder offentlige forskningsinstitutioner. Citation impact for alle internationale offentlig-private samarbejder var på 2,13 i perioden 2010-2013.

Forskningsfronter defineres som artikler som er blandt de 1% mest citerede i deres felt et år efter publication. Den højeste andel findes hos internationale offentlig-private samarbejder, hvor godt 4% af artikler betegnedes som forskningsfronter i 2010-2013. Dermed har internationalt offentlig-privat samarbejde en større tendens til at resultere i højt-citerede forskning.

Både graden af multi-disciplinaritet (antal discipliner som artiklen referrer til) og graden af inter-disciplinaritet (andel af referencer som stammer fra andre discipliner) er steget over tiden. Dog findes der ingen klar forskel i multi- eller inter-disciplinaritet i forhold til international samarbejde eller offentlig-privat samarbejde.

Der kan muligvis være en selektionseffekt ved sammenligning af rene offentlige publikationer og offentlig-privat samarbejder, eksempelvis hvis impact er generelt højere blandt de forskere, som indgår i offentlig-privat samarbejde. Vi forsøger at håndtere den form for selektion ved at undersøge forskelle i impact blandt en gruppe af forskere, som både har rene offentlige publikationer og offentlig-privat samarbejder. Blandt den udvalgte gruppe var den gennemsnitlige citation impact signifikant højere for offentlig-privat samarbejder end for publikationer uden offentlig-privat samarbejde. Resultatet drives af store forskelle blandt en mindre gruppe af forskere. For størstedelen er der ikke en signifikant forskel. For rene danske publikationer er der dog ingen signifikant forskel på den gennemsnittelige citation impact mellem de to typer af publikationer.

Forskellen i citation impact er størst blandt internationale publikationer. Når internationale samarbejdspublikationer inkluderer industripartnere, er den gennemsnitlige citation impact signifikant højere end for rene offentlige internationale samarbejder. Det skal bemærkes, at når der ses på hele fordelingen af forskere, finder vi, at citation impact for internationale offentlige private samarbejder kun er signifikant højere for den øverste halvdel af forskere, mens der ikke er en signifikant forskel for den laveste halvdel. Dermed ser det ud til at forskellen i citation impact mellem de to grupper primært drives af en mindre andel af forskere med internationale offentlige private samarbejder.

Forskningssamarbejde og virksomhedernes produktivitet

Den gennemsnitlige værditilvækst per ansat er signifikant højere for virksomheder, som aktivt publicerer i videnskabelige tidsskrifter. Det samme resultat findes, når man sammenligner virksomheder med offentlig-privat samarbejdspublikationer med virksomheder uden publikationer. Til gengæld er der ingen signifikant forskel i værditilvækst per ansat for virksomheder, som kun publicerer alene eller med andre virksomheder sammenlignet med virksomheder, som publicerer sammen med offentlige forskningsinstitutioner

Om analysen af forskningssamarbejde og virksomhedernes produktivitet

Til analysen af relationen mellem produktivitet, publicering og forskningssamarbejde anvendes publikationsdata samt registerdata fra Danmarks Statistik for firmaer med mere end 10 ansatte i perioden 1999-2013. I alt har 767 virksomheder (med mindst 10 ansatte) publiceret en videnskabelig publikation i perioden. Den primære afhængige variable er produktivitet, der er defineret som værditilvækst per ansat. Virksomheder med videnskabelig publicering matches med virksomheder uden publicering, men som er sammenlignelige på andre parametre såsom andelen af højtuddannede ansatte, virksomhedsstørrelse og branche

Analysen viser, at relationerne mellem produktivitet og tre typer af publikationsprofiler (kun offentlig-privat publikationer, kun industri publikationer og begge typer) er positive og signifikante. Effekten er næsten det samme for de tre typer af publiceringsprofiler. Således har virksomheder med videnskabelige publiceringer 12-13 pct. højere produktivitet end sammenlignelige virksomheder uden publicering.

Relationen mellem videnskabelig publikation, forskningssamarbejde og virksomheders produktivitet varierer i stort omfang i mellem industrier. Effekten af artikler uden offentligt samarbejde er højest for Fødevarer samt Maskiner, mens effekten for begge typer er højest for Gummi og Plast, Elektronik samt Råolie og Kemiske produkter). Det har ikke været muligt at identificere årsagerne til disse forskellige resultater inden for industrierne.

1 INTRODUCTION

There has long been focus on the role of collaboration in research and innovation, both within and across sectors. A cornerstone of theories such as the Triple Helix (Etzkowitz and Leydesdorff 2000) and of Innovation Systems (Lundvall 1992; Nelson 1993) is that collaboration increases knowledge transfer, allows for mutual learning and can lead to knowledge creation that would not have been possible for individual actors in isolation.

In the past few decades, there have been substantial increases in public-private collaboration, both in Denmark and internationally. This includes both formal collaboration and interactions of a more informal nature. Parallel to this has been strong increases in the number of policies to promote public-private collaboration, both in terms of research policy that promotes the so-called third mission activities of universities, commercialization and entrepreneurialism in general, and in terms of innovation policy that encourages firms to engage in interaction with public research.

This report seeks to examine the production of research in Denmark, the extent of public-private collaboration and its relation to both scientist's scientific performance and firm's economic performance in the period from 1995-2013. The focus of this report is on research measured in terms of scientific publications and research collaboration measured through the co-authorship of publications[4].

Scientific publication has been argued to contribute to firm performance through a number of channels, by improving access and relations with public research, by increasing internal research capacity, and by strategically influencing the development of research fields (Li et al. 2015). Firms may choose to engage in public-private collaboration for these same reasons, though with the added benefit of being able to draw on public research through close interaction.

Public-private interaction can take many forms, such as joint research activities, training and transfer of personnel, commercialization activities and informal contacts (see e.g. Ramos-Vielba et al. 2010; Martin and Tang 2007). Hence, research collaboration is only one of a number of possible channels for knowledge transfer, and collaborations that result in scientific publication are only a subset of these collaborations.

However, this channel is important for a number of reasons. First, it places focus on research, which represents a longer term focus on creating new knowledge that can lead to novel innovations. Second, co-authorship represents close interaction between public research and industry. Furthermore this channel enables us to examine the possible impact of research collaboration from both sides of public-private collaborations, both the scientific impact measured by the citation frequency of publications and the economic impact measured in terms of firm productivity. Furthermore, scientific publications allow us to measure the volume of research produced by Danish public research and the flows of this knowledge to Danish industry.

In order to set research collaboration based on co-publication in a broader context, we compare the share of firms with 10 or more employees that are engaged in R&D and innovation collaboration with public research overall, based on the Danish R&D statistics. In 2013, 28.2% of firms with R&D activities had engaged in R&D and innovation collaboration with a public research institution within the last three years[5]. In comparison, 18.3% of firms with R&D in 2013 had authored a scientific publication in the last three years and 15.8% had co-authored a publication with public research.

The **objective** of this study is threefold:

- to analyze scientific publication, public-private collaboration and knowledge flows from university research to the business sector;
- to analyze the scientific impact of public-private collaboration through analysis of the citation impact of public-private co-authored papers in comparison with other types of papers, including pure business collaborations and pure academic collaborations; and

[4] Co-authorship defined as publications with more than one author. This also publications, where all authors are affiliated to the same organisation
[5] Source: own calculations based on R&D data from Statistics Denmark. Based on population of firms with 10 or more employees within the industry sectors that are covered by the Danish R&D and innovation survey.

— to analyze the relation between scientific publication, research collaboration and productivity for Danish firms through matching and econometric analysis.

The report examines the following questions.

What is the total production of research in Denmark and what shares of research involve public-private collaboration and/or collaboration with international partners? Our aim here is both to characterize the extent of different types of collaboration involving industry and international partners and to examine how these have developed over time. We also examine research collaboration across different scientific fields and the degree of interdisciplinarity for different types of collaboration.

How important is Danish public research to Danish business in comparison with international public research? Research has increasingly become international, with both universities and industry increasingly choosing to collaborate with international partners. This can have clear benefits, in particular for a small country such as Denmark. The amount of research, competences and expertise abroad is vast compared to that in Denmark. On the other hand, a large number of studies have shown the importance of proximity to public research for business innovation, both in facilitating close contact and transfer of tacit knowledge and in strengthening local knowledge bases (Arundel and Geuna 2004, Hewitt-Dundas 2013, Fritsch and Schwirten 1999). Danish public research can also be vital in facilitating collaborative relations involving Danish business and international partners. This report examines the distinction between national and international knowledge transfer to Danish industry by examining collaboration patterns for journal articles co-authored by Danish firms.

How extensive is publication activity among Danish firms? Our goal here is to characterize research collaboration and publication activity overall for Danish firms in terms of the number of firms with publication activity and the distribution across industries.

What is the citation impact of academic research compared to public-private research collaboration? Given the large focus on collaboration, this is an important topic and one for which there is limited information on. There is now fairly widespread evidence that papers involving collaboration of some form are on average more highly cited than papers with a single author, and that papers involving international collaboration are even more highly cited. However, there is much less evidence on citation impact for public-private collaboration in particular. Lebeau et al. (2008) however examines this using data for Canada and finds that the average scientific impact of university-industry papers is significantly above that of both university-only papers and industry-only papers.

What are the differences in citation impact for collaboration at the level of the individual researcher? While it is likely that almost all university researchers write at least some of their articles either alone or with other academic researchers, only a share of academic researchers collaborate with industry[6]. Hence, when we compare citation impact for collaboration in the aggregate, we are to a certain degree comparing different sets of researchers potentially with different levels of citation impact. Earlier studies have also typically found that researchers (and universities) that engage in collaboration with industry on average have higher productivity and citation impact (Balconi and Laboranti 2006; Van Looy et al. 2004, Barnes et al. 2002; Abramo et al. 2009). This may stem from a selection bias, where firms prefer to collaborate with the best researchers and universities. In order to account for this, we select a fixed group of researchers that have engaged in both university-only publications and public-private collaboration and examine their citation impact for university-only compared to public-private articles.

How close is research based on collaboration to the research frontier compared to other types of research? An often raised question concerning public-private collaboration is whether or to what extent this collaborative research contributes to the advancement of state of the art within research fields. Arguments have been made that a focus on the utilization of research in commercial applications detracts attention from efforts to further state of the art research and may have negative consequences for the advancement of science in general. Based on well-established bibliometric methods and indicators, we will identify and map research frontiers within research specialties using citation data (e.g. Small & Griffith, 1974; Jarneving, 2005; Lucio-Arias & Leydesdorff, 2009; Small, Boyack & Klavans, 2014).

[6] In this report, "industry" refers broadly to all privately owned firms in Denmark. This includes private firms that deliver public services.

How is public-private collaboration and scientific publication related to productivity for Danish firms? Firms conduct research and engage in collaboration with public research with the goal of improving performance. Different mechanisms may be at work for the relation to productivity for Danish firms. Public-private collaboration may have direct benefits in itself by producing new research results that can lead to innovation and growth, but the learning and knowledge-building may also prove valuable for other innovation projects that are not connected to the collaboration. We examine both the relation of research collaboration and of scientific publication in general with firm productivity. A matching approach will be used in order to control for other factors such as firm size, industry and knowledge intensity.

Does the relation between publication, research collaboration and productivity vary across industries? There can potentially be large differences across industries, both in the scope and characteristics of research and in the impact of research on firm operations. In some industries, research, the publication of research results and collaboration with universities can almost be considered a necessity, where a direct linkage can be drawn between the published research and product development. For other industries, the connection between research and performance is perhaps less clear and direct. Knowledge and capacity building, in particular through interaction with public research, may be the most important outcome of the research, as opposed to the specific results themselves. We use mixed levels regression to examine how the relation between publication, collaboration and productivity varies across industries.

1.1 On the scope of this study

Both the measurements of university research knowledge and of flows to firms are very challenging. Knowledge creation may not always result in a tangible output, but instead in an increase in the knowledge and competences of the researcher (which potentially can be passed on to firms via close interaction). Inputs (for example, research expenditures or FTEs) can be seen as a proxy for knowledge creation, but these fail to take account of the actual creation of knowledge and the many variable factors that can influence research performance. The most recognizable output of public research is publications. However, there are also a number of other types of outputs, such as patents, instruments and other forms of commercialization. Though, in many cases, it is likely that these other forms build on published research results.

In this study, we seek to create a measure of research knowledge created in Denmark. Our measure is comprehensive in terms of what it seeks to measure but at the same time it has a number of limitations. Hence, it is important to explain what types of knowledge creation the study does and does not cover.

As our main measure of research knowledge, we define the research knowledge created in Denmark in a given year as the total number of journal articles or conference papers with at least one author from a Danish address. Hence, this includes both private firms, universities and other public research organizations located in Denmark.

Measurement of publications also varies, with great potential concerning journal articles and more limited possibilities for other types, such as conference papers, books and reports. Our study also includes conference papers, which are very prevalent in the engineering and computer sciences. However, data on field normalized citation impact are not available for conference papers and data quality is not sufficient to make some of the detailed classifications of publications that are possible with journal articles. For this reason, our use of conference papers, both in this section and elsewhere in the report, is more restricted than for journal articles.

In measuring research collaboration, our main focus is the use of co-authorship as an indicator of collaboration. Katz and Martin (1997) discuss in detail the advantages and limitations of co-authorship as an indicator of collaboration. They consider it a valuable, partial indicator of collaboration. Bozeman et al (2013) suggest that co-authorship should also be seen as one of a number of forms of interaction.

The definition used here excludes other forms of publications such as books or reports. It also excludes knowledge creation that either is not codified or is embodied in other forms such as patents or new products. Furthermore, as our focus is on research collaboration, and in particular co-authorship, we do not cover other channels of knowledge transfer from public research to industry. These include the transfer of human capital through mobility, teaching and training of researchers, and commercialization activities such as spin-outs, patents, licensing. Earlier work has indicated that commercialization and publication are two different things with different motivations. Though, on the other hand, it is clear that the two can be connected and can strengthen each other.

1.2 Data

While this report concerns a single topic, research collaboration, it does so using a variety of datasets and methods, where both the unit of analysis and sample vary across analyses. The main data sources are:

- Journal articles in the Web of Science database
- Conference papers in the Scopus database
- Linked employer-employee register data, Statistics Denmark

Table 1.1 provides an overview of the data, time periods and units of analysis used in the analyses in this report. Both data and method are described in greater detail in each individual section. Section 2 uses mainly data on journal articles from WoS. Data on conference papers are also shown in some figures, but their use is limited. However, note that publication variables constructed at the firm level are based on both journal article and conference paper data.

Table 1.1. Data, time period and unit of analysis for the main analyses in this report

Question	Unit	Data and full sample	Time period
Section 2			
What is the total production of research in Denmark and what shares of research involve public-private collaboration and/or collaboration with international partners?	Publication	Journal articles with at least one author with Danish address; Conference papers with at least one author with Danish address.	1995-2013
How important is Danish research to Danish industry in comparison with international public research?	Publication	Journal articles with at least one author with Danish address	1995-2013
How extensive is publication activity among Danish firms?	Firm	All Danish firms with a journal article or conference paper (includes also firms with less than 10 employees)	1995-2013
Section 3			
What is the citation impact of academic research compared to public-private collaboration?	Publication	Journal articles with at least one author with Danish address	1995-2013
What are the differences in citation impact for collaboration at the level of the individual researcher?	Individual	Public sector researchers that were corresponding author of a public-private collaborative paper	2006-2012
How close is research based on collaboration to the research frontier compared to other types of research?	Publication	Journal articles with at least one author with Danish address	2000-2013
Section 4			
How is public-private collaboration and scientific publication related to productivity for Danish firms?	Firm	Firms with 10 or more employees (with successful match with register data). Publication variables based on both journal articles and conference papers.	1999-2013
Does the relation between publication, research collaboration and productivity vary across industries?	Firm	Firms with 10 or more employees (with successful match with register data). Publication variables based on both journal articles and conference papers.	1999-2013

Data on firms in section 2 covers all firms regardless of size. However, the productivity analyses in section 4 are only based on firms with 10 or more employees, and where a match was found with register data. All citation data and analyses based on citation data are based only on journal articles and do not use conference papers.

The time period for analyses involving publication data is 1995-2013, while productivity analyses for firms are for the period 1999-2013. This is due to data availability for firm financial data.

1.3 Main results

Section 2 of this report examines the development in research publications and different forms of research collaboration over the period 1995-2013. Section 3 examines the citation impact[7] of research collaborations. Section 4 investigates the relation of research collaboration and firm productivity.

Box 1.1 below summarizes the main results of the study. A more detailed summary of results is included in the beginning of each individual section.

Box 1.1. Main results of the study

Large increase in publication activity overall with a parallel increase in public-private collaboration. Strong shift towards international collaboration.

The total annual number of journal articles has increased dramatically from 6738 in 1995 to 16351 in 2013. In particular, international collaboration with other public researchers has increased almost four-fold over the period, with the share of total publications involving international collaboration increasing from 39% in 1995 to 61% in 2013. The number of both national and international public-private collaborations has increased greatly over the period, with national collaborations more than doubling and international collaborations more than quadrupling. Public-private collaboration accounted for 10.5% of total publications in 2013.

Alongside the increase in public-private collaboration, an increasing number of Danish firms have engaged in scientific publication. An estimated 313 firms co-authored a journal article in 2013, compared to 104 in 1995. Danish firms have authored in all 1,163 journal articles in 2013. A large share of these firms have only published a single publication, while a small group of firms have co-authored the large majority of papers, in particular journal articles.

Danish industry publication activity has also become more and more international, though these international collaborations have increasingly also involved Danish public research. International collaboration not involving Danish public research has increased from 201 to 420 publications per year from 1995 to 2013; however international collaboration that does involve Danish public research has increased more than six-fold over the period from 49 to 321.

In 1995, 36% of Danish industry papers involved collaboration with Danish public research. The share has since risen to and remained at 60-61% from 2010 to 2013.

Higher citation impact for international public-private collaboration, but no clear difference between public research papers and public-private collaborations for national papers

Overall, citation impact is high for public-private collaborations, with a mean normalized citation score[3] (MNCS) at 1.95 in 2013, which is 95% higher than world averages. In comparison, MNCS for all publications with at least one Danish address was 1.48 in 2013. This difference is mainly driven by international collaborations, where MNCS for international public-private collaborations was 2.13 in the period 2010-2013 compared to 1.12 for national public-private collaborations in the same period.

[7] The mean normalized citation score (MNCS) indicator is obtained by averaging the normalized citation scores of all publications of a unit (e.g. researcher, institute or faculty). If a unit has an MNCS indicator of one, the publications of the unit have been cited on par with world averages.

National public-private collaborations have generally had a slightly higher citation impact than papers only involving Danish public research, though the difference is not large and in fact MNCS for Danish public research papers is slightly higher than Danish public-private collaboration in 2010-2013. The analysis suggests that the decline in citation impact for Danish public-private collaborations is mainly due to increased international orientation, where the best researchers now have a relatively greater tendency to seek international collaboration.

International papers involving public-private collaboration have on average substantially higher impact than international collaborations only involving public research.

Research fronts are defined as papers that are among the top 1% most highly cited within their field in the first year after publication. The highest share is for international public-private collaborations, where just over 4% of papers were research fronts in 2010-2013. This would suggest that these types of constellations of research partners are better suited to produce high impact research. These shares also provide an indication that high average citation impact for international public-private collaboration is at least in part driven by a small group of very highly cited articles.

Both the degree of multi-disciplinarity (defined as the number of different disciplines that a publication refers to) and of interdisciplinarity (defined as the share of references from other disciplines) of journal articles have increased over time. However, there does not appear to be any clear difference according to international collaboration or public-private collaboration. Hence, there is no indication that public-private collaboration is less multi- or inter-disciplinary.

Among a fixed group of researchers with both public research and public-private publications, average citation impact is significantly higher for public-private collaboration. However, this result appears to be driven by large differences among a smaller group of researchers. For the majority of researchers, there is no significant difference.

Similar results are found for international collaboration, where international public-private collaboration is only found to be significantly higher than international public research collaboration for the top half of researchers measured in terms of citation impact.

Higher productivity among firms that engage in scientific publication. No difference when comparing industry-only and public-private publication

Average productivity (measured as value-added per employee) is significantly higher for firms that actively (conduct and) publish their research in peer-reviewed journals compared to firms that don't publish.

Among firms with different publication profiles (only public-private, only industry and both types of publications), no significant difference was found in productivity for a matched sample. Hence, among firms that publish, we do not find evidence that public-private collaboration has a further effect on productivity.

However, in a simple comparison (without matching) for firms with these three types of publication profiles, average value-added per employee for firms with both types of publications was found to be 170,000 DKK higher than for firms with industry-only publications. This difference is though not significant.

The relation between scientific publication, research collaboration and firm productivity varies greatly across industries. Effects for industry-only publications are highest within Food and beverages and Machinery while coefficients for both types of publications are highest within Rubbers and plastics, Electronics, and Petroleum and chemicals. However, the analysis is unable to identify the specific causes behind this diversity.

2 KNOWLEDGE FLOWS TO DANISH FIRMS

2.1 Summary

The purpose of this section is to measure the scientific knowledge created in Denmark and knowledge flows from public research to industry. More specifically, the section seeks to shed light on three questions:

- What is the total production of research in Denmark and what shares of research involve public-private collaboration and/or collaboration with international partners?
- How important is Danish research to Danish industry in comparison with international public research?
- How extensive is publication activity among Danish firms?

As our main measure of research knowledge, we define the research knowledge created in Denmark in a given year as the total number of publications with at least one author from a Danish address. Hence, this includes both private firms, universities and other public research organizations located in Denmark. Collaboration is measured in terms of co-authorship of publications. While the focus of this study is on journal articles registered in the Web of Science database, the study also includes to a limited extent conference papers, which are very prevalent in the engineering and computer sciences. The coverage of research publications by Danish public and private sector researchers is thus very comprehensive.

Types of collaborations are classified according to whether Danish public research and/or Danish industry are involved and to whether there also is collaboration with international partners (public research and/or firm).

The total annual number of journal articles has increased dramatically from 6738 in 1995 to 16351 in 2013. Growth has been particularly strong in the last 10 years, where the total number of publications has increased by 87%. The large majority of publications are public research papers that do not involve industry collaboration. In particular, international collaboration with other public researchers has increased almost four-fold over the period and now accounts for over half of all publications. However, while it still accounts for only 10.5% of total publications, public-private collaboration has also increased greatly over this period. The number of both national and international public-private collaborations has increased greatly over the period, with national collaborations more than doubling and international collaborations more than quadrupling. In 2013, in all 1323 journal articles involved public-private collaboration. The increase in collaboration articles greatly exceeds the growth database coverage.

In addition to these, many public research-only papers are subsequently (within three years) cited by papers authored or co-authored by industry, accounting for 2.2% of all Danish journal articles in 1995 and 2.6% in 2011

In general, there has been a trend upwards in the share of public-private collaboration for Danish universities. In comparison with national public-private collaboration, there appears to have been greater convergence in shares with collaboration with international industry. Despite this trend, there are still fairly sizable differences across universities. At start of period in 1995, the overall share with public-private collaboration (both national and international) was markedly higher for DTU at 10% while shares for others were between 5-6%. Shares in 2013 are around 14% for DTU, 10% for Aalborg University (AAU) and University of Copenhagen (KU), and 7% for Aarhus University (AU) and University of Southern Denmark (SDU).

Alongside the increase in public-private collaboration, an increasing number of Danish firms have engaged in scientific publication. In all an estimated different 1674 firms have authored or co-authored a journal article over the period 1995-2013 and 416 a conference paper. For journal articles, the annual number of firms with articles has increased from 104 in 1995 to 313 in 2013. A large share of these have only published a single publication, while a small group of firms have co-authored the majority of papers, in particular journal articles.

The above has shown that research has increasingly become international, with both universities and industry increasingly choosing to collaborate with international partners. In all, the share of total publications involving some form of international collaboration has increased from 39% in 1995 to 61% in 2013. Danish public research can also be vital in facilitating collaborative relations involving Danish industry and international partners. The number of (national and international) publications involving Danish public-private collaborations has increased from 166 to 432 over the period. In 1995, 36% of DK industry papers involved collaboration with DK public research. The share has since risen to and remained at 60-61% from 2010 to 2013.

Furthermore, international collaborations have become increasingly likely to also involve Danish public research. International collaboration involving Danish industry but not involving Danish public research has increased from 201 to 420 publications; however Danish industry's international collaboration that does involve Danish public research has increased more than six-fold over the period from 49 to 321.

Key conclusions of this section:

- Public-private collaboration has increased among Danish researchers both in their number and as a share of total publications (10.5% in 2013)
- The number of firms engaged in scientific publication has tripled over the period, with 313 firms publishing journal articles and 109 firms publishing conference papers in 2013.
- International collaboration has increased markedly, from 39% of all journal articles in 1995 to 61% in 2013.
- Danish firms engage in international collaboration both with and without the involvement of Danish public research, however international collaborations have increasingly also involved Danish public research.
- The results of this analysis do not show any indication that increases in international collaboration imply a diminished role for Danish public research in public-private collaboration.

2.2 Introduction

In this section, we draw on comprehensive publication data to examine developments in research publication and different forms of collaboration. Given that collaboration involves the exchange and transfer of knowledge among partners, co-publications provide a measure of knowledge flows. The purpose of this section is to measure the scientific knowledge created in Denmark and knowledge flows from public research to industry. In doing so, the section examines trends in collaboration both between public research and industry and with international partners. In addition to characterizing overall collaboration patterns, this section will also examine the scope of publication activity among Danish firms and the extent to which Danish firms rely on Danish public research in comparison with international public sources.

As our main measure of research knowledge, we define the research knowledge created in Denmark in a given year as the total number of journal articles or conference papers with at least one author with a Danish address. Hence, this includes both private firms, universities and other public research organizations located in Denmark. Collaboration is measured in terms of co-authorship of publications. The data is described in greater detail below.

As noted earlier, collaboration is here measured in terms of co-authorship. We examine both whether collaborations are among firms and public research (public-private collaborations) and also whether collaborations involve international partners. The classification used in this study seeks both to identify whether there is international collaboration and whether Danish public research and/or Danish industry are involved. We have chosen a fairly detailed classification in order to examine a number of different forms of collaboration. For example, what share of publications involves public-private collaboration without any international partners or the shares of international collaborations for Danish firms that are with and without the participation of Danish public research? All groups involve at least one co-author with a Danish address, and the first five groups include Danish public research while the last four do not. Note also that two groups, Danish public research only and Danish industry only, can include solo papers involving only one author. We note below the number of solo papers in these two groups.

Publications only involving public sector research:

- Danish public research only (universities or government research institutes; no industry or international co-authors)
- Danish and international public research organizations (no industry)

Public-private collaborations

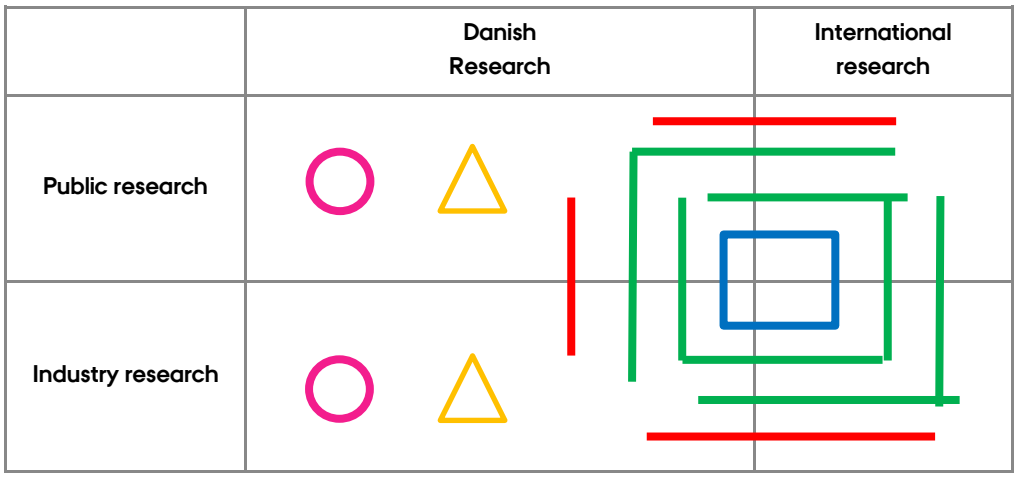
- Danish public research and Danish firms (no international partners);
- Danish & International public research and International firms (no Danish firms);
- Danish public research, Danish firms and international partners (public research and/or firm[8]);
- International public research and Danish firms (no Danish public research)
- International public research and Danish & International firms (no Danish public research)

Publications only involving industry

- Danish industry only (no public research)
- Danish and International industry (no public research)

Box 2.1 provides a visualization of all the different types of collaboration examined in this report. Purple circles depict solo publications with a single author. Solo publications can either be pure public research or pure industry. Yellow triangles depict collaboration among researchers within the same type of research institution (either pure public research or pure industry). Red lines depict collaboration involving two types of research institutions. These can be Danish and international research, Danish public-private collaboration, or Danish and international industry. Green lines and the blue box all depict different forms of international public-private collaboration, where the green lines depict collaboration involving three types of research institutions and Blue box collaboration involving all four types of research institutions

Box 2.1. Graphical illustration of the different types of collaboration



In addition to these classifications, we examine what share of public research only papers (only involving public research or other public sector organizations) were subsequently cited by a paper involving a Danish business publication in the three following years (i.e. no public-private collaboration, but the Danish public research was used/cited later by a Danish business)

2.3 Academic and business motivations for research collaboration

Research collaboration in a general sense can be defined as "social processes whereby human beings pool their human capital for the objective of producing knowledge." (Bozeman et al. 2013). Public-private research collaboration can be seen both from the perspective of universities and from that of business[9]. Research has shown that academic researchers' motivations to collaborate with business may vary greatly, from a more 'entrepreneurial logic' that focuses on technology development and commercialization, to a more 'academic logic' that reflects many of the traditional values of the scientific system (D'Este and Perkmann 2011). D'Este and Perkmann (2011) identify four main motivations for academic researchers to engage in collaboration with industry. The first is commercialization, which they define as "commercial exploitation of technology or knowledge" (D'Este and Perkmann 2011, p. 330). The second motivation is learning, defined as "informing academic research through engagement

[8] These groups are combined due to insufficient number of international collaborations without international public research.
[9] For a comprehensive review of the literature on research collaboration, see Bozeman, Fay and Slade (2013).

with industry" (D'Este and Perkmann 2011, p. 330). The last two motivations for academics to engage in collaborative research with industry are access to funding and access to in-kind resources as a motivation to collaborate.

Business motivations to collaborate with public research include assistance with actual development activities, learning and greater access to new knowledge, and the acquisition of new technologies. Just as academic researchers often collaborate with industry in order to learn and gain knowledge that can be used in their own research, general knowledge transfer also appears to be an important motivation for businesses to collaborate with universities (Lee 2000, Schartinger et al. 2001, D'Este and Perkmann 2011).

For example, Caloghirou et al. (2001) find that industry partners often are strongly motivated by less targeted work aimed at "enhancing their knowledge base, followed by improvements in production processes" (Caloghirou et al. 2001, p. 160). Based on a similar study, Hanel and St-Pierre (2006) argue that, "the major incentive to collaborate with a university is the access to research and critical competencies, which allows firms to reach the very edge of contemporary technology" (Hanel and St-Pierre 2006, p. 496).

The above identifies a number of motivations for why academic and private sector researchers may collaborate with each other. However, an important additional question is why firms should be interested in publishing scientific papers (often called scientific disclosure). A traditional view of this question is in terms of secrecy; whether firms have an incentive to make research results public or keep them secret due to strategic concerns. However, there are other issues related to scientific disclosure. The process of scientific disclosure requires distinct capabilities that would not appear to be directly applicable for firms' own R&D and innovation processes (Simeth and Lhuillery 2015). These include competences in effective knowledge codification, selection of which results to publish and which to keep secret, in-depth knowledge of the academic field, and the integration of theory with empirical work (Simeth and Lhuillery 2015). Firms that engage in scientific disclosure have been found to be more research intensive, have a larger share of PhDs and be more oriented to basic research than comparable R&D active firms that do not publish (Simeth and Lhuillery 2015). Despite the additional costs of scientific disclosure, firms may choose to publish for a number of reasons: reputational gains for the firm's research in relation to other firms and academics; as an employee incentive to attract talented researchers; to strengthen internal development capabilities through codification and publishing processes; and for strategic reasons (Li et al. 2015). In some cases where firms are not interested in patenting new knowledge themselves, publishing can be used as a mean to make sure that knowledge is public and cannot be patented by competitors.

2.4 Data

The Web of Science (WoS) covers publications from about 12,000 journals in the sciences, the social sciences, and the arts and humanities. Each journal in WoS is assigned to one or more "subject categories". We use an enhanced version of the WoS database, developed and maintained by the Centre for Science and Technology Studies (CWTS) at Leiden University. The CWTS in-house version of the WoS database includes a number of improvements over the original WoS database. Most importantly, compared to Thompson Reuters' WoS, the CWTS database uses a more advanced citation matching algorithm and an extensive system for address unification. The database also supports a hierarchically organized field classification system on top of the WoS "subject categories" constructed by Thompson Reuters.

The WoS, and in particular, corresponding citation databases, consist predominantly of journal articles. Hence, the population of publications that we consider in this study excludes other forms of publications, such as books, reports and other publications that are not published in these peer-reviewed journals. Typically, the coverage of publications[10] varies from field to field, with very high levels of coverage in the natural and medical sciences and lower coverage (roughly around half) in the humanities and social sciences.
The CWTS in-house version of the WoS database indicates whether individual publications include an author from private industry and whether the publication is an international collaboration involving authors from two or more countries. We have enhanced this data by manually validating and classifying all Danish addresses (public research institution, private business or other public organisation). Thereafter, we have sought to identify firm identification numbers (CVR) for all private business addresses.

[10] The internal WoS coverage of a unit can be defined as the proportion of the references in its oeuvre that points to publications (also) covered by WoS.

Our study also includes conference papers, which are very prevalent in the engineering and computer sciences. However, data on field normalized citation impact are not available for conference papers and data quality is not sufficient to make some of the detailed classifications of publications that are possible with journal articles. For this reason, our use of conference papers, both in this section and elsewhere in the report, is more restricted than for journal articles. And, for technical reasons concerning author address identification, data on conference papers has been taken from Elsevier's Scopus database.

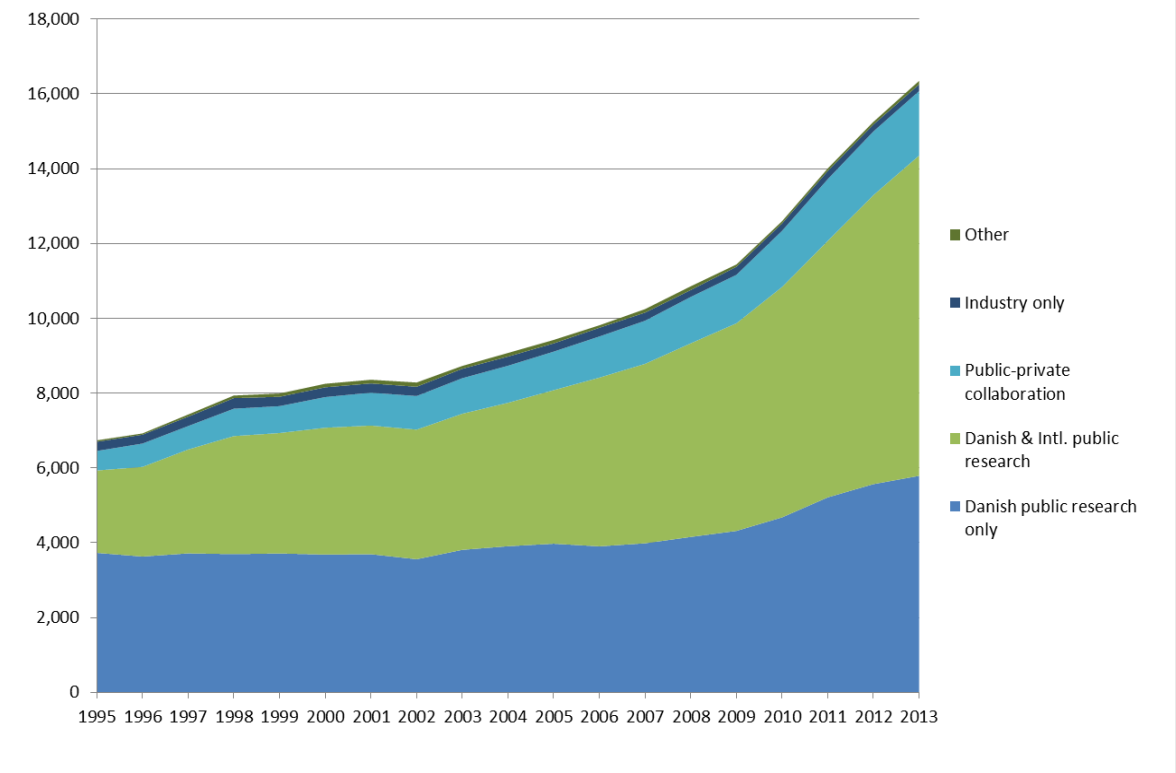
2.5 Total publications by type of collaboration partner

2.5.1 Journal articles

Figure 2.1 shows developments in Danish journal articles over time, from 1995 to 2013. As noted above, these publications are defined by the fact that the affiliation of at least one of the authors has a Danish address. In figure 2.1, publications are classified into five broad categories, Danish and international public research, public-private collaboration (both Danish and international), industry-only and a small 'other' group where it was not possible to identify whether the Danish participant was public research or industry.

The total annual number of Danish journal articles in WoS has increased dramatically from 6738 in 1995 to 16351 in 2013. Growth has been particularly strong in the last 10 years, where the total number of articles has increased by 87%. The far majority of publications are pure public research papers that do not involve industry collaboration. In particular, international collaboration with other public researchers has increased almost four-fold over the period and now accounts for over half of all publications. The share of journal articles involving public-private collaboration increased from 7.8% in 1995 to 11.9% in 2010. Since 2010, the share has fallen slightly, with the share at 10.5% in 2013.

Figure 2.1. Total number of journal articles with at least one Danish address, by type of collaboration partner, 1995-2013. Web of Science.



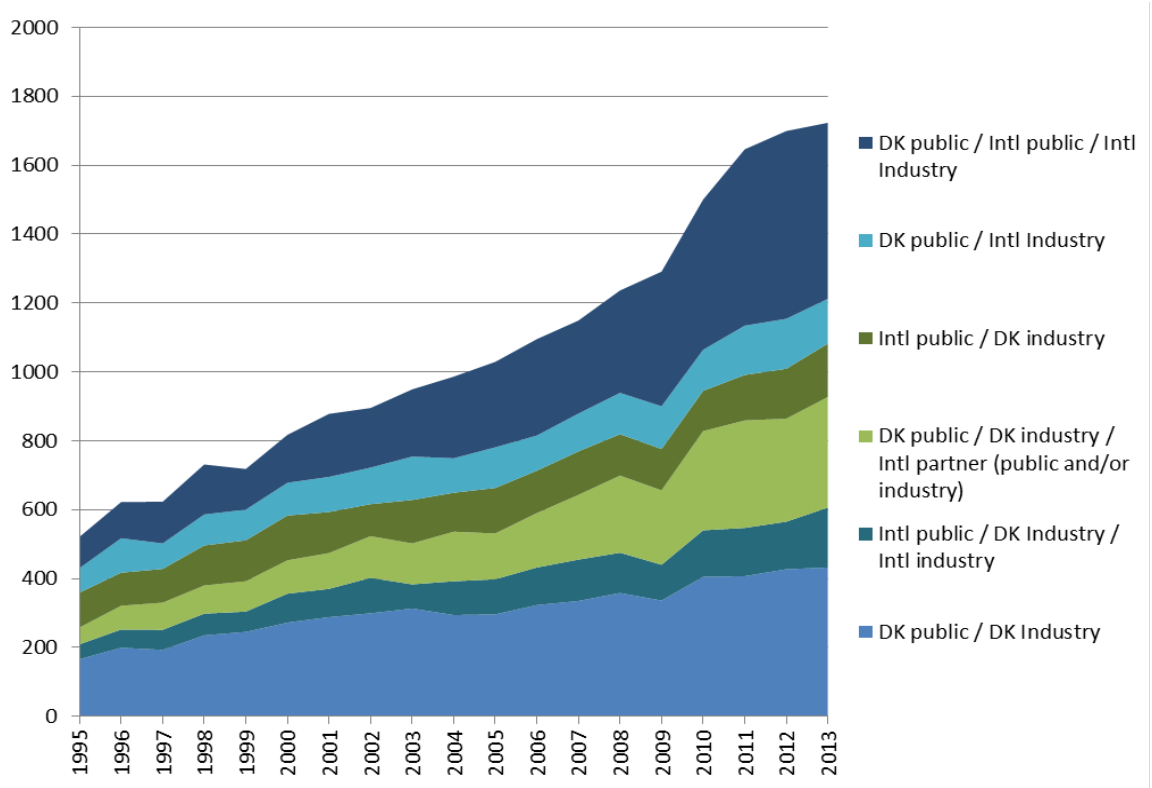
Note: Danish public research only and Industry only also include solo articles with no co-authors. Public-private collaboration includes both Danish and international collaborations.

As noted above, the two groups, Danish public research and Industry only, include papers with single authors. In both cases, the share of solo papers has declined greatly over time. The share of Danish public research papers with single authors has declined over the period from 26% in 1995 to 15% in 2013, while the share of industry-only papers with a single author has fallen from 36% (68 out of 187) in 1995 to 18% (15 out of 84) in 2013.

It should also be noted that there has been strong growth in the global, total number of journal articles in the WoS database, which can explain part of the development in the articles and collaboration. In the period from 1995 to 2013, the total annual number of articles has increased by 113% (based on own calculations) in comparison to 143% in our sample covering Danish authors. The growth in WoS is driven by two factors: strong global increases in research publication activity, particularly in Asia but also in Denmark and other western countries; and increases in the number of journals included in the database (in particular in 2006, where a large number of additional journals were included in the WoS database). The latter has large importance for many Asian countries, but is less important in relative terms for countries like Denmark, whose primary publication channels are already included in WoS. However, it is clear that this growth in journal coverage has had some degree of influence on the overall growth of journal articles (with a Danish address) in WoS. This is likely even more the case for conference papers in Scopus, as Scopus has undergone a more rapid expansion in the number of journals included in their database. Overall growth in the Scopus database over almost the same period (1996-2013) is 295% (based on own calculations). On the other hand, it should be expected that increases in publication activity lead to an expansion in the number of journals used, since most journals have a fixed number of articles that they can publish each year (though minor increases are possible through increases in the annual number of issues). The increase in data coverage in the databases does not seem to exceed the development in collaboration.

In order to better show developments in public-private collaboration, figure 2.2 shows only publications involving public-private collaboration, where we distinguish both between authors from public research and industry and between Danish and international co-authors. The categories in figure 2.2 and throughout this report correspond to the classification listed in the introduction to this section. The bottom four categories denote collaborations that include Danish industry, while the top two categories in the figure denote collaborations that do not include Danish industry.

Figure 2.2. Journal articles involving public-private collaboration, by type of collaboration partner, 1995-2013. Web of Science.



As the figure shows, the number of both national and international public-private collaborations has increased greatly over the period, with national collaborations more than doubling and international collaborations more than quadrupling. In all, the share of total publications involving some form of international collaboration (including both

pure public and public-private collaborations) has increased from 39% in 1995 to 61% in 2013. Among public-private collaborations, the share of papers involving international collaboration has also risen, from 68% to 75% over the same period. Note also that the three types of collaborations that have increased most all involve Danish public research.

In addition to the publications directly involving public-private collaboration, papers co-authored by industry may draw on other research conducted by Danish public research, either alone or in collaboration with international universities. To examine the scope of this we have identified all public research-only papers that have subsequently (in the following three years) been cited by papers (co-)authored by industry only. These public research papers that are cited by industry accounted for 2.2% of all Danish journal articles in 1995 and 2.6% in 2011. Figure 2.3 shows the developments in these papers together with papers involving public-collaborations, where the top two groups involve public research-only papers that were subsequently cited by papers co-authored by industry.

In order to simplify, in figure 2.3 public-private collaborations are combined into two groups, Danish public-private collaboration and international public-private collaboration. This combined measure of the three groups of papers involving public-private collaboration, industry-only papers and public research only papers that are cited by industry in the following three years accounted for in total 16% of all journal articles in 2011 with a Danish address.

Figure 2.3. Articles co-authored by industry, and pure public research articles cited by industry, 1995-2011. Web of Science.

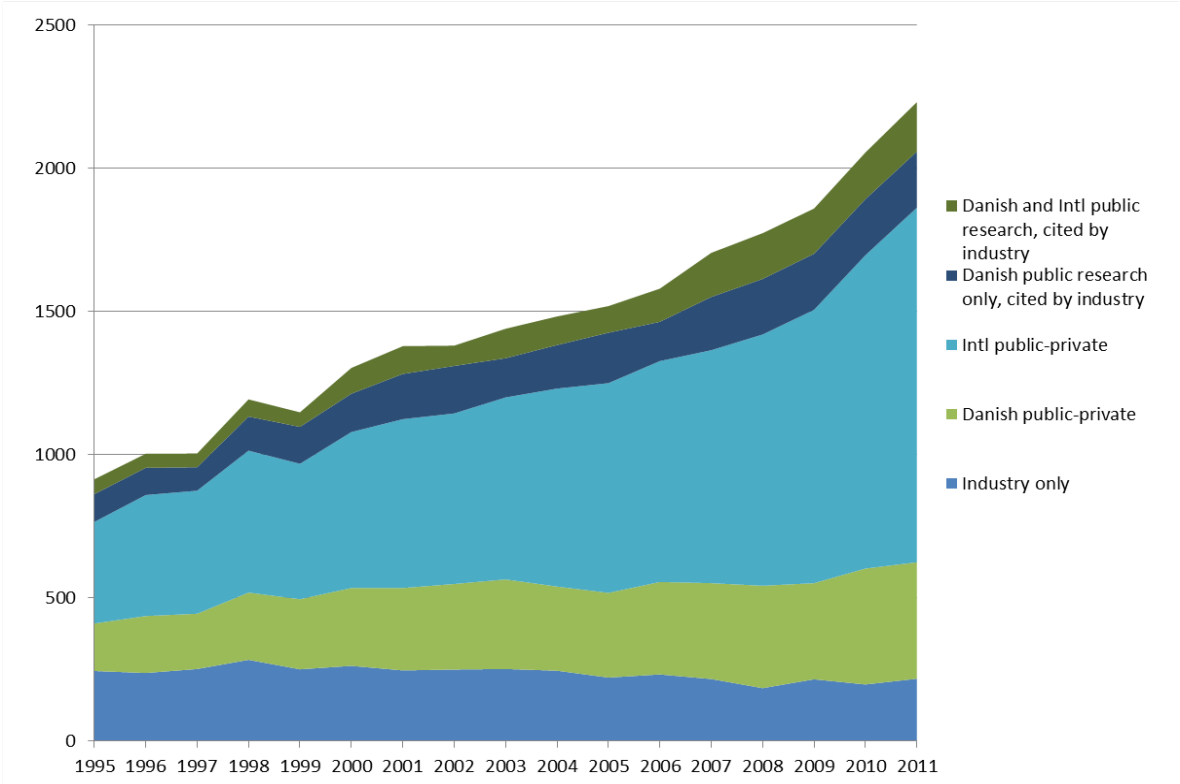


Figure shows articles at time of publication. Citations up to three years after publication.

2.5.2 Conference proceedings papers

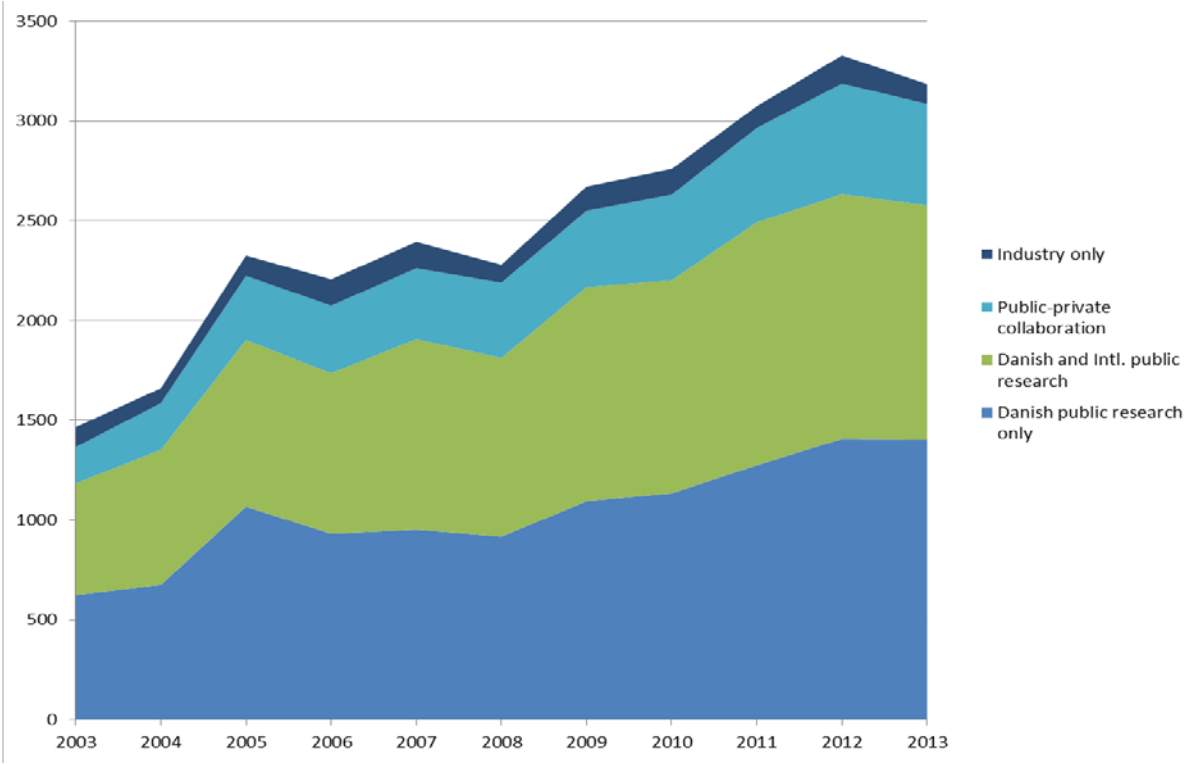
The next two figures show the same developments for papers that have been published in conference proceedings. Data quality for conference papers is not nearly as high as for journal articles, which for example means that citation analysis is not possible for these papers. And also due to technical reasons, we have used data from Scopus instead of WoS, as this improved our ability to identify the type (i.e. public research or industry) of all co-authors[11]. There are two main reasons for including conference papers in this analysis, despite its limitations. The first is completeness. Covering both types of publications broadens our coverage of knowledge production overall, and provides a more accurate calculation of the number of publications produced by individual firms. The second is sectoral coverage. Conference papers are the most common form of publication for some fields, such as engineering and computer

[11] The opposite is the case for journal articles, where CWTS's enhanced WoS database is in our view the most suitable source.

sciences. Excluding these could imply a sectoral bias in our measures of publication activity for the sectors that draw heavily on these fields, such as electronics, technical business services and IT services. Note also that data on both journal articles and conference papers are used to construct firm level publication variables that are used in the firm productivity analyses in section 4.

Scopus was established in 2003-04 and while the database has been extended back in time, there is greater uncertainty concerning the degree of coverage prior to 2003. Hence, we show here only developments for the period 2003-2013.

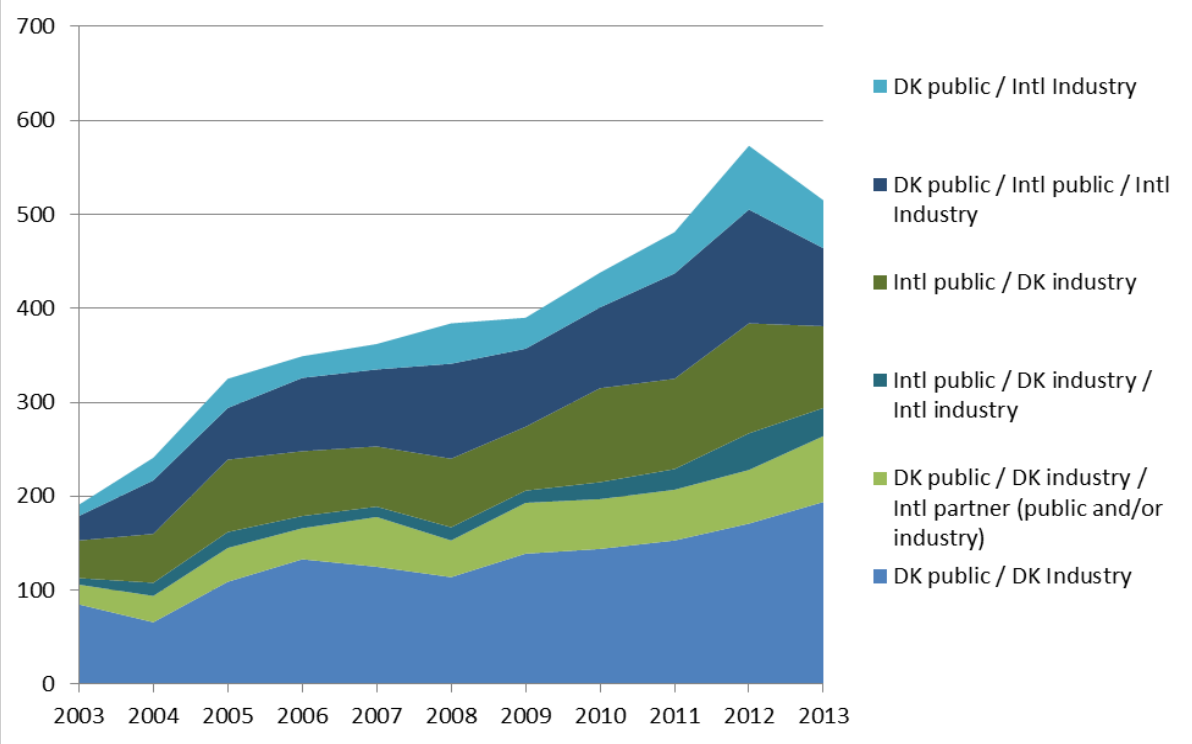
Figure 2.4. Total number of conference papers with at least one Danish address, by type of collaboration partner, 2003-2013. Scopus.



As with journal articles, there has been strong growth in the number of conference papers over the period. In comparison with journal articles, a larger share of conference papers are public-private collaborations or industry-only papers. The share of conference papers with public-private collaboration was 12% in 2003 and 16% in 2013, while it was around 11% in both cases for journal articles. Industry-only publications accounted for 7% of all conference papers in 2003 and 3% in 2013, while shares for journal articles fell from 3% to 1% over the same period. The share of Danish public research papers in conference proceeding has been stable in relation to international collaboration, with shares slightly increasing from 43 to 44% for Danish public research and falling from 38 to 37% for international public research collaborations.

The next figure shows the distribution of conference papers involving public-private collaboration. The number of papers involving public-private collaboration has more than doubled from 2003 to 2013 and, as mentioned above, it has also grown in terms of the share of total conference papers, from 12% to 16%. In general, there is a higher share of conference papers involving national collaboration only compared to journal articles, while there has been a stronger international orientation for journal articles.

Figure 2.5. Conference papers involving public-private collaboration, by type of collaboration, 2003-2013. Scopus.

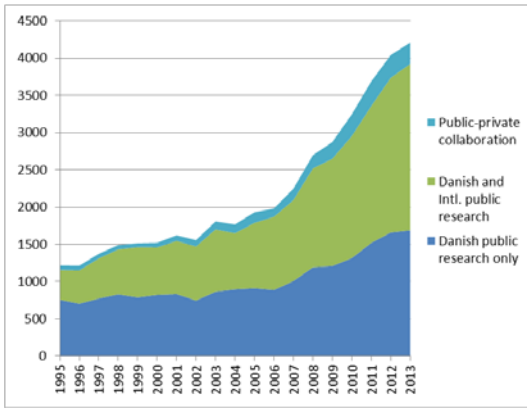


2.6 Publications and collaboration by university

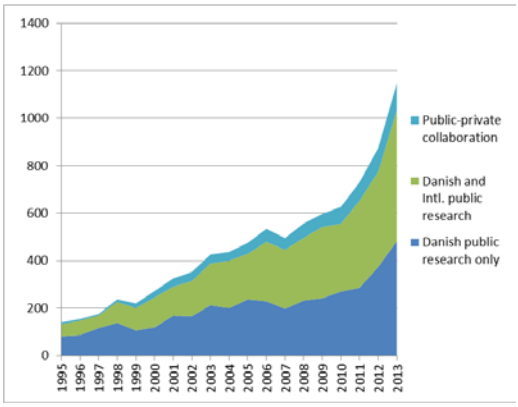
Figure 2.6 shows developments in the number of journal articles for individual universities. All of the five universities shown here[12] have experienced large increases in publications, with overall growth rates highest in Aalborg University (AAU) and Aarhus University (AU). Part of these increases is likely influenced by the merger of a number of smaller research institutions into these universities which may exaggerate the development.

Figure 2.6.Total number of journal articles for five Danish Universities, by type of collaboration, 1995-2013. Web of Science.

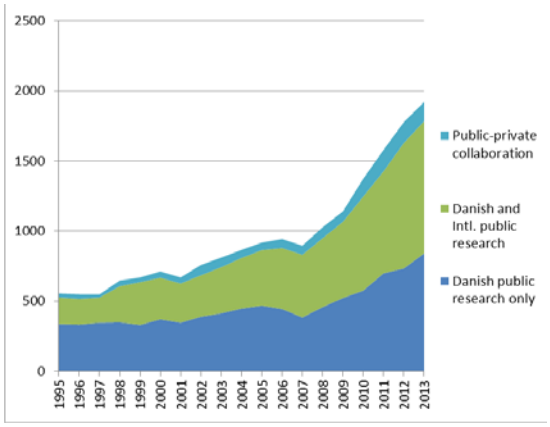
Aarhus University



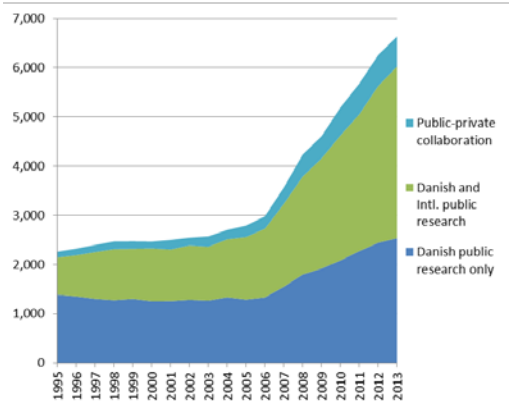
Aalborg University



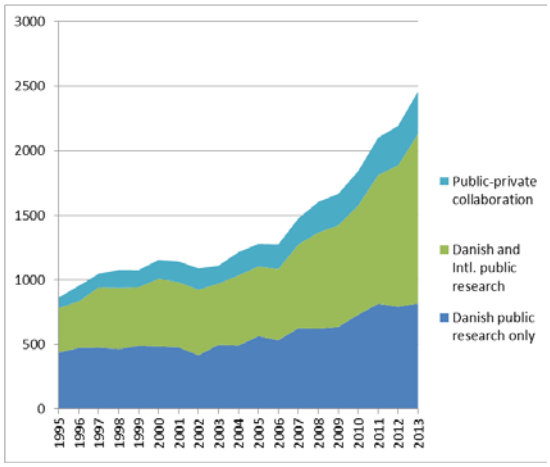
Technical University of Denmark



University of Copenhagen



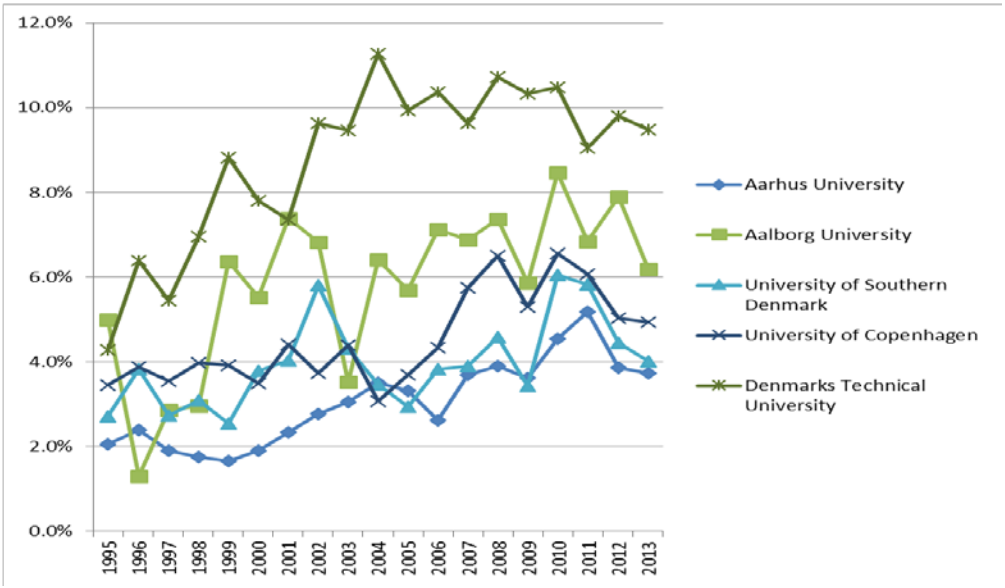
University of Southern Denmark



[12] Developments not shown for other universities due to insufficient annual number of journal articles with public-private collaboration.

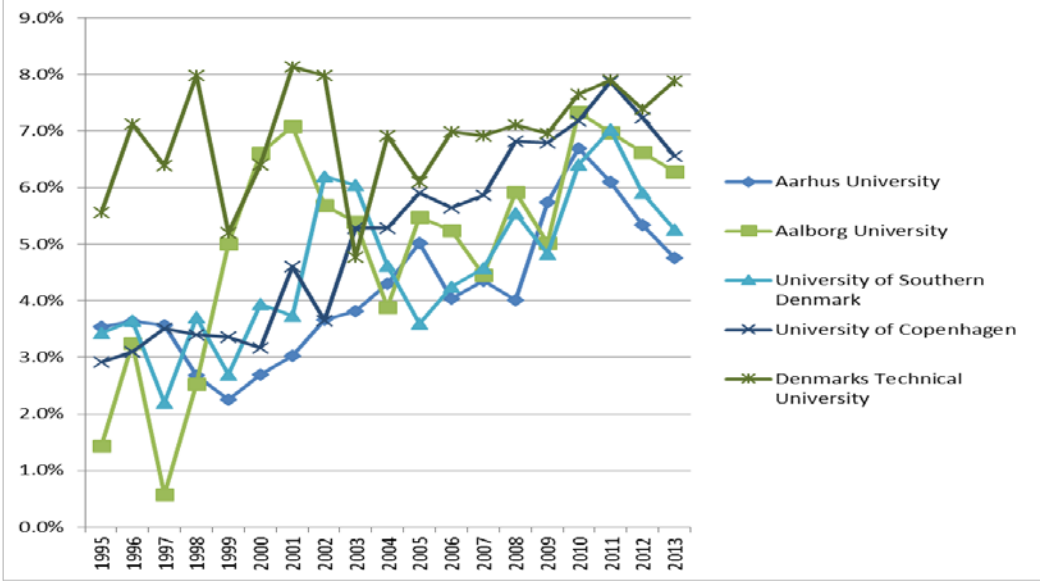
Figures 2.7, 2.8 and 2.9 below show developments in the share of publications that involve industry collaboration, indicating both increases in university-only publications and in collaborations with industry. Figure 2.7 shows shares with collaboration with Danish industry, while figure 2.8 shows shares with international public-private collaboration (which may also include Danish industry). Shares with national public-private collaboration are highest for the Technical University of Denmark (DTU), followed by AAU and the University of Copenhagen (KU). The share for DTU has also increased substantially over the period, from just over 4% to almost 10% in 2013. In general, there has been a trend upwards in share public-private collaboration for all 5 universities, though with University of Southern Denmark (SDU) and AU are at lower level at around 4%. It should be noted that some of the differences across universities can potentially be explained by differences in fields of research. Universities with a higher share of e.g. technical science like DTU and AAU may have more public private collaboration than universities with a higher share of humanities and social sciences. On the other hand, some of these differences may not be fully reflected due to the lower coverage of humanities and social science in the databases,

Figure 2.7. Percentage of university publications that involve collaboration with Danish industry, 1995-2013.



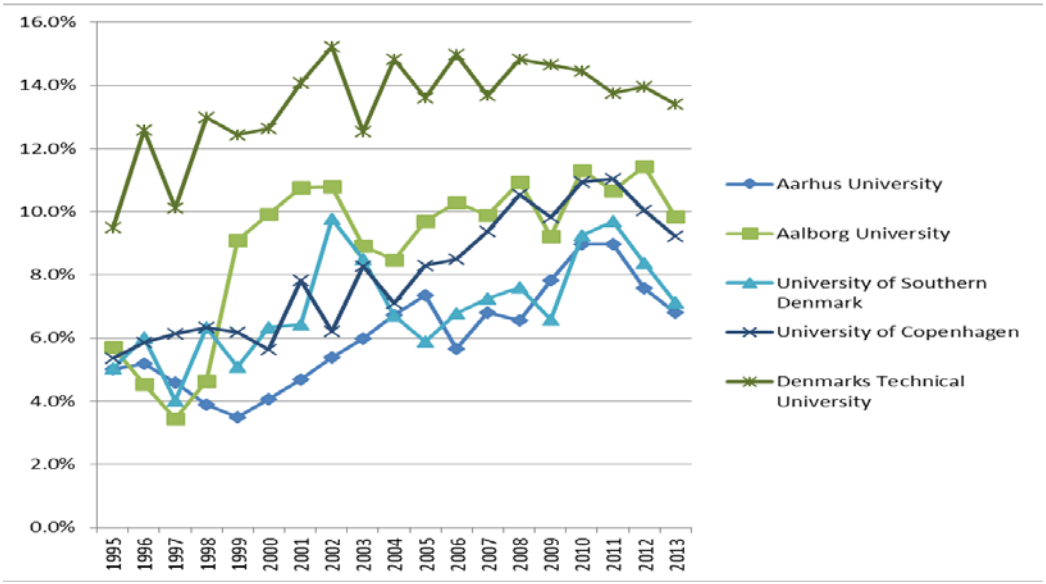
A large share of public-private collaboration involves international collaboration. In comparison with national public-private collaboration, there appears to have been some convergence in shares with collaboration with international industry. Shares have fluctuated around 7% for DTU while they have increased for the other universities.

Figure 2.8. Percentage of university publications that involve collaboration with International industry (can also include Danish industry), 1995-2013.



Despite this trend, there are still fairly sizable differences across universities. Figure 2.9 shows overall public-private collaboration including both national and international. At start of period in 1995, shares with public-private collaboration are markedly higher for DTU at 10% while all others are between 5-6%. Shares have increased for all five universities, though increases are moderate for SDU and AU. Shares in 2013 are around 14% for DTU, 10% for AAU and KU, and 7% for AU and SDU.

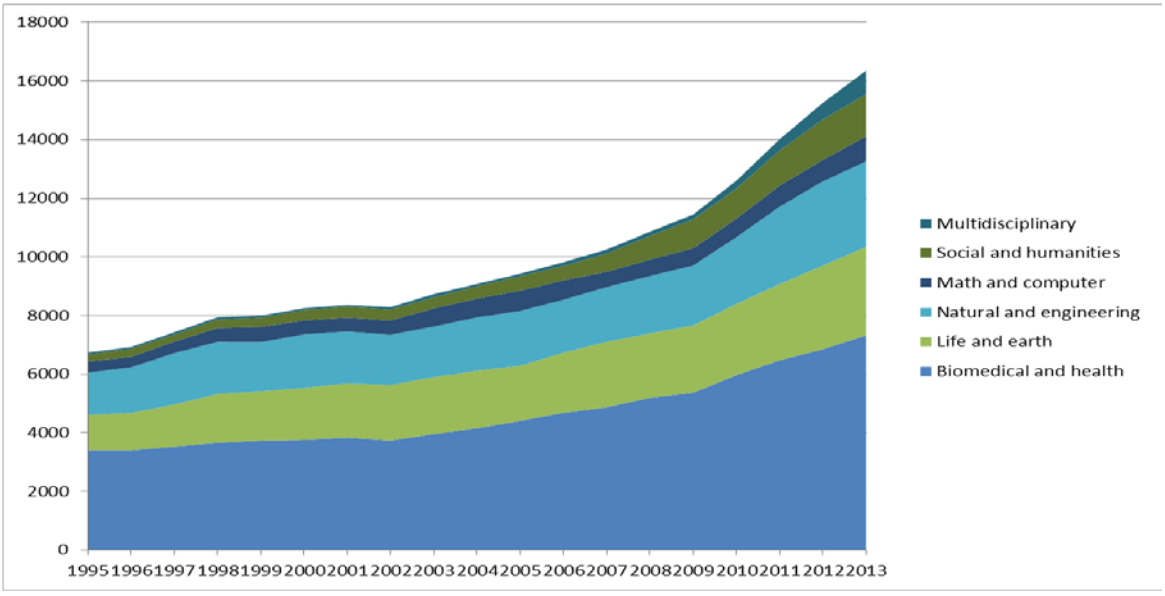
Figure 2.9. Percentage of university publications that involve collaboration with industry overall (both national and international), 1995-2013.



2.7 Public-private collaboration across scientific fields

Figure 2.10 below shows journal articles distributed across main fields where we have utilized CWTS's categorization of main scientific fields: biomedical and health sciences, life and earth sciences, natural and engineering sciences, math and computer sciences, social sciences and humanities, and multi-disciplinary fields[13].

Figure 2.10. Total number of journal articles with at least one Danish address, by scientific field, 1995-2013. Web of Science.



[13] Though it should be kept in mind that total publications in the social sciences and humanities are not well covered in the Web of Science.

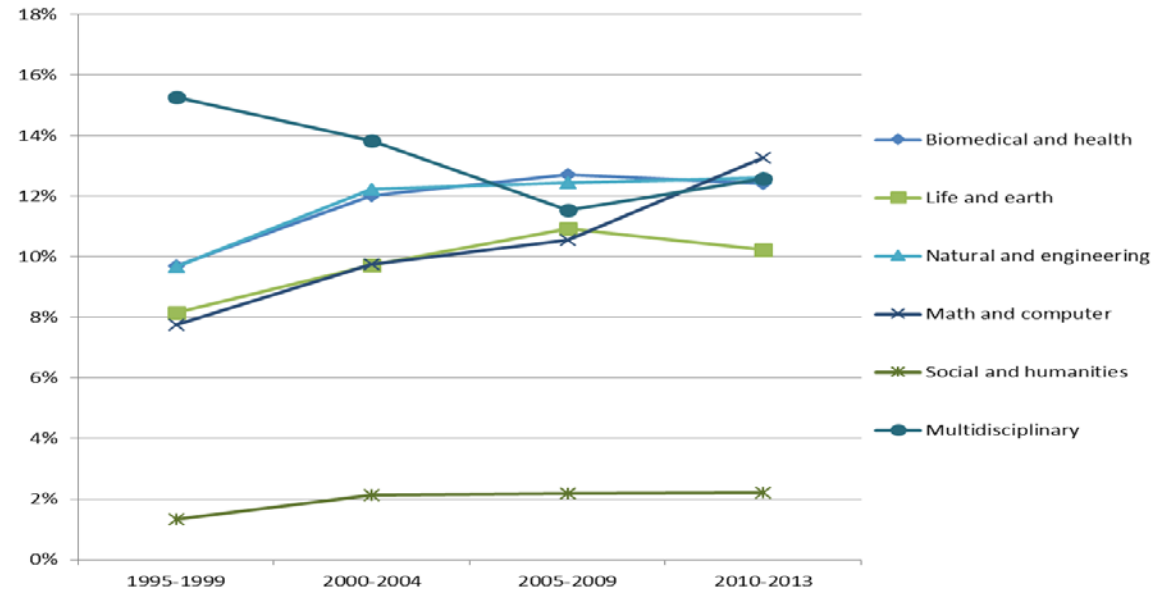
The latter, multi-disciplinary, represents multi-disciplinary journals (with well-known examples such as Nature and Science) that often include papers from a variety of fields, though where the papers themselves are often mono-disciplinary.

Biomedical and health has the largest number of papers at around 45% of total publications in 2013, followed by life and earth and natural and engineering, each with 18% in 2013.

In terms of scientific fields, the most visible examples of public-private collaboration are likely within biomedical and health. However, collaboration spans across a wide range of academic disciplines and involves firms from a very large number of industries. Figure 2.11 below shows the share of publications within each field that involves public-private collaboration. In the beginning of the period (1995-2004), the highest shares were found within multi-disciplinary fields.

However, shares within this field have fallen over the last 10 years. Shares with public-private collaboration have gradually increased over the period within biomedical and health sciences, life and earth sciences, and natural and engineering sciences. Though, shares for life and earth sciences have fallen slightly in the last period. Growth in shares with public-private collaboration has been greatest within math and computer sciences, rising from 8% in 1995-1999 to over 13% in 2010-2013. Shares with public-private collaboration are substantially lower within the social sciences and humanities, at around 2% for most of the period.

Figure 2.11. Percentage of publications that involve collaboration with industry by scientific field, four sub-periods in 1995-2013.



2.8 Cross-disciplinarity and Collaboration

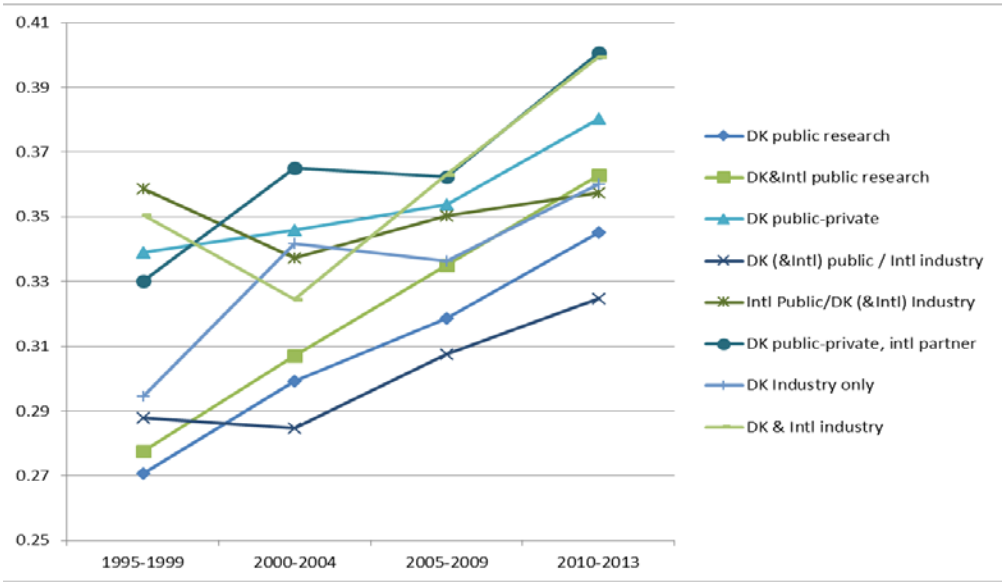
Cross-disciplinary research involves research that crosses the boundaries of different research areas. This type of research is seen as essential for the development of entirely new research areas or in solving complex problems that cannot be fully understood within a single area. On a lower level, cross-disciplinarity has been argued to have a positive impact on innovation, for example by contributing with new perspectives to solving problems or improving new ideas and innovations.

We measure here cross-disciplinarity in two ways. Each paper is categorized in terms of its main disciplinary area, based on a classification in all 31 disciplines. The first measure is an indicator of *inter-disciplinarity*, measured as the share of references in each paper that stems from other disciplines. A value of zero indicates that all references for a paper are within the same main discipline as the paper itself, while a value of 0.5 indicates that 50% of references are from a different discipline. This first indicator can be seen as a measure of depth of cross-disciplinarity. The second indicator is of *multi-disciplinarity*, measured as the number of other disciplines among each paper's references. This second indicator can be seen as a measure of breadth of cross-disciplinarity, and can take on a value

between zero (all references for a paper are within the same main discipline as the paper itself) and 30 (there is at least one reference from every other discipline).

The figure 2.12 below shows results for inter-disciplinarity for different types of collaborations. There appears to be a general trend over time towards greater inter-disciplinarity across all forms of collaboration. The two types of collaboration with highest degree of inter-disciplinarity are international collaborations involving both Danish public research and Danish industry and industry-only collaborations respectively. Hence, public private collaboration does not seem to lower inter-disciplinarity.

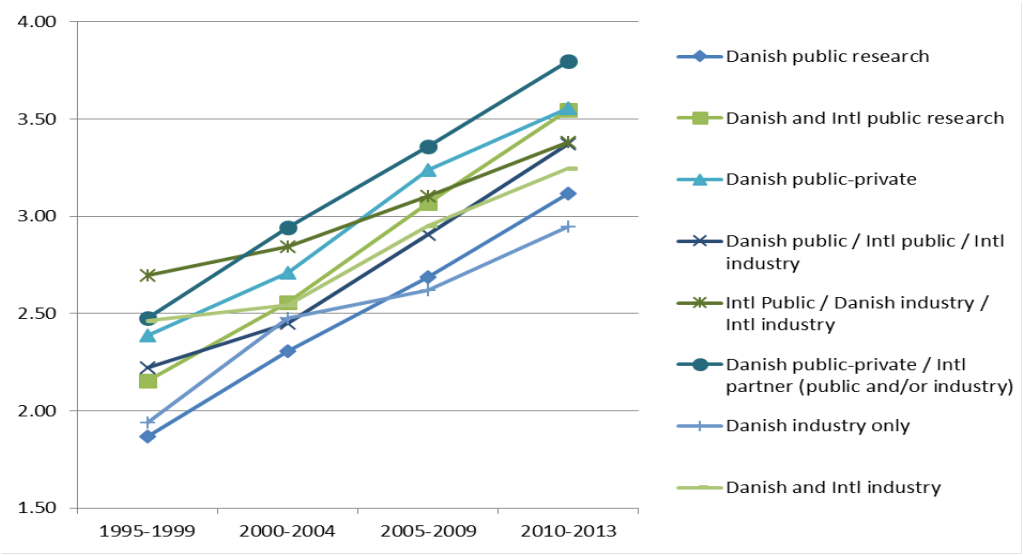
Figure 2.12. Degree of inter-disciplinarity (percentage of references within other disciplines), by type of collaboration



National public-private collaborations also have a higher degree of inter-disciplinarity. The difference was particularly large in the first half of the period but is still present in the last period. This could reflect that public and private researchers have different backgrounds and thus have a greater tendency to draw on different fields in their work.

Multi-disciplinarity measures the number of disciplines covered by papers. As shown in figure 2.13, multi-disciplinarity increases over time, while differences across types of collaboration are somewhat smaller.

Figure 2.13. Multi-disciplinarity (number of other disciplines covered in references), by type of collaboration



Again, international collaborations involving both Danish public research and Danish industry are highest over much of the period. While industry-only papers have a high degree of inter-disciplinarity relative to other papers, their

multi-disciplinarity is relatively lower. Again there is no indication, that public private collaboration lowers the degree of multi-disciplinarity.

2.9 Publication activity among Danish firms

In all an estimated 1674 firms have authored or co-authored a journal article over the period 1995-2013 and 416 firms have authored or co-authored a conference paper. A little less than half of them have only published a single journal publication, while a small group of firms have co-authored a very large number of papers, in particular concerning journal articles. Table 2.1 shows number of publications for the 10 firms with the largest publication activity, and the overall distribution of firms by number publications.

The list of the 10 firms with most journal articles is dominated by pharmaceuticals and biotech firms, with one pharmaceuticals firm (Novo Nordisk) accounting for around a quarter of all journal articles with a Danish industry co-author during the period. However, as will be shown below and later in the report, the full list of firms spans a very large range of industries.

Data quality and indicator development concerning citation impact and other factors is not nearly as good for conference papers as it is for journal articles. However, a main reason conference papers have been included in this report is that a number of fields publish primarily in conference proceedings, among these engineering sciences and computer sciences. Hence, coverage of the corresponding industries for these fields requires data on conference papers[14]. While the same firm (Novo Nordisk) tops the list for conference papers, there are in particular a number of electronics and engineering firms among the top 10 in terms of publications.

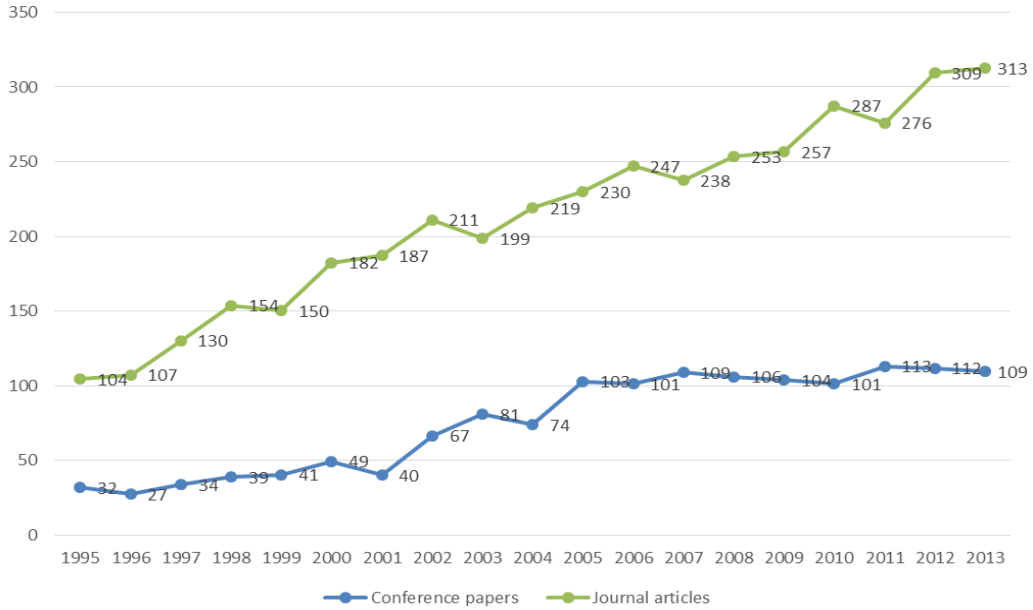
Table 2.1. Firms and number publications, overall for period 1995-2013. Journal articles in Web of Science, Conference papers in Scopus

Journal articles		Conference papers	
Firm	**Number publications**	**Firm**	**Number publications**
Novo Nordisk A/S	4530	Novo Nordisk A/S	193
H. Lundbeck A/S	953	OFS Fitel Denmark ApS	187
Carlsberg A/S	899	Haldor Topsøe A/S	184
Haldor Topsøe A/S	570	Brüel & Kjær A/S	172
Neurosearch A/S	451	Danfoss A/S	157
Leo Pharma A/S	438	Siemens A/S	152
ALK-Abello A/S	397	Koheras A/S	150
Nordic Bioscience A/S	285	Crystal Fibre A/S	143
Danisco A/S	279	COWI A/S	110
Center for Clinical and Basic Research A/S	226	DONG A/S	102
9 firms	101-225 publications		
24 firms	51-100 publications	9 firms	51-100 publications
148 firms	11-50 publications	44 firms	11-50 publications
135 firms	6-10 publications	48 firms	6-10 publications
564 firms	2-5 publications	139 firms	2-5 publications
784 firms	1 publication	166 firms	1 publication

Figure 2.14 shows for each year the number of firms with publication activity[15] for journal articles and conference papers. The annual number of firms with a journal article has tripled over the period, from 104 in 1995 to 313 in 2013. The trend for conference papers is very similar.

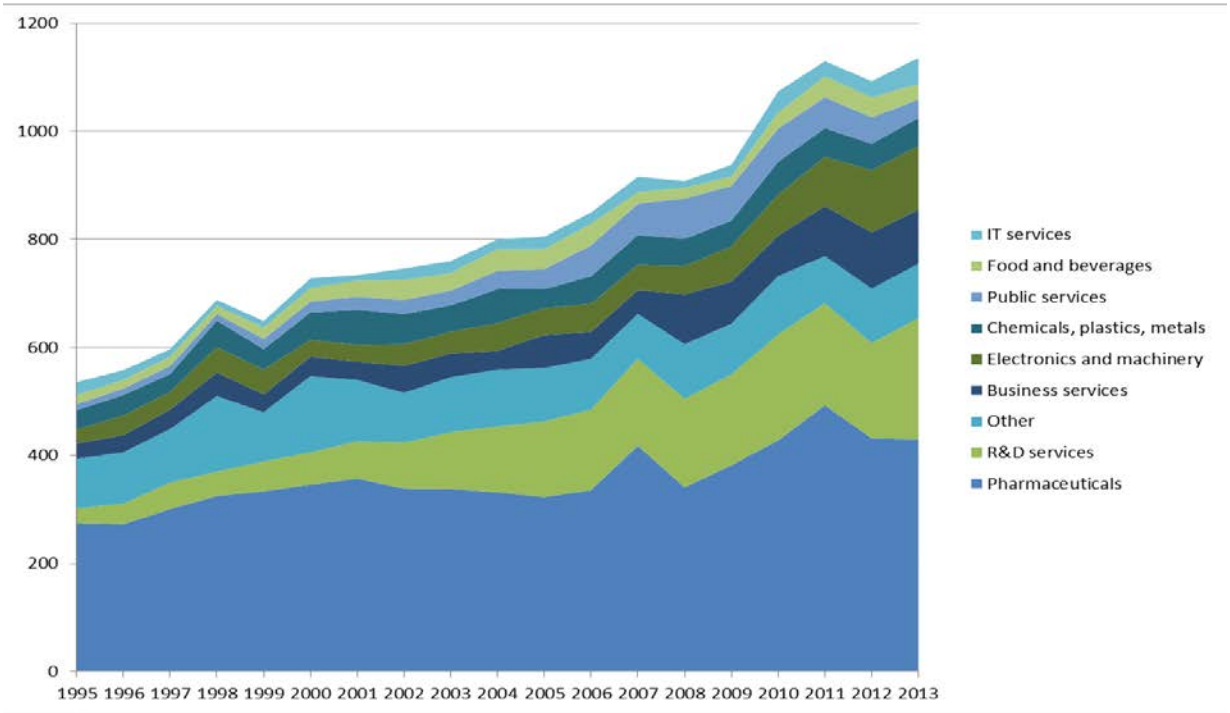
[14] This data is used both to produce descriptive statistics in this chapter and to create firm level indicators for the productivity analyses later in the report.
[15] Including both collaborations and solo publications.

Figure 2.14. Number of private firms with a publication, for journal articles and conference papers, 1995-2013.



For those firms for which we were able to identify a firm ID number (CVR number), we were also able to identify their industrial classification. Through this we were able to classify approximately 90% of journal articles involving Danish industry (both solo articles and collaborations) according their industrial classification. Figure 2.15 shows the distribution of papers involving Danish industry according to main industrial groupings.

Figure 2.15. Number of journal articles with industry (co-)author, by sector, 1995-2013.



Note: "industry" author is an author employed in a private firm, including private firms that deliver public services.

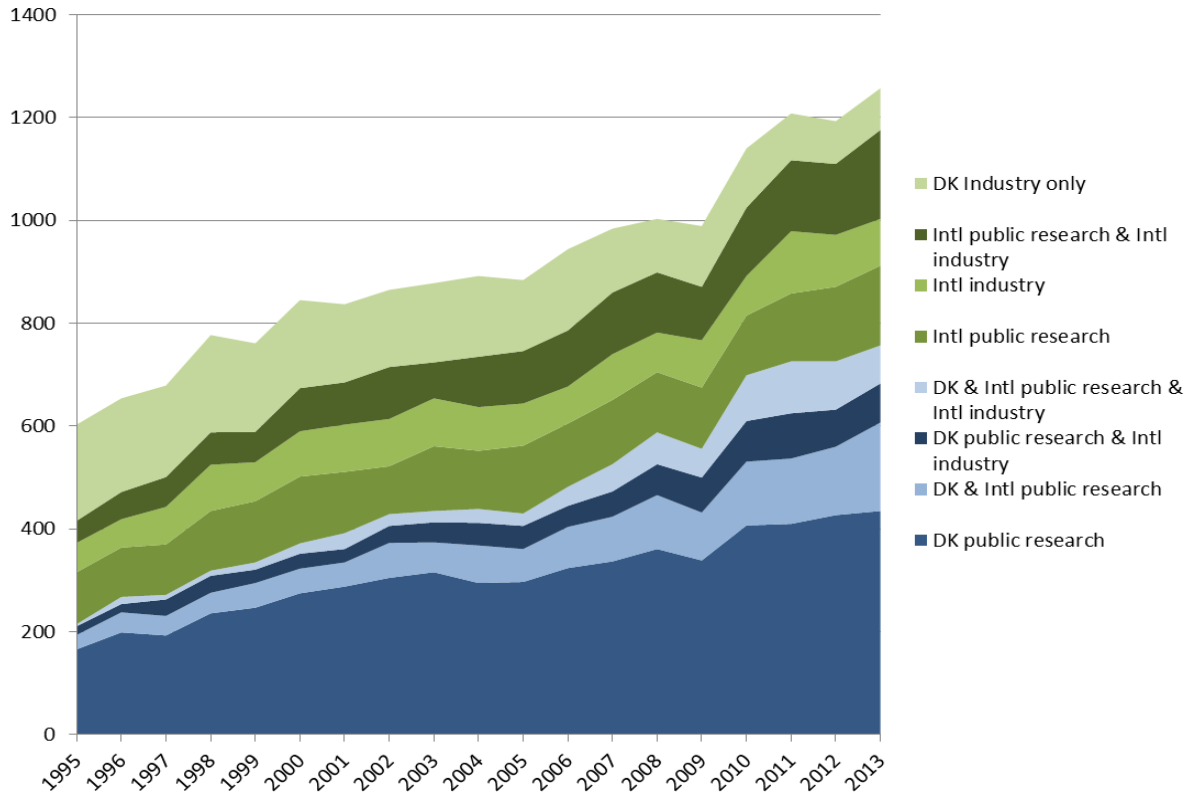
Pharmaceuticals has the largest share of publications though, while the number of publications has grown, its share of publications has fallen over time from 51 to 38%. In contrast, R&D services has increased greatly over the period. However, the industry R&D services is somewhat difficult to place as it can include research-based firms within a variety of other industries. One major area within R&D services is biotech firms, but other firms can be within a variety

of other areas. There have also been large increases in papers involving firms within electronics and machinery, and also within information technology, though the overall share of papers within IT services is still small.

2.10 National and international knowledge flows to Danish firms

The above has shown that research has increasingly become international, with both universities and industry increasingly choosing to collaborate with international partners. This section examines the distinction between national and international knowledge transfer to Danish industry by examining collaboration patterns for journal articles co-authored by Danish firms. Figure 2.16 below shows the total number of publications with a Danish firm as a co-author. Publications are classified according to type of collaboration partner (DK industry, Intl industry, Intl public research and DK public research). The collaborations involving Danish public research are in shades of blue while those not involving Danish public research are in shades of green.

Figure 2.16. Total number publications co-authored by Danish Industry, 1995-2013, by type of collaboration partner



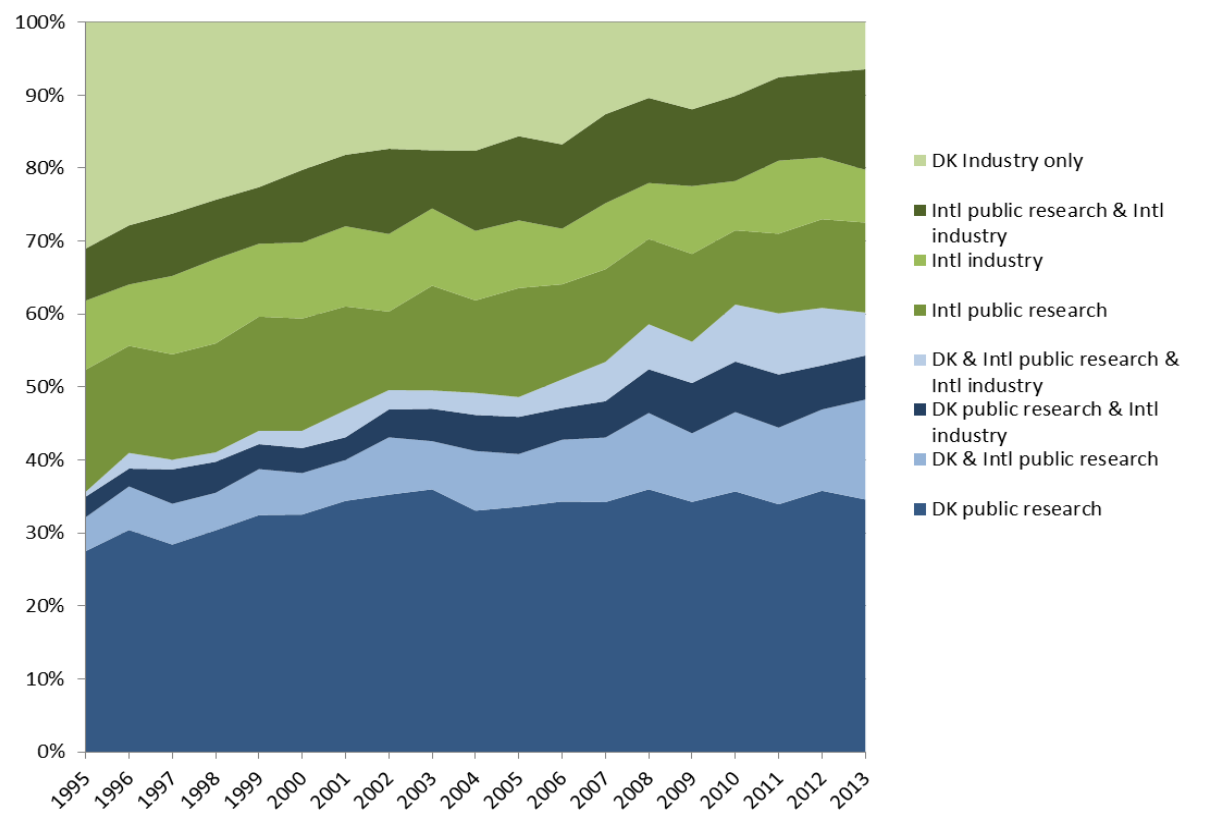
First, note that while the number of papers involving industry has more than doubled over the period, the number of papers only involving Danish industry has actually fallen from 187 in 1995 to 84 in 2013. While there have been strong increases in national public-private collaborations with Danish universities and other Danish public research institutions, the largest relative increases can be found in international collaborations. The number of Danish public-private collaborations has increased from 166 to 432 over the period. Furthermore, international collaborations have become increasingly likely to also involve Danish public research. International collaboration not involving Danish public research has increased from 201 to 420 publications; however international collaboration that does involve Danish public research has increased more than six-fold over the period from 49 to 321. Overall, the trend towards greater international orientation appears to have increased in tandem with Danish public-private collaboration.

In order to see these relative trends more clearly, figure 2.17 shows the relative percentage shares for the same groups of publications. In 1995, 36% of DK industry papers involved collaboration with DK public research. The share has since risen to and remained at 60-61% from 2010 to 2013. At the same time, the share of industry-only papers has fallen dramatically, from 31% in 1995 to only 6% in 2013.

These results reflect an interesting trend; in the beginning of the period, Danish firms' collaboration was either with Danish public research or with international partners, seldom with both. However, the largest percentage increases in publication activity are precisely in collaborations involving both Danish public research and international partners. There appear to be two trends behind this change in publication behavior. First, firms with ongoing publication activities (eg. five or more publications during the entire period) have increasingly sought collaborations with both Danish public research and international partners. Among firms with 5 or more publications over the period, the share of firms with both international collaboration and collaboration with Danish public research in a given year has increased from 37% to 54% during the period. In contrast, the share of firms that have international collaboration but no collaboration with Danish public research have been essentially unchanged over the period, at 17-18% in a given year.

At the same time, the number of firms with a publication in a given year has almost tripled over the period, implying an ever increasing number of new firms with respect to publication activity. Firms with a single publication have also had an increasing tendency to seek collaborations involving both Danish public research and international partners, increasing from 8% per year to 22% per year over the period. Yearly shares with international collaboration but no collaboration with Danish public research have remained constant at around 19-21% of firms with only one publication during the entire period.

Figure 2.17. Publications co-authored by Danish Industry, 1995-2013, percentage shares by type of collaboration partner



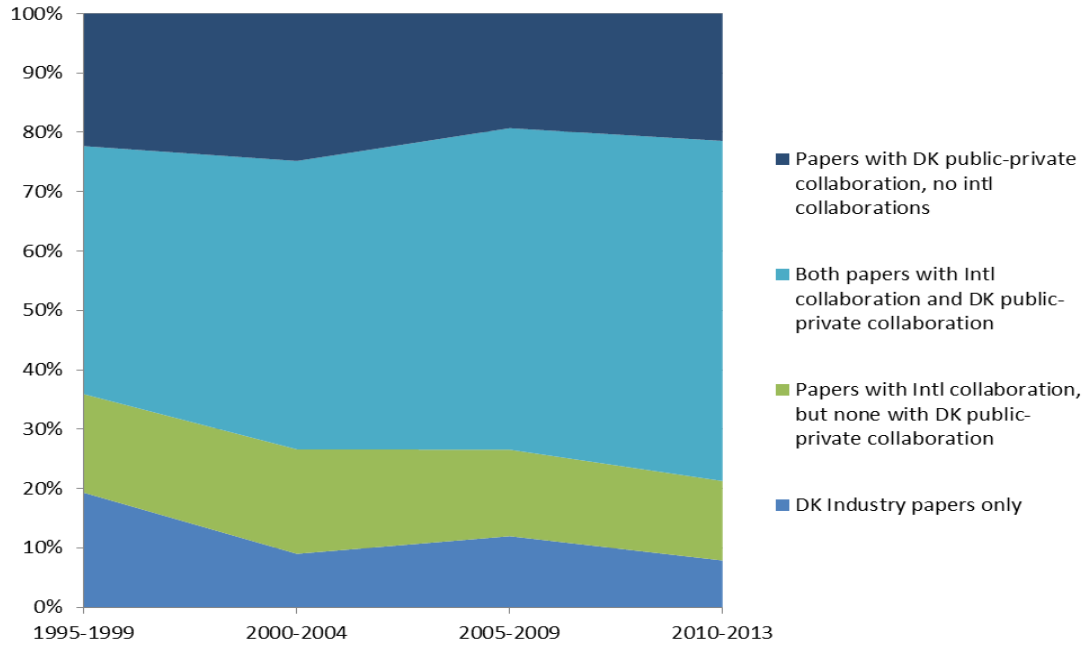
This next part focuses on the individual firm instead of each publication. Many firms have ongoing research and publication activities and have published a number of papers over the period, and we have seen that many engage in both public-private collaboration and at the same time publish industry-only papers. In such cases it is clear that these firms draw on public research in their work, and their public-private collaboration may likely also benefit or inform their industry-only work. Hence, it is relevant to examine publication profiles at the firm level to see what share has international collaboration in a given period and what share has collaboration with Danish public research. For each period in which a firm has co-authored a publication, we have examined which different types of collaborations they were involved in over a three year period. The question is how often firms' overall publication

activities (or total number of publications) over a three year period which do not involve collaboration with Danish public research.
Firm publication activities are categorized here in 4 groups:

- DK industry papers only – the firm has only produced Danish industry only papers in the last three years
- Intl collaborations, no DK public research– the firm has also engaged in international collaboration, but without any papers involving DK public research in the last three years
- Intl collaboration, with DK public research – international collaboration, but publication activity also involves DK public research (though, not necessarily in all papers) in the last three years
- Danish public-private collaboration, no international collaboration in the last three years

Shares of firms within these 4 categories are grouped across four five-year periods over 1995-2013. The overall picture when looking at publications at the firm level supports the conclusions made above, that there is a large and increasing international orientation, but Danish public research appears to play an important role in facilitating and contributing to these collaborations.

Figure 2.18. Distribution of firms according to their publication profiles, four sub-periods in 1995-2013



The earlier figure shows that Danish industry-only papers are declining in number. This figure shows that the share of firms that solely rely on DK industry only papers has also declined greatly, from 19% in the late 1990's to only 8% since 2010. The share of firms with international collaborations, but without any collaboration with Danish public research, has dropped from 17% of firms to 13%. In other words, the share of firms that is able to engage in international collaboration without any involvement of DK public research in their publications is quite small and is declining. International collaboration is growing, and in 2010-13, 70% of the publishing firms engaged in international collaboration. However, most of these firms engage in collaboration with Danish public research at the same time. Finally, while the overall share of firms with Danish public-private collaboration is very large and has increased greatly, from 64% to 78%, this increase is parallel with increasing international orientation. The share with only Danish public-private collaboration has been constant over the period, at slightly over 20%.

3 CITATION ANALYSIS OF RESEARCH COLLABORATION

3.1 Summary

In this section, we examine the citation impact of research collaboration. To some extent, the citation analysis can be seen as an analysis of the impact of public-private collaboration for research and science activities, i.e. from an academic or university perspective. The section examines two issues:

- Comparison of citation impact across different types of collaboration
- Analysis of citation impact for different types of collaboration for a fixed group of researchers

The analysis relies in particular on two indicators, the mean normalized citation score (MNCS) and the proportion of publications among the 10% most cited published within the same field and year (PPtop10%). The MNCS indicator is obtained by averaging the normalized citation scores of all publications of a unit. If a unit has an MNCS indicator of one, the publications of the unit have been cited on par with world averages (or more precisely, database averages) for similar publications in terms of research field, publication year, and document type. As results for both indicators are very similar, this summary primarily describes results for citation impact.

Overall, citation impact for research collaborations with a Danish address involving two or more authors is substantially higher than average impact for Danish single author papers. Average citation impact for research collaborations is 51% higher than world averages in 2013, while impact (MNCS) for single author papers (including both public research and industry papers) was at world averages (1.00) in 2013.

Compared to research collaboration overall, citation impact is higher for public-private collaborations, with MNCS at 1.95 in 2013, which is 95% higher than world averages. For comparison, MNCS for all publications with at least one Danish address was 1.48 in 2013.

Shares of top 10% cited articles, PPtop10%, follow closely the qualitative developments in MNCS. In 2013 21.5% of articles with public-private collaboration involving a Danish partner were among the top 10% most highly cited, compared to 15.7% for Danish all articles.

Among collaborative papers, MNCS has generally been lowest for papers only involving Danish public research. Taking the entire period into account, national public-private collaborations have typically had a slightly higher MNCS, though the difference is not large and in fact MNCS for Danish public research papers is slightly higher in 2010-2013, 1.20 compared to 1.12. MNCS for international collaborations only involving public research is higher than national collaborations, at around 1.5 for much of the period and 1.64 in 2010-2013. Hence, in this last period, citation impact is around 40 percentage points higher for international public collaborations than for national collaborations. For comparison, MNCS for Danish public research papers involving a single author was 1.1 in 2010-2013.

Hence, the analysis does not find any clear difference between public research papers and public-private collaborations when considering pure national papers. Furthermore, average citation impact among Danish public-private collaborations has slightly declined over the period, despite the fact that the share of papers without any citations has fallen. We conjecture that the fall in MNCS for Danish public-private collaborations is mainly due to increased international orientation, where the best researchers now have a relatively greater tendency to seek international collaboration.

By far the highest citation impact is found for international, public-private collaborations involving both Danish and international public research and international industry. Over the period, MNCS ranges from 2.55 to 3.05 in the last period. The latter implies citation impact that is 205% higher than world averages. Citation impact for international public-private collaboration overall (all public-private collaborations involving at least one international partner) is somewhat lower, but has also increased over the period, from 1.87 in 1995-1999 to 2.13 in 2010-2013.

These results thus also show that international papers involving public-private collaboration have on average substantially higher impact than international collaborations only involving public research.

Research fronts are defined as papers that are among the top 1% most highly cited within their field in the first year after publication. The highest share is for international public-private collaborations, where just over 4% of papers were research fronts in 2010-2013. This would suggest that these types of constellations of research partners are better suited to produce high impact research. These shares also provide an indication that high average citation impact for international public-private collaboration is at least in part driven by a small group of very highly cited articles.

Higher impact from public-private collaboration compared to pure public collaboration or solo papers can result from selection, where firms have a greater tendency to collaborate with the most highly cited researchers. To check this, we have identified a fixed group of researchers with both public research papers and public-private collaborations, where this selection bias is eliminated.

Overall for the fixed group of researchers, average citation impact is significantly higher for public-private collaboration than for public collaboration only. However, this result appears to be driven by large differences for a smaller group of researchers as no significant difference is found in the overall distribution of citation impact across researchers. The higher average citation impact for public-private collaboration also appears to be driven by international collaborations. For the comparison of Danish public research with Danish public-private collaboration, no significant difference is found between mean values of MNCS. This supports earlier results that impact mainly arises from the international angle of collaboration.

Among international papers, there is a large and significant difference in mean values, with average MNCS over 0.8 points higher for international collaborations involving industry compared to international collaboration involving. However, statistical tests show that the overall distributions are not different from each other. We find though that the for the top half of researchers in terms of citation impact, the distribution of MNCS is significantly higher for international public-private collaboration, while there is no significant difference among the lower half of researchers.

The results for the fixed group, where selection bias is eliminated mirror to a large degree the results for publications overall. Hence, we do not find any evidence that differences in aggregate citation impact across types of collaboration can be attributed to a selection effect where the best researchers mainly engage in one type of collaboration.

Key conclusions of this section:

- Overall, average citation impact is higher for public-private collaborations than for all journal articles in total.
- However, for pure national collaboration there is no clear difference in impact between public research only and public-private collaboration, though impact for public-private collaborations has been falling over time.
- Citation impact for international public-private collaborations is substantially higher than international public research collaborations.
- The share of very highly cited articles (research fronts) is also highest for international public-private collaborations.
- Statistical tests based on a fixed group of researchers confirm results for national papers, but find that results for international papers only hold for top half of researchers measured in terms of citation impact.
- Results for the fixed group indicate that aggregate differences in citation impact between public research and public-private collaboration are not due to a selection effect.

Figure 3.1 below also indicates that overall average citation impact (MNCS) has risen over time, from 1.23 to 1.48. MNCS for public-private collaborations fluctuates more due to the smaller number of publications and values at the beginning and end of the period are almost the same (1.99 in 1995 and 1.95 in 2013). However, examination of the fluctuations over time gives the impression that MNCS for public private collaboration has generally followed an upwards trend over the period. While not shown in the figure below, shares of top 10% cited articles follow closely the developments in MNCS. In 2013 21.5% of articles with public-private collaboration were among the top 10% most highly cited, compared to 15.7% for all articles.

3.2 Introduction

In this section, we examine the citation impact of research collaboration. To some extent, the citation analysis can be seen as an analysis of the impact of public-private collaboration for research and science from an academic or university perspective. Later in this report, we will examine the impact on the business side of public-private collaboration by looking at the relation between collaboration and business performance.

While an imperfect measure, citations can be seen as indicators of the diffusion of research, and of their impact and importance or usefulness to science. Citations are thus often used as a measure of performance for researchers. In this section, we will examine a number of issues concerning the citation impact of research collaboration. As noted in section 1, we will focus in particular on three issues:

- Comparison of citation impact across different types of collaboration
- Analysis of citation impact for different types of collaboration for a fixed group of researchers
- Analysis of the production of frontier research across types of collaboration

The goal of the first is to examine citation impact of public-private collaboration in relation to publications only involving public research, and the role of international collaboration. We will compare citation impact for the same groups and classifications of collaborations examined in chapter 2. Furthermore, we will examine both average citation impact and shares of highly cited articles. Finally, the measures we examine here are all normalized according to research field and year of publication, which is important given large differences in publication and citation practices across research fields. The citation based indicators used in this section are described in greater detail below.

The goal of the second point is to conduct a more rigorous testing of the differences between citation impact for publications only involving public researchers and those with public-private collaboration by examining a fixed group of researchers publishing both types of research. In doing so, we eliminate potential selection bias, where firms prefer to collaborate with the best researchers and universities. Finally, the goal of the third point is to examine whether public-private collaborations are more or less likely to produce very highly cited papers that often lie at the frontier of individual research areas. Based on well-established bibliometric methods and indicators, we will identify and map research frontiers within research specialties using citation data (e.g. Small & Griffith, 1974; Jarneving, 2005; Lucio-Arias & Leydesdorff, 2009; Small, Boyack & Klavans, 2014). The indicators used are described in greater detail below. We also examine the relation between these research fronts and cross-disciplinarity using the same measures shown in section 2.

3.3 Citation data and indicators

Here we describe the citation data and indicators used in the analysis. Citations generally indicate that the researcher has found the publication useful in his research and can be seen as a form of peer recognition, an acknowledgement of the contribution of others' work (Merton 1988). Though, studies have shown that not all citations have a central relevance to the main issues addressed in the citing author's paper (Bornmann and Daniel 2008). However, in general, studies have concluded that citations are an imperfect but reasonable indicator of impact in aggregate terms (eg. Gläser and Laudel 2007, van Raan 1996, van Raan 1998).

We use data from CWTS' in-house version of Thompson Reuter's Web of Science citation database. In calculating citation impact, we apply fixed-length three year citation windows including the publication year, except for publications from 2013, where the citation window is only two years.

As noted above, the analysis relies in particular on two indicators, the mean normalized citation score (MNCS) and the proportion of publications among the 10% most cited within the same field and year (PPtop10%). Such relative indicators are needed here because the typical number of citations is highly dependent on research field, publication type and the time allowed before citations are counted. Self-citations are excluded from the calculation of citation rates and citation rates are calculated with three-year citation windows, i.e., the citations obtained during the publication year and the following years are counted.

In addition, this section develops and uses four additional indicators. Research fronts are defined as articles that are among the top 1% most highly cited within their field in the first year after publication. Intellectual bases are defined

as articles that are among the top 5% most highly cited within their field after five years. Inter-disciplinarity of an article is defined as the share of the article's references that lie outside the discipline of the article itself, and thus ranges from 0 to 1. Multi-disciplinarity is defined as the number of other disciplines covered by the articles. There are 31 broad disciplines in all, so this measure can range from 0 to 30.

Citation data is typically highly skewed, where a large number of publications have a small number of citations (or a low citation score) and a small number of publications have a very high number of citations. For this reason, it is important that averages are calculated for large groups of papers. To improve the robustness of results, instead of calculating citation based indicators for each individual year, we have constructed citation-based indicators for four time periods of 4 to 5 years, i.e. from 1995-1999, 2000-2004, 2005-2009 and 2010-2013.

3.4 MNCS over time in total for all publications, all collaborations and public-private collaborations

In order to provide an overview for the citation impact of research collaborations, figure 3.1 below shows MNCS over time for all journal articles (with a Danish address) involving two or more authors and for public-private collaborations. As a benchmark, figure 3.1 also shows MNCS for all articles with a Danish address and for single author articles (i.e. all articles without research collaboration). Citation impact for single author papers has been around world averages for the period, though with a slight trend upwards. In the years from 2008 to 2012, MNCS has been around 1.1, though it has fallen back down to world averages in 2013. There is little difference in citation impact for all collaborative papers compared to overall averages, though with MNCS for research collaboration slightly higher. This reflects that the large majority of journal articles involve collaboration.

Figure 3.1. MNCS over time in total for all journal articles, single-author articles and for public-private collaborations

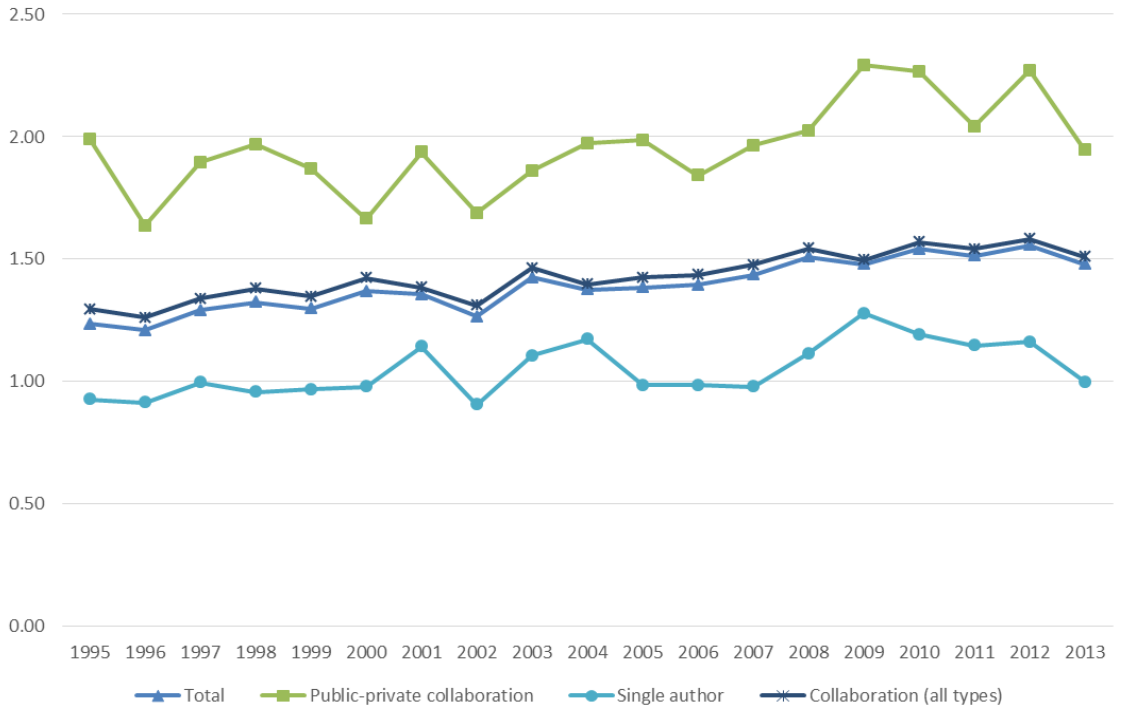


Figure 3.1 thus shows that, overall, citation impact is substantially higher for papers involving collaboration compared to papers without collaboration, while impact is even higher for public-private collaborations. As will be seen below, this difference does not hold across all types of public-private collaboration. For national papers, there is no difference in citation impact between public research papers and public-private collaborations. In contrast, among papers involving international collaboration, citation impact is indeed higher for public-private collaborations. Results for different types of collaborations are shown in detail below.

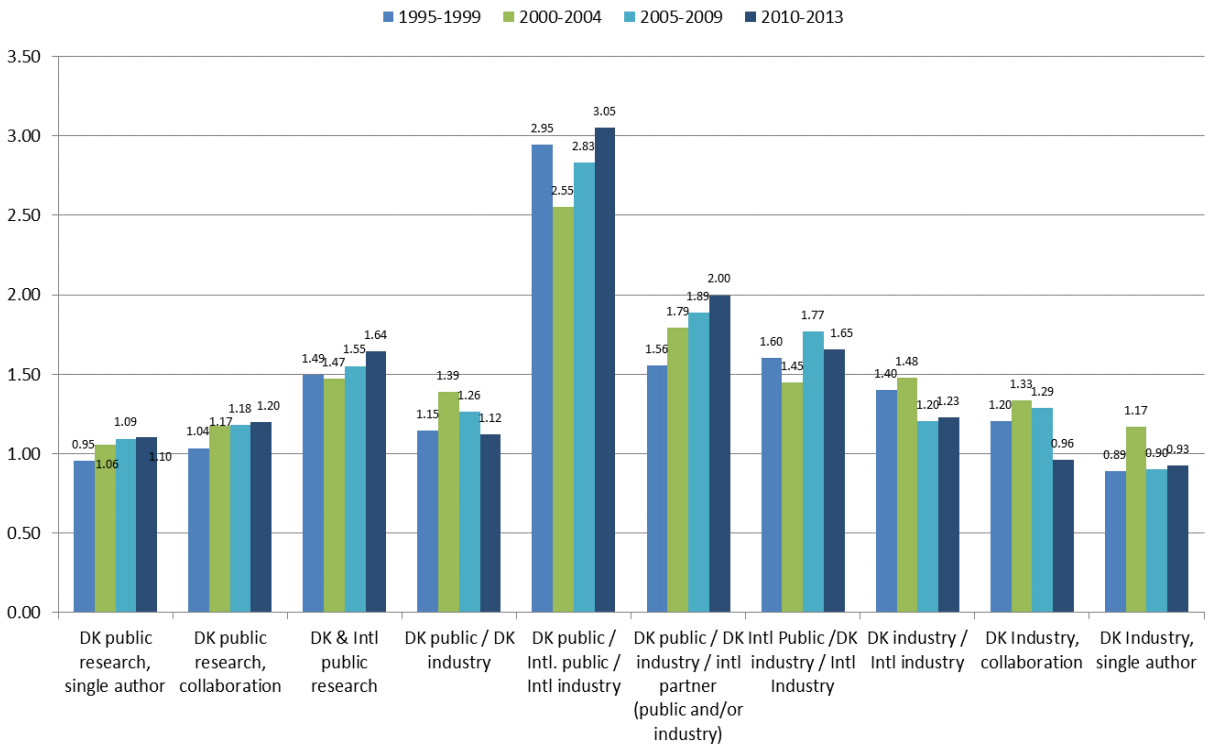
3.5 MNCS by type of research collaboration

Figure 3.2 shows MNCS for different forms of collaboration. As mentioned above, these indicators are normalized both across fields and according to global averages. A value of 1 corresponds to the world average number of citations within the respective fields. Overall, citation impact for Danish research is high in international comparison, with Denmark ranking among the top five countries in average citation impact. Note that some papers only involving Danish public research or only Danish industry may have a single author. We have isolated these papers in order to create a benchmark for comparison with the different types of collaborations. The number of single author papers within Danish public research is quite high, at around 8-900 papers per year, however, the number of industry-only papers with a single author is much lower, particularly for the last period with only 74 papers for the four year period.

While the difference is not always large, average citation impact is generally higher for papers with collaboration. For example, among Danish public research papers, MNCS for 2010-2013 is 1.20 for collaborative papers compared to 1.10 for single author papers. MNCS among Danish industry-only papers with collaboration is higher than single author industry papers, though the difference is very small in the last period (0.96 to 0.93).

Among collaborative papers, MNCS is generally lowest for papers only involving Danish public research. Taking the entire period into account, national public-private collaborations have typically had a slightly higher MNCS, though the difference is not large and in fact MNCS for Danish public research papers is slightly higher in 2010-2013, 1.20 compared to 1.12.

Figure 3.2. MNCS by type of collaboration, four sub-periods in 1995-2013



When examining these figures, it is important to take into account the overall developments in research production, where there is a growing shift towards international collaboration. It may very well be the case that many research projects and papers that would typically have been conducted nationally 15-20 years ago are now performed with the involvement of international partners. And, it may also be the case that these papers often tend to be above average in terms of performance. We will attempt to examine this in more detail below.

MNCS for international collaborations only involving public research is higher than national collaborations, at around 1.5 for much of the period and 1.64 in 2010-2013. Hence, in this last period, citation impact is around 44 percentage points higher for these international public collaborations than for national public collaborations.

As the figure clearly shows, by far the highest citation impact is found for international, public-private collaborations involving both Danish and international public research and international industry (though not Danish industry). Over the period, MNCS ranges from 2.55 to 3.05 in the last period. The latter implies citation impact that is 205% higher than world averages.

These results thus also show that international papers involving public-private collaboration have on average substantially higher impact than international collaborations only involving public research. In the course of this section, we will attempt to look more closely at this result and what potentially lies behind it. For example: are the topics or types of research that these papers cover different, having a greater importance and attracting greater attention? Do they more often involve top researchers? Is there something about the synergies of the collaboration that produces higher impact papers? Are the results driven by a small group of very influential papers involving an extremely large number of co-authors, such as papers related to the CERN project?

The sixth and seventh groups in figure 3.2 show MNCS for international public-private collaborations involving Danish industry. MNCS for international public-private collaborations involving both Danish public research and Danish industry has increased steadily over the period and was 2.00 in 2010-2013. MNCS for international public-private collaborations not including Danish public research is somewhat lower (1.65 in 2010-2013).

Figure 3.2 thus shows international public-private collaborations broken down into three groups according to the types of collaboration partners involved in the publication. Citation impact for international public-private collaborations overall (i.e. all public-private collaborations involving at least one international partner) is an average of these three groups, with MNCS at 1.87 in 1995-1999 and increasing to 2.13 in 2010-2013. Hence, overall MNCS for international public-private collaboration has been around 40-50 percentage points higher than for international public research collaborations.

An interesting result is that there does not appear to be any large difference between the three different types of national collaborations: Industry only publications, Danish public research only papers and Danish public-private collaborations. They are all among the least cited papers. However, trends over time have differed, with MNCS increasing for Danish public research and declining for Danish public-private collaboration and Danish industry-only papers.

At the same time, impact has generally increased for papers involving international collaboration. We examine this result in greater detail below.

As was noted above, average citation impact is strongly influenced by high-impact papers. Hence, median values for citation impact are typically much lower than mean values. Median values of citation impact[16] follow the same pattern as for mean values (MNCS), though differences are somewhat smaller. For example, in the last period (2010-2013), median citation impact was 0.58 for Danish public research collaboration and 0.52 for Danish public-private collaborations, 0.78 for international research collaborations and 1.19 for collaborations involving Danish and international research and international industry.

3.5.1 Examining distributions in citation impact over time for Danish public-private collaboration

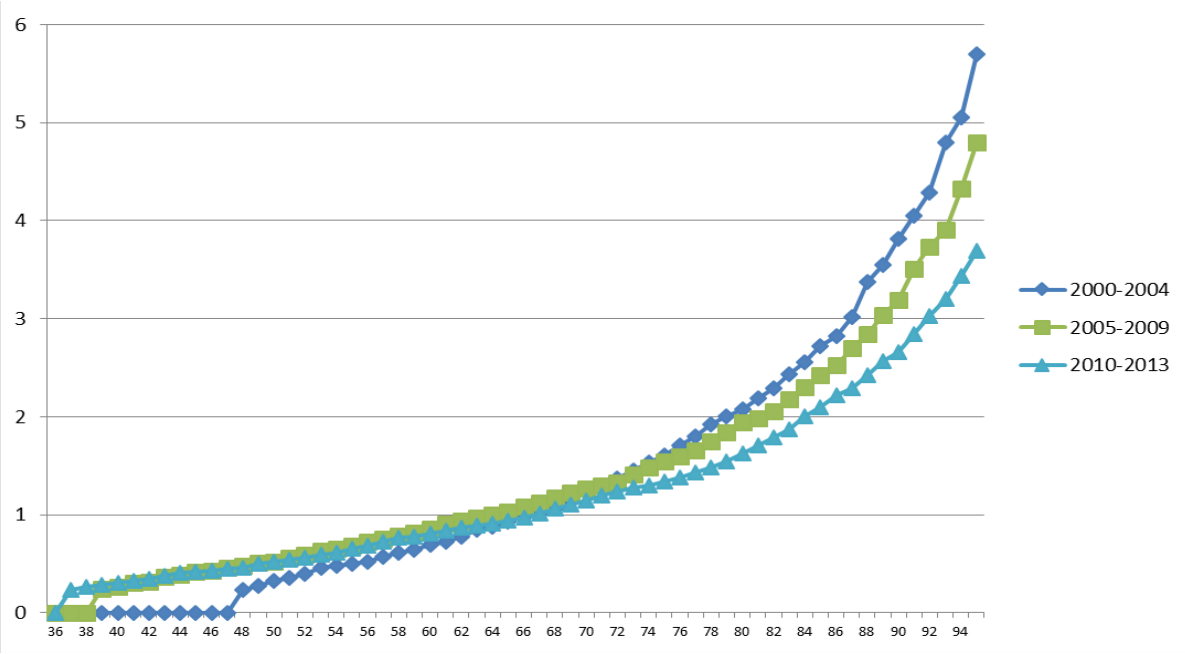
In order to examine in greater detail the developments in citation impact for Danish public-private collaboration, we have compared the distributions of publications according to citation impact for the different time periods (2000-2004, 2005-2009, 2010-2013). Figure 3.3 shows the distribution for publications according to percentiles for Danish public-private collaborations. If we rank publications in each group by citation impact, the lowest 36-38% have no citations for 2010-2013 and 2005-2009 respectively, compared to 47% for 2000-2004.

If we keep moving upwards, citation impact is still higher in 2010-2013 and 2005-2009 compared to 2000-2004 for the lowest two thirds of publications. Hence, while mean values have fallen over time, citation impact has actually increased or was unchanged for the majority of papers with Danish public-private collaboration (i.e. the lowest two thirds). In contrast, for the best 25% in each period, there is a clear difference across periods, with MNCS highest in 2000-2004 followed by 2005-2009 and lastly 2010-2013. At the same time, we have seen that there has been a strong trend from national to international public-private collaboration. One possible interpretation of this result is that many of the best papers that previously would have been based on national public-private collaboration now

[16] Median values of the normalised citation score.

involve international partners. This would suggest that declines in citation impact over time for Danish public-private collaboration are mainly due to a shift towards greater internationalization for the most highly cited work.

Figure 3.3. Distribution of MNCS for DK public-private collaboration across percentiles (36th to 95th percentile), for sub-periods.



Lowest 35 percentiles (zero citation impact in all periods) and highest 5 percentiles (large values make it difficult to see patterns for the rest of the distribution) are not shown.

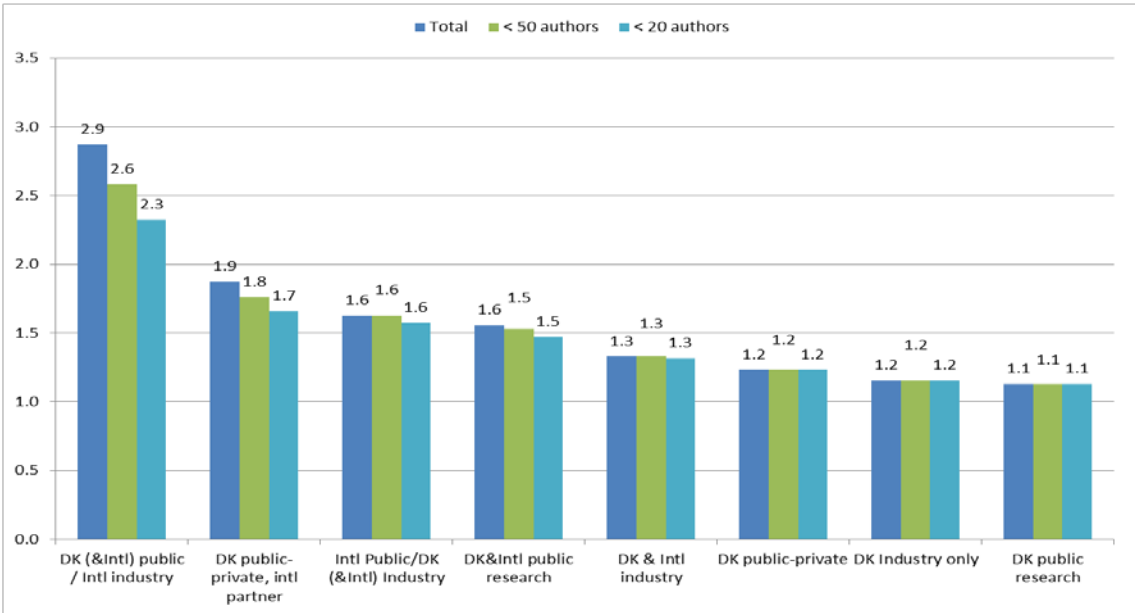
3.5.2 Citation impact and the number of co-authors

As noted above, many papers involve a large number of co-authors. We are particularly interested in the role of papers involving extremely large consortia, with hundreds and in a few cases, thousands, of co-authors. Participation in these large consortia may be very beneficial for both firms and public researchers, but it is clear that the nature of the research activity for these consortia is different from that for a concrete research project that involves a handful of participants. It is also clear that these extremely large projects are primarily international public-private collaborations.

In order to examine the influence of these large consortia on average citation impact, we calculate mean MNCS when the largest collaborations are excluded. Figure 3.4 shows MNCS for the full sample and with the exclusion of first papers with 50 or more authors, and thereafter 20 or more authors. MNCS for national collaborations are essentially unaffected by this removal while MNCS for both international public research and international public-private collaborations decline.

The largest decline is for international public-private collaborations, though MNCS is still substantially higher even after removal of papers with 20 or more authors. The indication is thus that these large consortia do appear to have some influence on differences in impact between international public research and international public-private collaborations, but only a partial one. Differences are still very large even after removing papers with a large number of authors.

Figure 3.4. MNCS for period 1995-2013 for full sample and excluding papers with large number of authors



Note: Danish industry only and Danish public research only include both collaborations and single author papers.

3.6 Comparing citation impact of collaboration at the level of the individual researcher

The goal of this sub-section is to examine to which degree the impact of public-private collaboration can be explained by selection bias, where firms choose to collaborate with the best researchers. To do this, we have identified a group of corresponding authors of articles involving both public-private collaboration and pure public research and constructed a list of all articles authored by these researchers within a period of time. In doing so, we can see how articles with public-private collaboration compare to academic-only articles authored by the same researchers. As will be shown below, we find the following:

- Average citation impact for the fixed group of researchers that have engaged in public-private collaboration is higher than for the full sample of publications.
- There is no clear difference in impact between public research and public-private collaborations for Danish papers. This result is similar to that for the full sample.
- When comparing public research and public-private collaborations for international collaborations or for all papers (i.e. both national and international), average citation impact is significantly higher for public-private collaboration. This result also follows that for the full sample.
- However, in contrast to the full sample, there is no difference in median citation impact for this fixed sample of researchers. This suggests that there is some degree of selection for researchers than engage in public-private collaboration.
  Differences in citation impact between public-private collaboration and pure public research are increasing in overall citation impact for the researcher.

The sample examined here includes all corresponding authors with a Danish university address for articles in 2008-2010 involving public-private collaboration, which amounts to a total of 798 researchers. For each researcher, publication portfolios over the period 2006-2012 were found in the WoS database using a name disambiguation algorithm developed by CWTS that has generally shown very high recall rates (90-95%) especially with sets of non-Asian author names and affiliations (Caron & van Eck, 2014). This seven year period (2006-2012) was chosen in order to ensure an adequate number of publications for individual researchers in the fixed group. The rate of precision is considered to be even higher when a specific article, email address and institution can be identified for the researcher, as is the case here. Though, it is still important to note that this process is not perfect where both incomplete lists (where some articles are missing) and false positives (articles are matched that are actually authored by

a different researcher with the same or very similar name). Of these 798 researchers, 46 had only one publication during the period, which precludes the possibility of any comparison across types of collaboration. Hence, these were removed from the sample.

In all, a total of 18,215 articles were identified over the period 2006-2012 for these 752 researchers. Table 3.1 shows the distribution of individuals according to number of publications.

Table 3.1. Distribution of individuals according to number publications

	2 to 5 pub.	6 to 10 pub.	11 to 19 pub.	20 or more pub.	Total	Number publications
Total	177	132	160	283	752	18,215

The main question that we examine here is: How does citation impact compare for academic papers and public-private collaborations when examining the same group of researchers?

As we have seen above, citation impact is typically much higher for papers involving international collaboration. Hence, we want to take account of international collaborations in the analysis here, and will utilize the same classification of collaborations used elsewhere in the paper. Only 1.3% of the 18,215 papers in this sample have a single author. Due to this very small share, we do not distinguish between papers involving a single author and papers with multiple authors.

We will first conduct an aggregated analysis, where we calculate MNCS for this entire subset of papers for each of these four types of collaboration partners. Compared to the full set of publications that we examine in this report, this subset of papers has in common that they are co-authored by the same group of researchers.

Our second and main part of this analysis focuses more directly on a comparison of citation impact for the individual researcher. For each researcher covered in our sample, we calculate MNCS for the researcher's publications in each of the four categories. Not all of the researchers in the sample have publications in all four categories, so average citation impact (MNCS) for the individual researcher can only be calculated for those categories that include publications. In order to be as inclusive as possible, we only require that one publication is needed in a category in order to calculate the MNCS. This can imply greater variation in average citation impact, but on the other hand this gives a large number of researchers in the sample, which helps to enhance the precision of our results.

We will make pairwise comparison of different types of collaboration in order to ensure that we are comparing the same group of researchers. So, when we for example compare MNCS for Danish public papers with Danish public-private collaboration, we only include researchers that have publications in both groups.

Finally, it is important to keep in mind that citation data are highly skewed, which calls into question the validity of tests that assume that the data is normally distributed. While there are differing opinions on how extreme the skewness should be before precluding the use of t-tests in practice, it may be more appropriate to use non-parametric tests that essentially test whether overall distributions for two groups are equal.

Table 3.2 below shows both mean and assorted percentile values for each type of collaboration. If we consider the mean values in comparison with the full sample, there are some general similarities. MNCS for Danish public research and Danish public-private collaboration, as well as industry only papers, are quite similar, while MNCS for international public collaboration is higher and international multi-partner collaborations are clearly the highest.

Table 3.2. Mean Normalized Citation Score (MNCS) for different types of collaboration. Mean, median and percentile values for sample, and average values per individual. Period: 2006-2012.

	Sample mean	Median	75th pctl.	90th pctl.	99th pctl.	Avg. per indiv.	Mean for full sample 2006-2012
DK public research only	1.44	0.68	1.66	3.26	11.69	1.23	1.20
DK public research & DK industry	1.41	0.61	1.58	3.23	11.16	1.24	1.23
DK & intl. public research	1.67	0.83	1.92	3.94	14.00	1.41	1.61
Intl. collaboration incl. DK public research and industry partner	2.74	0.93	2.30	5.45	34.49	2.14	2.70
DK industry only	1.42	0.65	1.32	3.78	14.68	1.15	1.41
Total	1.67	0.75	1.80	3.66	15.06	1.46	1.50

The sample mean is the aggregate mean, calculated for all articles. For averages per individual, mean values are first calculated for each individual; thereafter the mean of individual averages is calculated.

However, note that MNCS is substantially higher here than for the full sample. MNCS is around 1.4 in this sample for Danish public papers and Danish public-private collaboration, compared to around 1.2 for the full sample over the same period (2006-2012). And overall MNCS here is 1.67, which again is close to 20 percentage points higher than the average for the full sample. This suggests that researchers that engage in public-private collaboration have higher citation impact than those that do not.

As can be seen from the table, median values are much lower than mean values, less than half of the mean in all cases. This indicates the large influence that the highest impact papers have on overall averages[17]. In comparison of Danish public papers and Danish public-private collaboration, the distributions are very similar, both for mean values, the median and also higher percentiles. Median values for papers with international collaboration are higher than for national collaborations, but in particular the median for international multi-partner collaborations is only slightly higher than for international public research collaborations. The difference in median values between these two groups is only 0.10, while the difference in means is much larger at 1.10.

The main results of this analysis are shown in table 3.3. The table shows the results of pairwise comparisons of MNCS within the four types of collaborations. Industry only papers are not included here as only a small number of researchers have these papers and a comparison would thus not be generalizable in any meaningful way.

As noted above, comparisons are only made for researchers that have publications with both types of collaboration. For example, the first comparison is Danish public research papers vs. Danish public-private collaborations. Of the in all 752 researchers in the sample, 552 have at least one paper in each of these two groups. The table shows the average MNCS per researcher and median value of MNCS for this group of 552 researchers. We have conducted both standard t-tests and non-parametric Mann-Whitney tests on the data. P-values for the test statistics are shown in the table. The Mann-Whitney test is two-sided, while the t-test is one-sided (of whether the mean for the second group is significantly larger than the first).

Consider first the comparison of public research papers overall (i.e. both Danish and international) and public-private collaborations (last row of results in table 3.3). Mean citation impact is significantly higher for public-private collaboration, while there is no significant difference in overall distributions. In other words, there is no 'across the board' difference in citation impact, but citation impact is substantially higher for a smaller group of highly cited researchers.

[17] Due to this effect of high impact papers, it is a common pattern for citation data that mean values are higher that median values.

For the comparison of Danish public research papers and Danish public-private collaboration, the distribution of MNCS values for Danish public-private collaboration is significantly lower than for Danish public research only. Hence, for the majority of researchers with both types of collaboration, MNCS is higher for Danish public research.

Table 3.3. Comparing mean and median values per individual. Results of non-parametric and parametric tests.

	Obs.	Mean	Median	Mann-Whitney (p-value)	T-test (p-value)
DK public research & DK industry	552	1.262	0.768		
DK public research only	552	1.198	0.964	**0.003**	0.231
DK public research only	504	1.273	1.015		
DK & Intl. public research	504	1.442	1.153	**0.015**	**0.027**
DK public research & DK industry	406	1.263	0.768		
Intl. collab. incl. DK public research and industry partner	406	2.283	1.15	**0.000**	**0.002**
DK & Intl. public research	416	1.449	1.190		
Intl. collab. incl. DK public research and industry partner	416	2.270	1.172	0.382	**0.006**
Public research only (DK or Intl.)	674	1.299	1.066		
Public-private collab. (DK or Intl.)	674	1.551	1.017	0.670	**0.002**

Mann-Whitney is a test of whether entire distributions of MNCS are the same for the two groups while T-test is a test of whether mean values for the two groups are equal. P-values under 0.1 (i.e significant at the 10% level) are highlighted in bold.

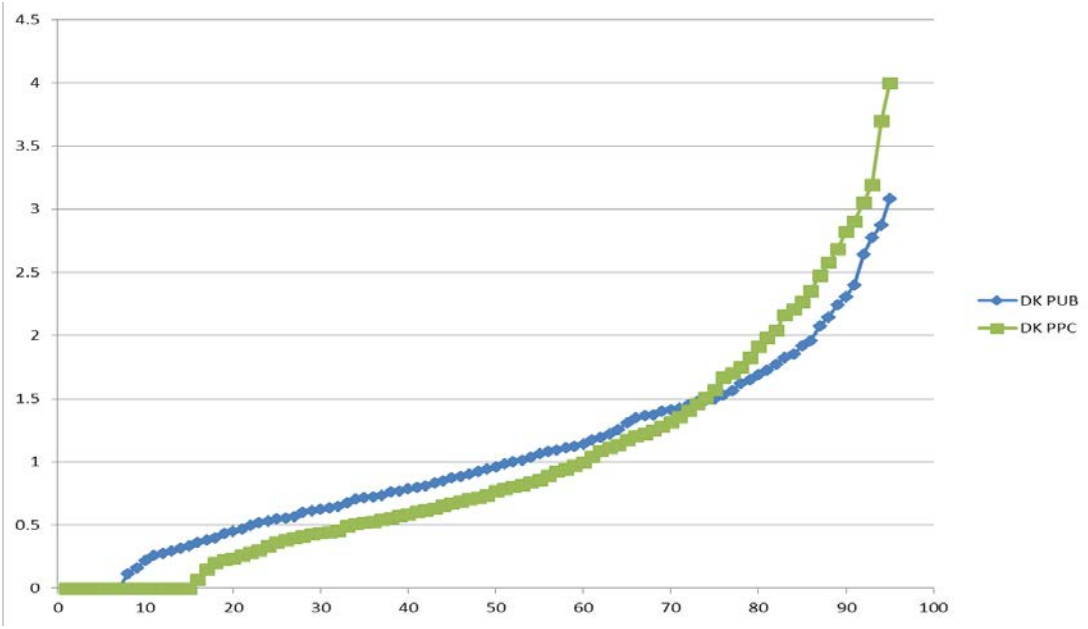
In comparison of Danish public research with International research collaboration, international collaboration has both a significantly higher mean and the overall distribution is also significantly higher in terms of MNCS.

In comparison of Danish public-private collaboration with international public-private collaboration, the results show clearly that citation impact for international public-private collaboration is higher than national public-private collaboration.

The final comparison is between international collaboration only involving public research and multi-partner collaborations that also involve public-private collaboration. Here there is a large difference in mean values, with average MNCS over 0.8 points higher for international collaborations involving industry. However, at the same time, median values for MNCS are almost the same. The statistical tests show that mean value of MNCS is significantly higher for multi-partner, public-private collaborations, but that the overall distributions are not different from each other. This suggests that high citation impact for a small number of publications with international public-private collaboration are driving the difference in mean values. We examine this further in figure 3.6.

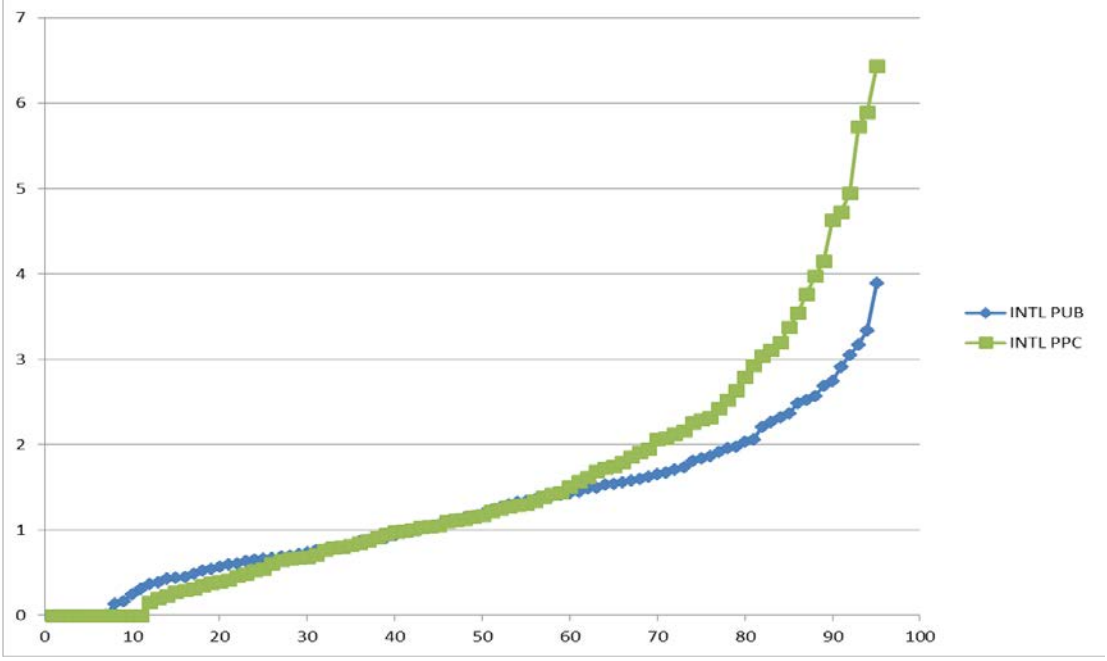
These results indicate that there may be some differences in the distributions of publications in relation to citation impact. To examine this further, we have compared distributions for national public research with national public-private collaborations, and international public research with international public-private collaborations. These distributions are shown in figures 3.5 and 3.6.

Figure 3.5. Distribution of researcher MNCS for Danish public research publications and Danish public-private collaboration across percentiles (1st to 99th percentile)



For Danish papers, citation impact (MNCS) is consistently higher for the bottom 75% of individuals for public research papers (where in particular, there is a much larger share with zero citations for public-private collaboration), while it is consistently lower for the top 25%. Note though that if we consider only the top half of the performers in terms of MNCS, the mean value is significantly higher for public-private collaboration. We can also calculate the difference for each individual, i.e. the difference between MNCS for Danish public-private collaboration and Danish public research. When doing this, we find that MNCS for Danish public-private collaboration is lower for 310 researchers and higher for 242 researchers. Finally, the mean value of the difference is 0.064 (not significantly different from zero). Overall MNCS is positively correlated with this difference (correlation coefficient), but not strongly so: 0.197 (i.e. a weak tendency that the higher the overall MNCS, the higher the impact of public-private collaboration is compared to public research only articles).

Figure 3.6. Distribution of MNCS for Intl public research publications and Intl public-private collaboration across percentiles (1st to 99th percentile)



For international papers, citation impact (MNCS) is higher for the bottom 25% of the individuals for public research papers. In the middle the two groups are equal, while public-private collaboration is much higher for the top 40%. If we consider only the top half of performers in terms of MNCS, the mean value is significantly higher for public-private collaboration.

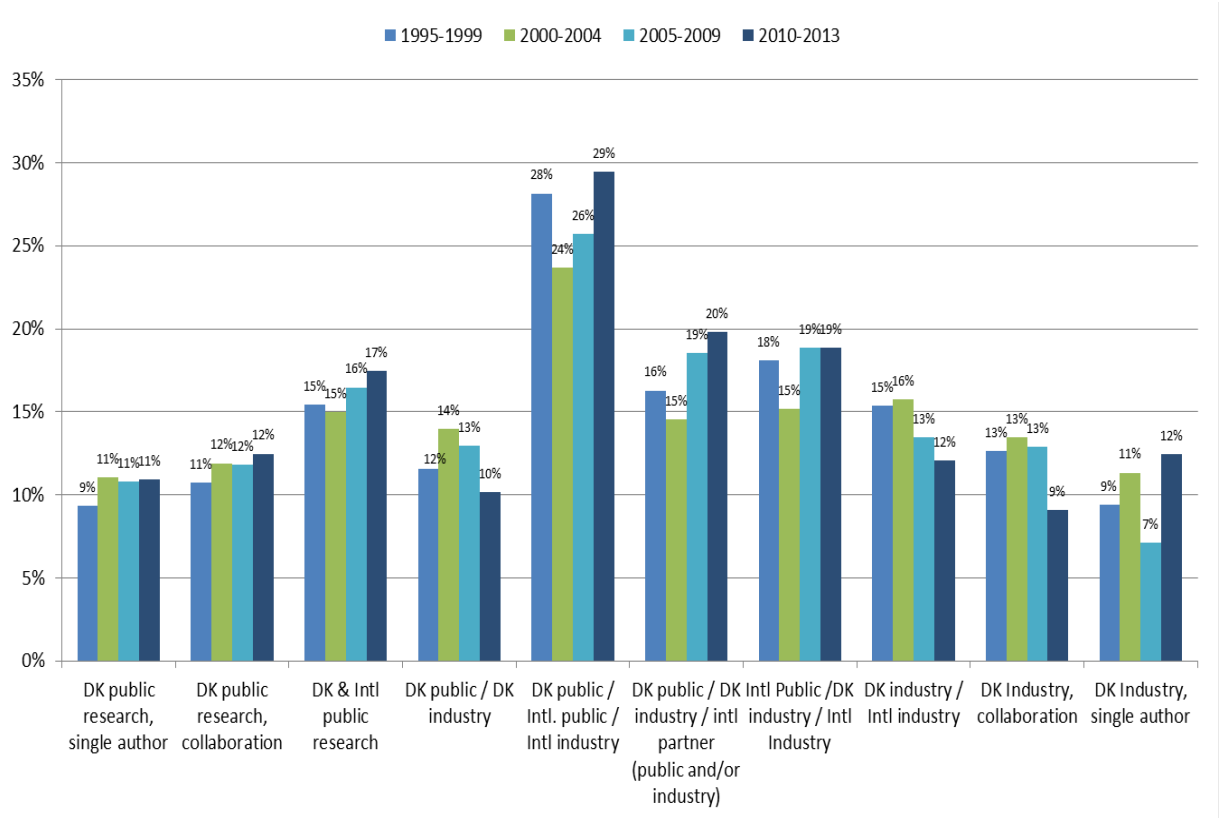
As above, we can also calculate the difference for each individual, i.e. the difference between MNCS for international public-private collaboration and international public research. MNCS for international public-private collaboration is lower for 203 researchers and higher for 213 researchers. Mean value of the difference is 0.821 (significantly different from zero). Overall MNCS is positively correlated with this difference (correlation coefficient), more strongly than for Danish papers: 0.523 (i.e. a strong tendency that the higher the overall MNCS for the researcher, the higher the impact of public-private collaboration is compared to public research only articles).

In general, this analysis of individual researchers indicates that researchers that engage in both purely academic and public-private collaboration papers experience a higher impact when international co-authors are included, while the impact of national papers is on the same level with small differences in the distribution of impact. Concerning national collaborations, encouraging researchers to pursue industry research partners does not seem to be backed up by an argument that they experience a higher academic impact; on the other hand it does not seem that there is a trade-off between industrial involvement and scientific impact. However, pursuing international collaborations be they public or private, is associated with a higher impact on average in this analysis.

3.7 Highly cited publications

PPtop10% measures the share of publications that are among the top 10% most highly cited in their field. Hence, shares above 10% imply a greater share of highly cited papers than the world average. The share is also less influenced by papers with extremely high citation impact (as they count the same as other papers among the top 10%). Figure 3.7 shows results for PPtop10% for different types of collaborations.

Figure 3.7. The percentage share of journal articles among the top 10% most highly cited (PPtop10%) by type of collaboration, four sub-periods in 1995-2013.

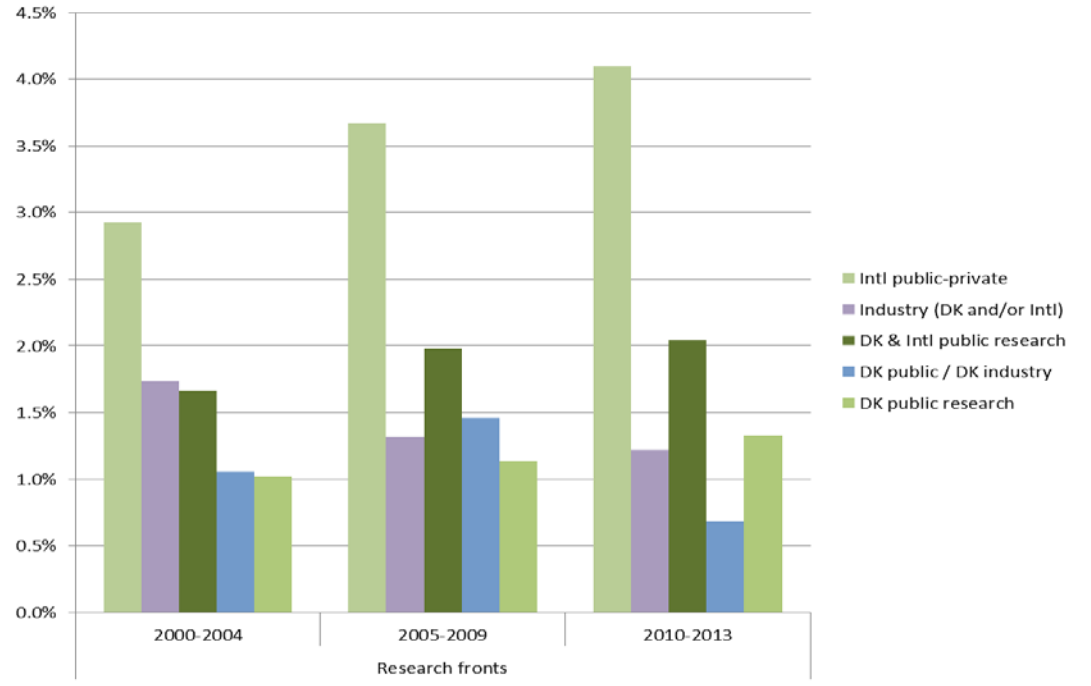


The results resemble to certain degree those for MNCS. As with MNCS, shares of highly cited articles are slightly lower for single author papers. An exception though is Danish industry only papers in the last period. However, the number of single author industry papers is low and thus can be influenced by results for individual papers. Among national publications with collaboration, the share of highly cited articles has fallen for both public-private collaborations and industry-only papers, while it has increased slightly for Danish research only papers. PPtop10 has been fairly stable for both Danish and international public research papers, while MNCS has increased slightly over the same time period. And, PPtop10 is highest among papers with international public-private collaboration where, as with MNCS, the highest shares are found among collaborations involving Danish and international public research and international industry. PPtop10% for international public-private collaboration overall (not shown in figure 3.7) was 22.1% in 1995-1999, falling to 19.3% in 2000-2004 and thereafter increasing to 24.6% in 2010-2013.

3.8 Research fronts

Some papers may impact their field gradually over time while others may impact almost immediately, effectively establishing themselves as state of the art within their field. These latter papers are often called 'research fronts' as they lie at the front of their field. They both represent the newest results and also the highest impact on current research. Research fronts are here defined as papers that are among the top 1% most highly cited within their field in the first year after publication. In comparison, our measures of MNCS and PPtop10% use three year citation windows. Given that research fronts comprise a very small share of papers, small groups of papers can be sensitive to results of a few papers. In order to improve precision, we have combined groups of papers for international public-private collaboration and for industry-only papers.

Figure 3.8. Research fronts (among top 1% most cited in first year) by type of collaboration



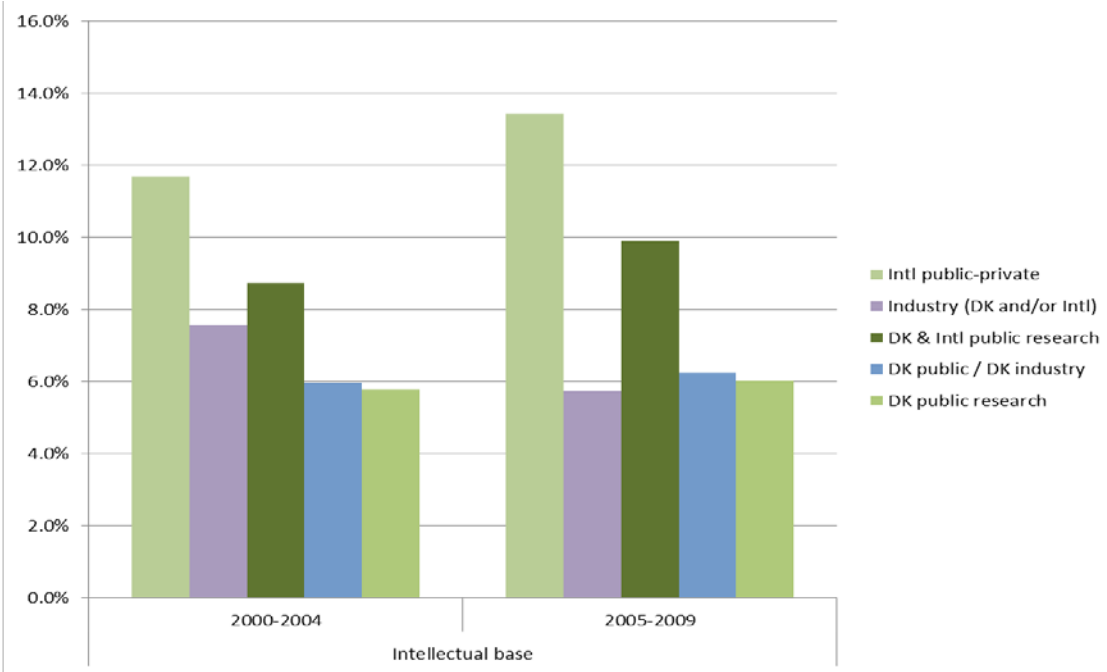
Note that Danish public research and Danish industry only include both collaborative and single author papers.

As a reference point, world averages correspond to 1%. The highest share is for international public-private collaborations, where just over 4% of papers were research fronts in 2010-2013. And in comparison with PPtop10% (where shares for international public-private collaboration were 2.5 times the world average in 2010-2013), shares are higher here, and have increased from 2000 to 2013.
This would suggest that these types of constellations of research partners are better suited to produce top research, measured in terms of citation impact These shares also provide an indication that high average citation impact for international public-private collaboration is at least in part driven by a small group of very highly cited articles.

Shares for Danish public research alone are lower, though they have increased over the period from 1.0% to 1.3%. The same holds for international public research collaborations, with a share of 2.2% in 2010-2013.

Research fronts measure the immediate, high impact of papers. An alternative indicator, intellectual bases, measures whether papers sustain or more gradually accumulate high impact over a longer period. Intellectual bases are defined as papers that are among the top 5% most highly cited after five years (the measures of MNCS and PPtop10% in this report use a three year window). For reference, world averages in this case are 5%. In general, results are fairly similar for research fronts and intellectual bases, though relative shares are lower for intellectual bases for international public-private collaborations. One exception here is for Danish public-private collaboration, where shares of research fronts have fallen while shares of intellectual bases have remained stable over time.

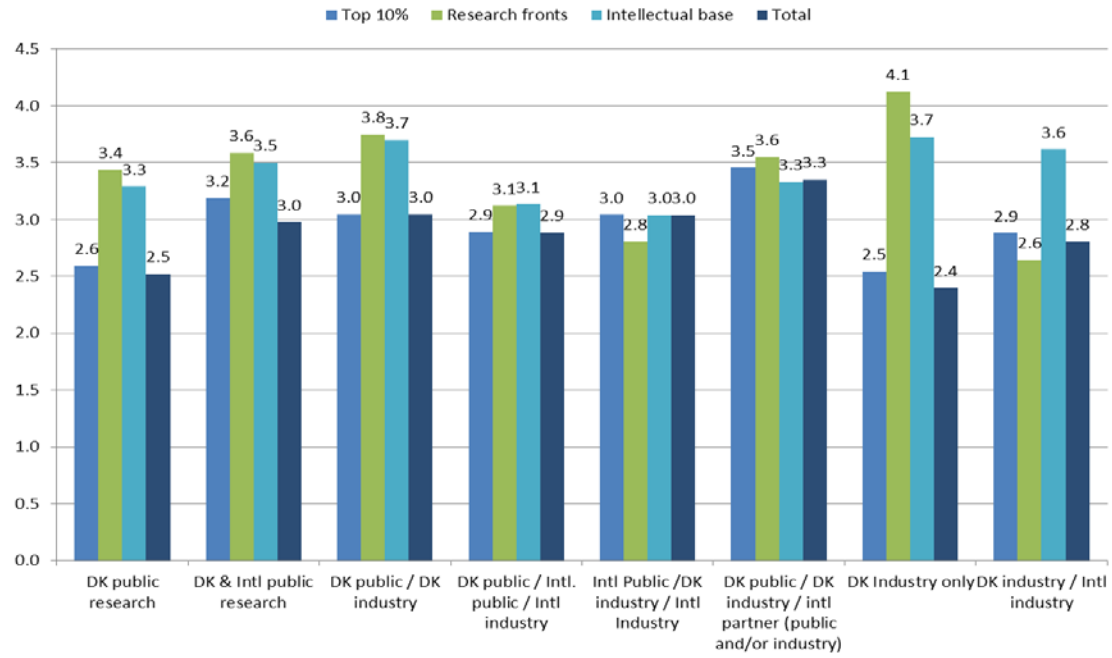
Figure 3.9. Intellectual bases (top 5% most cited after five years) by type of collaboration



Due to 5-year window, it is not possible to calculate intellectual base for the period 2010-2013. Note that Danish public research and Danish industry only include both collaborative and single author papers.

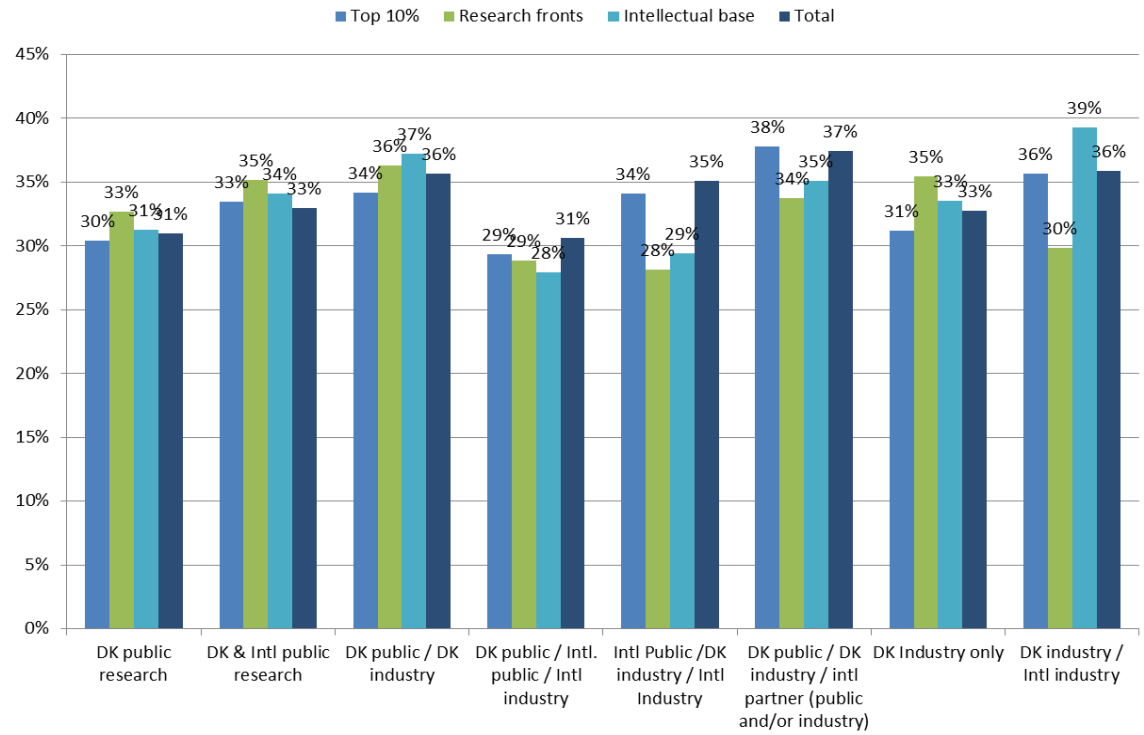
How is cross-disciplinarity related to the citation impact of papers? Are highly cited papers more cross-disciplinary, and is there any difference in terms of collaboration? To examine this, we have calculated the average degree of multi-disciplinarity (number of different disciplines among article references) and inter-disciplinarity (share of references from other disciplines) for research fronts and for top 10% papers in comparison with overall averages. For multi-disciplinarity, there is little difference between top 10% papers and overall averages, however multi-disciplinarity is higher for research fronts and intellectual bases. Differences are quite large for national collaborations, particularly Danish industry-only papers, and international public research collaborations, and smaller for international public-private collaborations. In terms of total papers for each type of collaboration, multi-disciplinarity ranges from references to between 2.4 and 3.3 other disciplines, while the range for research fronts is 2.6 to 4.1.

Figure 3.10. Average degree of multi-disciplinarity for highly cited publications, by type of collaboration.



Differences between highly cited papers and overall averages are much less pronounced concerning inter-displinarity, as shown in figure 3.11.

Figure 3.11. Average degree of inter-disciplinarity for highly cited publications, by type of collaboration



4 RESEARCH COLLABORATION AND FIRM PRODUCTIVITY

4.1 Summary

Public-private collaboration may have benefits by producing new research results that can lead to innovation and growth, and also through learning and knowledge-building that may also prove valuable for other innovation projects. In addition to benefits from collaboration, scientific publication may have a value for firms in itself, for example through: reputational gains for the firm's research in relation to other firms and academics; as an employee incentive to attract talented researchers; to strengthen internal development capabilities through codification and publishing processes; and for strategic reasons to establish rights for new knowledge.

The goal of this section is to examine the relation between scientific publication, research collaboration and firm productivity. In particular, the section will:

- examine the relation between firm productivity and scientific publication (both with and without collaboration), public-private collaboration overall, and international public-private collaboration
- compare productivity for different types of scientific publications (public-private collaboration, industry-only publication and firms that publish both types of publications)
- examine the relation between firm productivity and citation impact
- examine how the relation between scientific publication, research collaboration and firm productivity varies across industries.

Our formal approach is propensity score matching (PSM). The idea behind the approach is to compare the productivity of firms that have engaged in scientific publication or collaboration with firms without publication or collaboration, but that are similar in all other aspects. The approach thus seeks to isolate the relation of productivity and publication or collaboration by matching firms so that publication or collaboration is the only observed difference between them.

The analysis uses both publication data and register data from Statistics Denmark for firms with 10 employees or more over the period 1999-2013. In all, 767 firms (with 10 or more employees) have published a scientific paper during the period[18].

In the matching analysis, we conduct five comparisons (all concerning publication activities in the last three years, from year *t* to *t-2*):

- Scientific publication compared to no publication
- Public-private collaboration compared to no publication
- Public-private collaboration compared to other (industry-only) publications[19]
- Both public-private collaboration and industry-only publication compared to other publishing firms
- International public-private collaboration compared to other publishing firms

The main outcome variable that we consider is productivity, measured as value-added per employee. Average value-added per employee is significantly higher for firms that actively (conduct and) publish their research in scientific journals (both single and collaborative research), at 573,000 DKK compared to 503,000 DKK for a control group of similar firms that have not published in the last three years. Results are almost exactly the same when

[18] Note that this number is substantially lower than the total number of 1674 firms found to have published during 1995.-2013. There are a number of reasons for this difference: Exclusion of firms with less than 10 employees; publication activity only in the years 1995-1998; exclusion of firms not in a market business sector; and data inavailability typically due to incomplete firm names in the publication data.
[19] Note that industry-only publications can both be with and without collaboration.

comparing firms with public-private publications with those without publications, and in both cases, these results are highly significant (p-value=0.000).

When comparing productivity among firms with different types of publication profiles (e.g. Public-private collaboration compared to industry-only publications; both public-private collaboration and industry-only publication compared to other publishing firms; and international public-private collaboration compared to other publishing firms), we find no significant differences in value-added per employee for the matched samples.

Regression analysis based on the matching sample shows that effects of all three types of publications (only public-private, only industry and both types of publications) are positive and significant compared to non-publishing, but that there are no significant differences in effects for the different types of publication profiles. Hence, the results of the regressions support that of the matching analysis. Coefficient estimates for publication activity range from 0.117 to 0.129, implying that engaging in scientific publication is associated with 12-13% higher productivity compared to firms without publication activity.

We have also calculated average productivity over the entire period for firms with these three types of publication profiles. In a simple comparison (unmatched) of these averages, we find that average value-added per employee for firms with both types of publications is over 170,000 DKK higher than for firms with industry-only publications. However, this difference is not significant at a 10% level (p-value=0.117).

Note also that there are large differences in publication activity for firms with only one type of publication (industry-only or public-private collaboration) compared to firms with both types. Firms with both types of publications are typically firms with ongoing publication activity, where the average number of publications in a three year period ranges from 8 to 144 publications. Activity is much less for firms with industry-only *or* public-private collaboration only publications, where most firms have only published 1-2 publications during a three year period.

The relation between scientific publication, research collaboration and firm productivity varies greatly across industries. Effects for industry-only publications are highest within food and beverages and machinery while effects for both types of publications are highest within rubbers and plastics, electronics, and petroleum and chemicals. However, the analysis is unable to identify the specific causes behind this diversity.

4.2 Introduction

The citation analysis above examines how public research values scientific publication and collaboration by measuring the citation impact of different forms of research collaborations. However, we also noted in our discussion of motivations for research collaboration that many benefits may not be that direct. General knowledge exchange and learning may imply that the relative importance of indirect benefits on future research is substantial.

Similar mechanisms may also be at work for private firms. Public-private collaboration may have direct benefits by producing new research results that can lead to innovation and growth, but the learning and knowledge-building may also prove valuable for other innovation projects that are not connected to the collaboration. In addition to benefits from collaboration, scientific publication may have a value for firms in itself. Firms may choose to publish for a number of reasons: reputational gains for the firm's research in relation to other firms and academics; as an employee incentive to attract talented researchers; to strengthen internal development capabilities through codification and publishing processes; and for strategic reasons to establish rights for new knowledge.

The goal of this section is to examine the relation between public-private research collaboration and firm productivity. More specifically, this section will examine the following questions.

Is productivity higher for firms that engage in scientific publication? To analyze this, we compare firms that have published in the last three years with similar firms that have not published in the same three year period. Firms are matched according to industry, knowledge intensity, size and international orientation.

Is productivity higher for firms that engage in public-private collaboration? As above, public-private collaboration is measured through co-authorship of publications. Firms with public-private collaboration are compared firstly with similar firms that have not published at all and secondly with firms that have published, but have not engaged in public-private collaboration?

Is productivity higher for firms that both publish industry-only papers *and* engage in public-private collaboration? Many firms have both engaged in public-private collaboration and published industry-only papers. This combination may indicate both that firms are drawing on public research through close collaboration and the capability of firms to conduct research and publish results on their own.

Is productivity higher for firms with international public-private collaboration? In section 3, we found that citation impact is substantially higher for international collaborations. Given that the scientific valuation of these papers is higher, a relevant question is whether this is also associated with higher productivity for firms involved in international collaboration.

Is citation impact positively associated with higher firm productivity? This point also seeks to examine whether there is a correspondence between scientific impact and firm productivity. We will examine whether average citation impact (MNCS) and top cited papers (research fronts) are positively related to firm productivity. In addition, we examine the relation between cross-disciplinary and productivity.

Does the relation between scientific publication, collaboration and firm productivity vary across industries? There are large differences in publication activity across industries and arguably also differences in how closely related firms' R&D activities are with public research. We will analyze potential differences both in terms of scientific publication overall and for different types of publications (industry-only, public-private collaboration only and both types of publications).

Ideally, we would like to establish causality and analyze the direct impact of collaboration on firm productivity. However, this is complicated by a number of factors:

- Time lags of research projects can vary greatly, and collaborative research papers can be at different stages of the research process, from early explorative research to the testing and application of research results.
- Research, publications and collaboration are typically not one-off events. Most firms will have conducted research projects beforehand and have other ongoing projects. This makes it difficult to conduct a before-after analysis that identifies when an event has occurred and then what the impact has been afterwards.
- As we noted above, potential impacts of research collaboration may be both direct and indirect. This makes is difficult to measure the impacts.
- Causality is very difficult to establish, both for the reasons above and for others. One additional issue is the difficulty in discerning whether an additional factor is behind both research results and performance. For example, knowledge intensive employees may have driven the research results and they may also have had a large impact on firm productivity in other ways.

Taking these issues into account, our efforts to analyze the impacts of public-private research collaboration on firm productivity should more appropriately be seen as an analysis of the relation between collaboration and productivity. Firm productivity is measured in this report as value-added per employee.

Our main approach is to compare the productivity of firms that have engaged in public-private collaboration with firms that do not have collaboration, but are similar to firms with collaboration in all other aspects. The approach thus seeks to isolate the impacts of public-private collaboration by matching firms so that collaboration is the only difference between them. The approach is described in greater detail below and in the appendix. In addition, we will use multivariate regression analysis to further examine the relation between scientific publication, collaboration and productivity.

4.3 Data

This analysis uses both publication data and register data from Statistics Denmark. We have compiled a series of bibliometric indicators at the firm level, based both on journal articles and conference papers, and merged these with register data. This data integration was only undertaken for firms with at least 10 employees, and it was not possible to match all firms with publication activity. In all, 767 firms were successfully matched with business register data. Table 4.1 shows descriptive statistics for the sample across industries. Out of 767 firms, 651 have had at least one publication involving collaboration with public research. Hence, while a large share of these 767 firms have both public-private and industry–only publications, only 15% have solely industry-only publications.

Around 45% of the publishing firms have had at least one paper that was among the top 10% most highly cited in its field and 18% have published a paper that was classified as a research front. Hence, a substantial share of these firms has produced top papers in terms of their citation impact.

In all, these 767 firms published 15,886 papers in the period. The number of firms within pharmaceuticals is 65, accounting for around 8% of firms with publications, though these firms account for 5,740, or 36% of total publications. Other industries with a large number of publications are electronics, engineering and technical services, and R&D services. Measured in terms of number of firms, the largest numbers are within engineering and technical services and R&D services, followed by IT services and electronics. These four industries account for over half of all firms with a research publication.

Table 4.1. Descriptive statistics for full sample – number firms, year observations and publications by industry. 1999-2013.

	Any publication	Public-private publication	Industry-only publications	Top10% publications	Research fronts	Any publication	Public-private publication	Total # publications
	# firm	# firm	# firm	# firm	# firm	# obs	# obs	
Agriculture	11	9	4	4	1	31	26	155
Food & beverages	34	31	13	8	5	107	92	256
Textiles, paper and wood	6	2	4	1	1	7	5	9
Petroleum and chemicals	33	28	16	17	6	150	136	619
Pharmaceuticals	65	61	22	32	12	248	225	5,740
Rubber and plastics	27	20	12	7	3	82	64	192
Metals	16	15	5	6	2	38	33	89
Electronics	77	64	48	39	20	306	219	1,646
Machinery	55	41	28	25	9	174	120	714
Utilities and construction	44	38	19	19	4	96	78	476
Wholesale trade	13	11	6	6	0	34	24	52
IT services	131	104	76	46	20	371	261	824
Financial services	20	14	11	11	3	53	45	560
Engineering and other technical services	122	106	65	58	19	409	318	2,464
R&D services	112	106	56	65	31	506	460	2,085
Total	767	651	385	344	136	2,616	2,110	15,886

Note: where possible, firms within wholesale trade were re-allocated to their related industries (this was done for wholesale trade in pharmaceuticals, petroleum and chemicals, electronics, and machinery).

Firms may participate more than once in the analysis, if they have published in multiple years. This means analyses below are based on yearly observations, with indicators often based on publication activity within a three year period. There are a total of 2616 yearly observations with a publication. Hence, on average, the 767 firms have had a publication in 3.4 years during 1999-2013. Table 4.2 below shows the number of firm level observations for each year, both in terms of publication in the current year and for the current and two previous years. Of these 2616 firm year observations, 81% included a public-private publication, 46% collaboration with an international research organization, while 44% included an industry-only publication.

Table 4.2. Descriptive statistics for full sample by year – number firms and publications

	Any publication	Public-private publication	Intl. Public-private publication	Industry publication	Any publication in 3 years	Number publications
1999	93	67	38	51	167	694
2000	127	100	53	52	192	830
2001	129	101	53	51	199	796
2002	146	118	62	67	221	839
2003	155	122	66	82	243	918
2004	167	139	76	66	265	945
2005	185	141	84	91	286	1,029
2006	190	143	80	102	302	1,044
2007	195	160	94	93	313	1,170
2008	185	153	96	76	308	1,063
2009	184	152	88	83	312	1,141
2010	209	173	103	83	314	1,276
2011	200	162	94	87	315	1,358
2012	220	176	102	86	336	1,368
2013	231	203	124	93	350	1,415
Total	2,616	2,110	1,213	1,163	4,123	15,886

4.4 Method

Our formal approach to analyze the relation between scientific publication, collaboration and firm productivity is propensity score matching (PSM). The idea behind the approach is to isolate the relation between treatment and outcome by ensuring that compared groups have similar, observable characteristics. For example, if two firms are similar in all other respects except that one firm has engaged in public-private collaboration and the other firm has not, then differences in firm productivity can be attributed to public-private collaboration. The specific propensity score matching approach we employ in this analysis, "Nearest-Neighbor Matching", is described in the appendix. Specifications were set so as to allow as large a resulting matched sample as possible while at the same time achieving balance between the matched treatment and control groups (i.e. that there are no significant differences in mean values for key matching variables).

As a key priority was to ensure comparability in terms of firms' knowledge intensity, we have adopted a fairly simple framework that includes only a limited number of other variables. This section first describes the variables that we seek to analyze ("treatment variables"), the variables used in the matching procedure (i.e. the variables that capture observable characteristics) and the outcome measures used to measure productivity.

In the analysis, we conduct the matching procedure and compare performance for the following treatment variables. In the first two cases the control group is drawn from the full population while in the last three cases the control group is drawn from the population of observations with a publication in the last three years (i.e. where, in addition to the other matching variables, an exact match is required in terms of having a publication). Treatment groups and the populations from which control groups and selected are show in table 4.3 below.

Table 4.3. Treatment and control groups used in the matching analyses

Treatment group	Control group population
Publication during time t-2 to t	No publication during time t-2 to t
Publication involving public-private collaboration during time t-2 to t	No publication during time t-2 to t
Publication involving public-private collaboration during time t-2 to t	Publication (solo or co-authored) but no public-private collaboration during time t-2 to t
Both publication involving public-private collaboration and industry-only publication during time t-2 to t	Publication (solo or co-authored), but not both publication involving public-private collaboration and industry-only publication during time t-2 to t
Publication involving international public-private collaboration during time t-2 to t	Publication (solo or co-authored), but no publication involving international public-private collaboration during time t-2 to t

The matched control group is taken from a large pool of firms with ten or more employees. Annual firm observations are matched according to knowledge intensity, year, firm size and capital intensity, industry and exports. The following variables are used in the matching procedure:

- Share employees with PhD[20]
- Share employees with Master's degree or higher
- Year for productivity measure
- Physical capital intensity class, an ordinal measure of capital intensity, with a value of 1 for low capital intensity (under 1 mn DKK per employee) and high capital intensity (1 mn DKK or more per employee).
- Firm size (measured using four size classes, 10 to 49 employees, 50 to 249, 250-499 and 500 or more employees)
- Industry (15 industry groupings constructed based on NACE 2-digit industry classifications)
- Exports (dummy=1 if firm has had exports in time t-2 or t-1)

See the appendix for a more detailed description of the variables and the control group.

The main outcome variable that we consider is productivity, measured as value-added per employee at time t. This variable is not a before-after measure and does not attempt to establish causality. With this measure, we are in principle mainly examining whether productivity for firms that publish or engage in research collaboration with public institutions is greater than productivity for similar firms that do not publish. In addition, we also examine two year changes both in value-added per employee.

4.5 Probit model and testing for balance in the matched sample

As described above, we are conducting five matching comparisons using essentially the same procedure[21]. To illustrate the approach, we describe briefly the procedure for the comparison of public-private publications with no publications. Thereafter, we present the results of all five comparisons.

First, a probit regression is used to estimate the propensity score. The dependent variable in this case is a dummy variable for whether the firm has co-authored a publication with a public research institution within the last three years (t-2 to t). The regression sample includes yearly observations both for firms with a public-private publication

[20] Note that education data is typically only available for educations undertaken in Denmark, which means that we are often unable to identify foreign PhDs.
[21] Very slight modifications were made for two of the five procedures in order to obtain a match that was more balanced according to the matching variables, particularly shares of highly educated employees.

in the last three years and firms without a publication in the last three years. The sample includes in all 52,059 observations, 2,523 with a public-private publication and 49,136 without a publication. Of the 2,523 observations with a public-private publication, 1,248 were outside the common support (the estimated propensity to have a public-private publication was too high, or too close to 100%, which precludes the possibility of finding a valid match) and were removed from the analysis.

The remaining 1,275 observations were matched with observations without a publication. Each observation in the treatment group was matched with the observation in the control group which had the closest propensity score[22]. In addition, it was required that observations were only matched with other observations from the same industry (i.e. an exact match was required for industry group). A key criterion for the quality of the resulting matched sample is that firms with and without a public-private publication are comparable in terms of the variables used in the procedure. The table below shows means for the matched sample.

Table 4.4. Comparison of means for matched sample

	Mean	Mean	t-test	
	Public-private publication in last 3 years (Treatment group)	No publication (Control group)	t-stat	p>|t|
Propensity score	0.106	0.104	0.66	0.508
Matching variables				
Capital intensity class	1.135	1.173	-3.02	0.003
Size class	3.980	3.939	1.06	0.288
Year	2006.4	2006.2	1.66	0.096
Share employees with Master's degree or higher	0.227	0.221	0.88	0.380
Share of employees with PhD	0.026	0.025	0.32	0.749
Other variables				
Number employees	509.8	229.73	8.59	0.000
Capital intensity	2636.3	1796.5	1.51	0.131

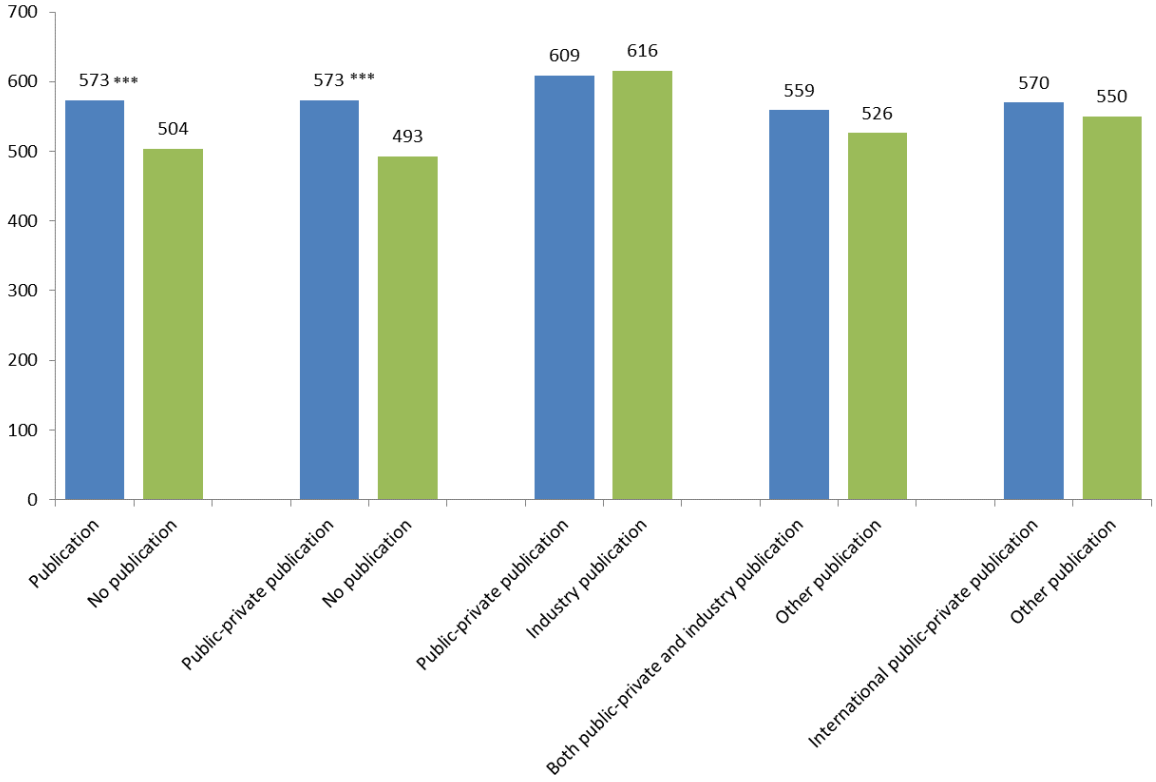
As can be seen, there is no significant difference for years and shares of highly educated employees. Size classes are also in balance, though we can see that the actual variable is not fully in balance as the result of using these more simplified classes. In contrast, the capital intensity class is not in balance, but the actual variable for capital intensity is in balance. However, capital intensity was not found to be an important determinant of research collaboration and while we argue that it is important that matched firms are in the same size class, it is less important for the matching analysis that matched firms have precisely the same size[23].

4.6 Results

Having selected the matched samples, in each of the five cases the groups are compared both in terms of value-added per employee at time t and later in the section the two year change in value-added per employee. Results for value-added per employee are illustrated in figure 4.1 while the full results are shown in table A.5 in the appendix. Starting from the left of figure 4.1, we can see that average value-added per employee is significantly higher for firms that actively (conduct and) publish their research in scientific journals, at 573,000 DKK compared to 504,000 DKK for firms that have not published in the last three years. Results are almost exactly the same when comparing firms with public-private publications with firms without a publication, and in both cases, these results are highly significant (p-value=0.000).

[22] After testing, it was found that the best match for knowledge intensity was achieved by requiring an exact match for narrow intervals for shares of employees with a masters degree and shares with a phd degree. See the appendix for further details.
[23] As noted in the appendix, there is little or no correlation between value-added per employee and number employees for this sample.

Figure 4.1. Value-added per employee for matched samples (in 1000 DKK)



When considering the role of research collaboration, it is unclear which comparison is most useful. Do we want to compare with firms without any research publications at all or with firms with industry-only publications? To some extent, engaging in research publication indicates research activities that must include interaction with public research of some form. However, it is at the same time also clear that actual co-authorship more explicitly indicates formal collaboration. Both comparisons likely add to the picture. One challenge however is that many firms produce both industry-only and public-private publications, meaning that only a minority of publishing firms only produce industry-only publications (or only have done so in the last three years). This leaves a fairly small sample of firms from which matches are to be made, and it also appears that firms with industry-only and public-private publications tend to differ in their characteristics.

The results show that average value-added per employee for firms with only industry publications is the same as for public-private publications. The results thus show on the one hand that firms that actively publish their research results, either in collaboration with public research, alone or with other industry co-authors, have markedly higher productivity than comparable firms that do not publish. On the other hand, among firms that publish, productivity is not higher for firms that collaborate with public research. Scientific publication of any form indicates strong focus on research that goes much deeper than later stage development work. There is also little question that such work must draw to a certain extent on public research indirectly[24], and likely also directly. At the same time, the research in question would not appear to have had the deep involvement of public researchers; i.e. there was no formal public-private collaboration.

With public-private collaboration, we do not know the extent of involvement of the firm itself. It can potentially span from cases where firm researchers fully lead the work to cases that essentially represent contract research with little active involvement from the firm. If the firms' own involvement influences how much the firm is able to utilize the research in their later innovation activities, then benefits of public-private collaboration may be quite variable. In contrast, for industry-only papers, we would expect that firm researchers are intricately involved in the research work

[24] As noted in section 2, scientific publication typically requires an in-depth of research publication within the field.

that is conducted. In general, what we find here is that both public-private collaboration and industry-only publications are associated with higher productivity, although we are unable to find a difference in productivity between the two based on the matching analysis. However, the nature of research behind public-private collaborations and industry only work may be quite different in many cases, and may also vary from industry to industry. It should also be noted once again that 80% of the firms in the sample with publications have public-private collaborations.

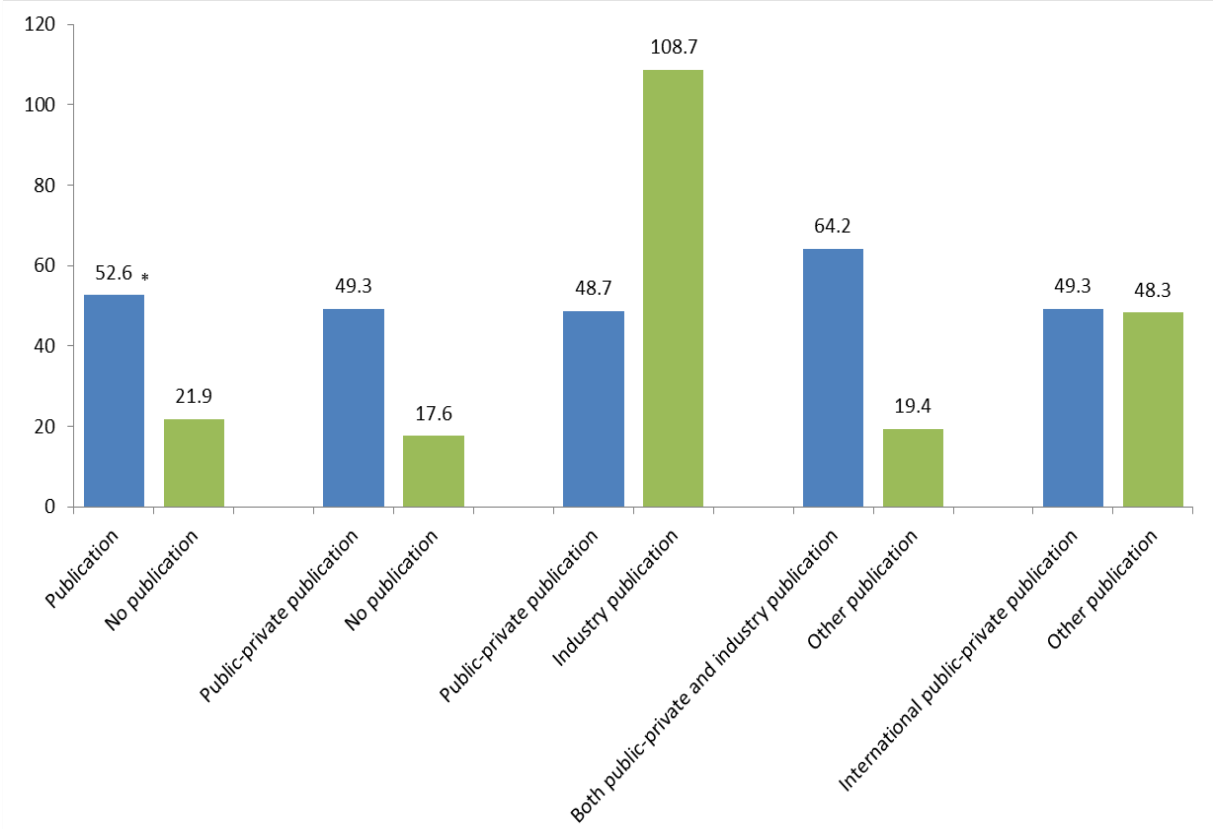
The above might suggest that firms that both collaborate with public research institutions and have the capacity to produce industry-only publications may be better suited to utilize research results in their innovation activities and thus experience greater benefits economically. Based on this, we have also examined productivity for firm observations with both types of publications in comparison with a matched sample of firm observations with only one type of publication. However, we do not find a significant difference in productivity between firms with both types compared to other firms with publications.

The final comparison is for firm observations with international public-private collaboration, where, as can be seen from figure 4.1, productivity is not significantly higher than for other firms with purely national publication activity. Hence, we do not find that international research collaboration yields the same large positive impact for firms as was found in chapter 3 for researchers.

Hence, the first two comparisons find highly significant results that are also robust to changes in specifications for the matching approach. Results for the final three comparisons are not significant.

As we mentioned above, it is extremely difficult to determine causality or isolate the impacts of a specific research project on firm productivity. Time horizons of research projects can vary greatly, in many cases, firms have also published previously, and the potential benefits of a specific research project may be less related to its specific application as opposed to general knowledge building. While we are unable to take these aspects fully into account, we still attempt to approach the question of impacts by looking at the changes in productivity over time. Figure 4.2 shows the results of the matching analyses for two year changes in value-added per employee from time t-2 to t (results are also shown in table A.5 in the appendix).

Figure 4.2. Two-year change in value-added per employee for matched samples (in 1000 DKK)



The results for the change in value-added per employee follow to some extent those for value-added in levels; the two-year change is substantially larger (and weakly statistically significant) for firms with publications compared to firms without. Higher levels of value-added appear to be associated with larger changes over time for industry-only publications compared to public-private collaboration and firms with both types of publications compared to others, but this result is not statistically significant. In contrast, while levels for international public-private collaborations are higher than for other publications, two year changes in value-added are almost equal.

4.7 Comparing firm-level average productivity over the entire period

In order to examine the relation between productivity and public-private collaboration further, we have divided firms into three groups for analysis of firm level averages over time (as opposed to individual yearly observations):

1. Only industry only papers over the entire period
2. Only public-private collaboration over entire period
3. Both types of publications during the period.

Thereafter, we have calculated average value added and other statistics over the period from one year before first publication and onwards. As can be seen from table 4.7. below, average value-added per employee for firms with both types of publications is around 100,000 DKK higher than for public-private collaborations only and around 170,000 DKK higher than for industry-only publications. However, none of these differences in value-added per employee are statistically significant at a 10% level. P-values for comparison of firms with both types of publications with industry-only or only public-private collaboration are though close to the 10% level. Note also that average knowledge intensity for firms with both types of publications are 4-5 percentage points higher than averages for firms with public-private collaborations only or with industry-only publications. While these differences are not significant, it is still interesting that differences are so much larger here than with the matched samples. These larger differences can potentially be due to differences in knowledge intensity or reflect industry differences.

Table 4.7. Firm-level averages for value-added, education and size, by type of publications

	Industry only	Public-private collaboration only	Both types
Value-added per employee (1000 DKK)	563.9	632.2	738.4
Avg. share employees with master's degree or higher (%)	25.3%	27.5%	33.3%
Avg. share employees with PhD degree (%)	3.4%	4.4%	8.2%
Avg. number employees	309.5	305.2	462.2
Number firms	77	258	296

T-test of Industry-only vs. Public-private collaboration only: p-value=0.245
T-test of Both types vs. Public-private collaboration only: p-value=0.127
T-test of Industry-only vs. Both types: p-value=0.117

4.8 Regression analysis

Regression analysis based on the matched sample has two important benefits in combination with the matching analysis above. First, it provides an added control to the matching procedure. Especially when a number of variables are used, there may be questions concerning how well the approach is able to match across all variables. By including these variables in a regression analysis, we are able to control for them in a more precise way. Second, using a matched sample helps control for selection bias due to difference in the propensity to publish or engage in public-private collaboration.

Following standard approaches for productivity analysis, we model a standard production function where the dependent variable, value-added per employee, and physical capital per employee and labor are in logs. We also include the share of employees with a PhD as a measure of knowledge intensity and a dummy for exports to account for international orientation. Industry and time dummies are also included in the regressions.

In addition, this allows us to examine the effects of additional variables. In particular, we are interested in the role of citation impact and whether higher citation impact is related to greater productivity. We consider both MNCS for firms' publications over a three year period, and whether the firm has a paper at the front of its research field. Finally, we also examine the role of inter-disciplinarity. The results of the regression are shown in table 4.8.

Table 4.8. Regression results – publications, collaboration and productivity. Based on matched sample for firms with any publication

VARIABLES	(1) Log value-added per emp.	(4) Log value-added per emp.	(5) Log value-added per emp.	(6) Log value-added per emp.	(7) Log value-added per emp.	(8) Log value-added per emp.
Log capital per emp.	0.035*** (0.000)	0.0349*** (0.000)	0.0349*** (0.000)	0.0350*** (0.000)	0.0347*** (0.000)	0.0349*** (0.000)
Log emp.	0.0291*** (0.000)	0.0291*** (0.000)	0.0295*** (0.001)	0.0287*** (0.001)	0.0291*** (0.001)	0.0291*** (0.001)
Share knowledge-intensive emp.	-0.479** (0.012)	-0.486** (0.012)	-0.488** (0.011)	-0.491*** (0.010)	-0.469** (0.010)	-0.486** (0.014)
Exports (dummy)	0.086*** (0.001)	0.084*** (0.000)	0.083*** (0.000)	0.084*** (0.000)	0.085*** (0.000)	0.084*** (0.000)
Any publication	0.124*** (0.000)					
Industry-only publication		0.127*** (0.000)	0.125*** (0.000)	0.126*** (0.000)	0.129*** (0.000)	0.126*** (0.000)
Public-private only		0.117*** (0.000)	0.129*** (0.000)	0.114*** (0.000)	0.126*** (0.000)	0.116*** (0.000)
Both types publication		0.129*** (0.000)	0.150*** (0.004)	0.122*** (0.000)	0.133*** (0.000)	0.127*** (0.000)
International public-private			-0.0310 (0.345)			
Research front				0.0464 (0.368)		
MNCS					-0.009* (0.093)	
Inter-disciplinarity						0.007 (0.889)
Constant	5.763*** (0.000)	5.769*** (0.000)	5.771*** (0.000)	5.771*** (0.000)	5.768*** (0.000)	5.769*** (0.000)
Observations	3,214	3,214	3,214	3,214	3,214	3,214
R-squared	0.164	0.165	0.166	0.166	0.166	0.165

All models estimated with OLS. Time and industry dummies included in all regressions. P-value in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Each of the five matching analyses in the previous analysis generates a specific matched sample. For the regression analysis, we use the largest and most general of these; the sample matching firms with any publication in the last three years and those without a publication. This allows us to compare the role of different types of publications.

First, the share of knowledge intensive labor is negative and significant in all regressions. This indicates that, among knowledge intensive firms, value-added per employee is declining in knowledge intensity. This result is somewhat surprising given that the results above suggest that productivity is increasing with knowledge intensity. However, in separate regressions using the full sample of observations (i.e. including firms with no knowledge-intensive staff), the coefficient for knowledge intensity is positive and significant (results not shown). Second, the variable for any publication is positive and significant, as would be expected from the above results.

In all remaining regressions, three dummies are included for publication activity: industry-only publication, public-private collaboration only, and both types of publications. Coefficient estimates for all three variables are positive

and highly significant, and of similar size, ranging from 0.117 to 0.129. These results thus imply that scientific publication on average is associated with12-13% higher productivity compared to firms without publications.

In section 3 we saw that citation impact was much higher for international collaborations, in particular those involving public-private collaboration. The coefficient for international public-private collaborations in the regression is however insignificant, and thus does not provide any indication that firms with international public-private collaboration have higher productivity. However, it should also be noted that many firms with international public-private collaboration may be involved in both types of publications and also in export activities, which could mean that potential effects of international collaboration are captured by these other variables.

Research fronts are not significant while MNCS is negative and weakly significant. One possible factor behind this could be that these two indicators of citation impact can only be calculated for Web of Science (WoS) journal articles and thus are equal to zero if a firm only has conference papers in a given period. However, we have also run the regressions only with firms with WoS papers and the results are essentially the same (results not shown). An additional explanation can be that firms value research differently than academia, as the result for MNCS implies that productivity is declining in the average citation impact of the firm's publications. Finally, the coefficient for interdisciplinarity is also insignificant.

4.9 Sectoral differences in the relation between collaboration and productivity

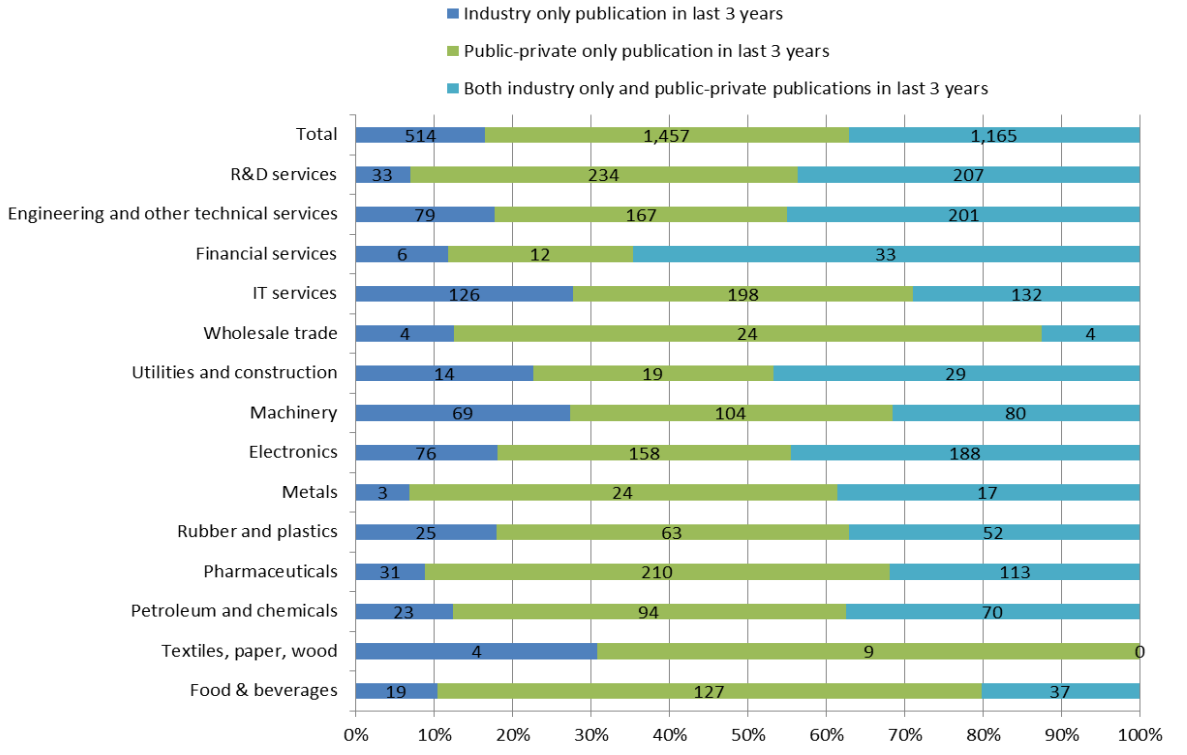
There can potentially be large differences across industries, both in the scope and characteristics of research and in the impact of research on firm operations. In some industries, research, the publication of research results and collaboration with universities can almost be considered a necessity, where a direct linkage can be drawn between the published research and product development. For other industries, the connection between research and performance is perhaps less clear or direct. Knowledge and capacity building, in particular through interaction with public research, may be the most important outcome of the research, as opposed to the specific results themselves.

Based on analysis of surveys of academic and industry researchers, Bekkers and Bodas-Freitas (2008) examine to what degree the industrial context of firms ('sectoral effects') influences the importance of different knowledge transfer channels. In comparison of four industries, Chemicals, Pharmaceuticals, Electrical and Machinery, they for example find that scientific output and informal contacts are more important for Pharmaceuticals and Electrical, while there is no difference across industries in the role of collaborative and contract research (Bekkers and Bodas-Freitas, 2008).

The goal of this sub-section is to examine how the impact of research publication and collaboration varies across industries. Among firms with publication activity, there are also large differences in collaboration patterns across industries, as indicated by figure 4.3.

First, there are in particular three industries where the relative concentration of firms with industry only publications is highest. Among firms with publications, around 30% only have industry publications in IT services, Machinery and Textiles, paper and wood. IT services and Machinery account for a fairly large share of total firm observations with only industry publications, while the number of firm publications within Textiles, paper and wood is very small, with only 13 observed publications over the period. These numbers suggest that there is something specific about these sectors that makes industry only publications more attractive. In both of these industries, research may be fairly applied or at least closely related to commercial application. However, this could also be expected of some of the other industries. There may also be a question of time horizons for research, where in particular IT service firms operate under very tight timelines. Correspondingly, among industries with a high level of publication activity, the highest shares with both types of publications are found in Electronics, Engineering and technical services and R&D services. Hence, these industries also have a high share with industry publications, but the majority of these also engage in public-private collaborations.

Figure 4.3. Sectoral distributions of publication activities for selected industries (% of total firm observations with a publication. Number firm observations also shown for each type of publication)



A standard linear regression estimates the average effect on productivity across industries. However, we are also interested in measuring how these effects vary across industries. Multilevel mixed-effects linear regression allows the coefficients of both intercepts and selected variables to vary across groups, and can be used to estimate both average effects industry-specific effects. If these industry-specific effects are significantly different from zero and the model is found to have a significantly better fit than the linear model, then this provides us with an indication that the relation between publication and public-private collaboration and firm productivity varies across industries.

In order to better model relations across individual industries, a larger sample is used here. In addition to all firm observations with a publication in the last three years, the sample includes all firms in the selected industries with 10 or more employees that have either a PhD employed or conduct in-house R&D. We have also excluded all industry groupings that have less than 50 firm observations with a publication. Given that publications are distributed into three groups, a low number of observations with a publication would mean that results can be greatly influenced by individual values. The sample is thus limited to nine industry groupings, which are shown in table 4.9. The resulting sample consists of 37,469 firm-observations, of which 2,840 have published in the last three years. Table 4.9 shows some descriptive statistics for this sample.

In all industries except R&D services and Petroleum and Chemicals, average value-added per employee is higher for firms with a publication. Average value-added for R&D services is in general very low compared to other industries, which likely reflects that many of these firms are still in a development stage with technologies and products that have not yet fully matured. In terms of size, firms with both types of publications are on average much larger than firms with industry-only or public-private collaboration only publications. However, this does not generally mean that only small and medium sized firms have industry-only or public-private collaboration only publications. Average size among firms with industry-only publications is over 300 employees in 4 out of 9 industries and 294 in Engineering. However, differences are extreme for Pharmaceuticals, where average size for firms with industry-only or public-private collaboration only publications is only around 100 employees, compared to around 1900 for firms with both types of publications. Size for industry-only publications is also small in Rubber and plastics (127 employees).

Table 4.9 Mean values of value-added, firm size and knowledge intensity across industry groups and types of publication

	Value-added per employee					Number employees				
	Total	Any publication	Industry-only	PPC-only	Both types	Total	Any publication	Industry-only	PPC-only	Both types
Food & bev.	454	749	1052	668	860	169	939	396	362	2856
Petroleum and chemicals	674	673	545	640	747	181	721	823	484	1047
Pharmaceuticals	683	775	830	720	870	169	697	107	105	1886
Rubber and plastics	450	662	540	628	722	149	761	127	713	1011
Electronics	473	530	490	482	585	123	297	199	238	367
Machinery	467	531	629	523	469	147	1263	621	459	2545
IT services	502	650	604	688	659	90	485	335	349	803
Engineering	464	505	510	470	524	62	444	294	138	739
R&D services	288	220	329	216	220	62	56	33	41	75
	Firm observations					Number publications				
		Any publication	Industry-only	PPC-only	Both types	Total	Any publication	Industry-only	PPC-only	Both types
Food & bev.		162	18	111	37	0.3	4.2	1.3	1.8	12.3
Petroleum and chemicals		184	22	94	70	1.3	9.8	1.2	3.6	20.3
Pharmaceuticals		340	31	207	113	10.2	49.9	1.3	2.5	143.7
Rubber and plastics		110	24	41	52	0.3	4.8	1.0	2.2	8.1
Electronics		387	70	138	188	1.6	11.0	2.2	2.1	19.8
Machinery		222	60	86	80	0.4	8.1	1.8	1.8	19.0
IT services		441	123	195	132	0.2	3.6	1.5	1.8	8.2
Engineering		433	78	167	201	0.9	15.1	2.0	2.2	30.3
R&D services		460	33	227	207	5.2	10.3	2.1	3.9	18.3
	Share employees with PhD									
	Total	Any publication	Industry-only	PPC-only	Both types					
Food & bev.	0.1%	0.4%	0.3%	0.3%	0.4%					
Petroleum and chemicals	0.8%	3.0%	0.2%	3.5%	3.1%					
Pharmaceuticals	1.4%	2.6%	4.7%	2.6%	2.4%					
Rubber and plastics	0.2%	0.3%	0.5%	0.3%	0.2%					
Electronics	1.8%	6.6%	8.4%	6.7%	6.0%					
Machinery	0.2%	1.0%	0.8%	1.7%	0.6%					
IT services	0.9%	5.3%	4.5%	5.8%	5.4%					
Engineering	0.9%	6.1%	5.1%	4.0%	7.9%					
R&D services	11.9%	17.0%	11.3%	17.0%	17.4%					

There are clear differences in the extent of publication activity across the three types. Firms with both types of publications typically appear to have ongoing publication activity, where the average number of publications in the three year period ranges from 8 to 144 publications. Activity is much less for firms with industry-only or public-private collaboration only publications, where most firms have only published 1-2 publications during the three year period.

When comparing total values with those with a publication, it can be seen that firms in the sample without a publication are generally much less knowledge intensive than those with a publication.

Table 4.10 shows the estimates of the average effects and industry-specific effects. Results for the industry-specific effects consist of estimates of the standard deviation for each coefficient and the standard error of these standard deviation estimates. As with coefficient estimates, if estimates of the standard deviation across industries are large relative to their variance, then this indicates that there are significant differences in effects across industries.

The main regression using mixed effects is the second regression in table 4.10. For comparison, the same model is also estimated using OLS (first regression). The last two regressions use slightly different specifications in order to check the robustness of the results, in particular concerning the role of industry-only publications. In the third regression, all observations for firms that have not had a publication in the last three years, but have had at least one publication during the entire period, have been removed from the sample. This seeks to control for potential effects of earlier publications, three or more years prior to the year of observation. In the fourth regression, publication indicators are calculated over the last five years as opposed to three years. A goal with this specification is to examine if firms with industry-only publications in the last three years also only have industry publication when a longer period is taken into account.

The effect estimates for each of the three types of publications are very similar to those found when using OLS. However, while dummies for industry-only publications and public-private publications are both positive and significant in this mixed levels regression, the coefficient for public-private publications is not significant, with a p-value of 0.108. In addition, coefficients for industry-only publications and both types of publications are both slightly larger in the mixed effects regression.

The difference between the results using mixed effects compared to standard OLS reflects the large variation in effects across industries. When we allow coefficients to vary across industries this variation is apparently so large that the average effect for public-private collaboration only is no longer significantly different from zero.

Table 4.10 also shows the estimates of the industry-specific effects. These are estimates of the standard deviation of coefficients across industries. If these estimates are much larger than their standard error, then this provides an indication that there are significant differences in effects across industries. We can see from the table that this is the case for the intercept and all three types of publications.

Finally, note that the likelihood ratio (LR) test of the model against the linear regression in which these parameters are set to zero rejects the linear regression model. This thus provides evidence that the importance of publication activity, both with and without public-private collaboration, differs significantly across industries.

Table 4.10. Results of the mixed levels analysis

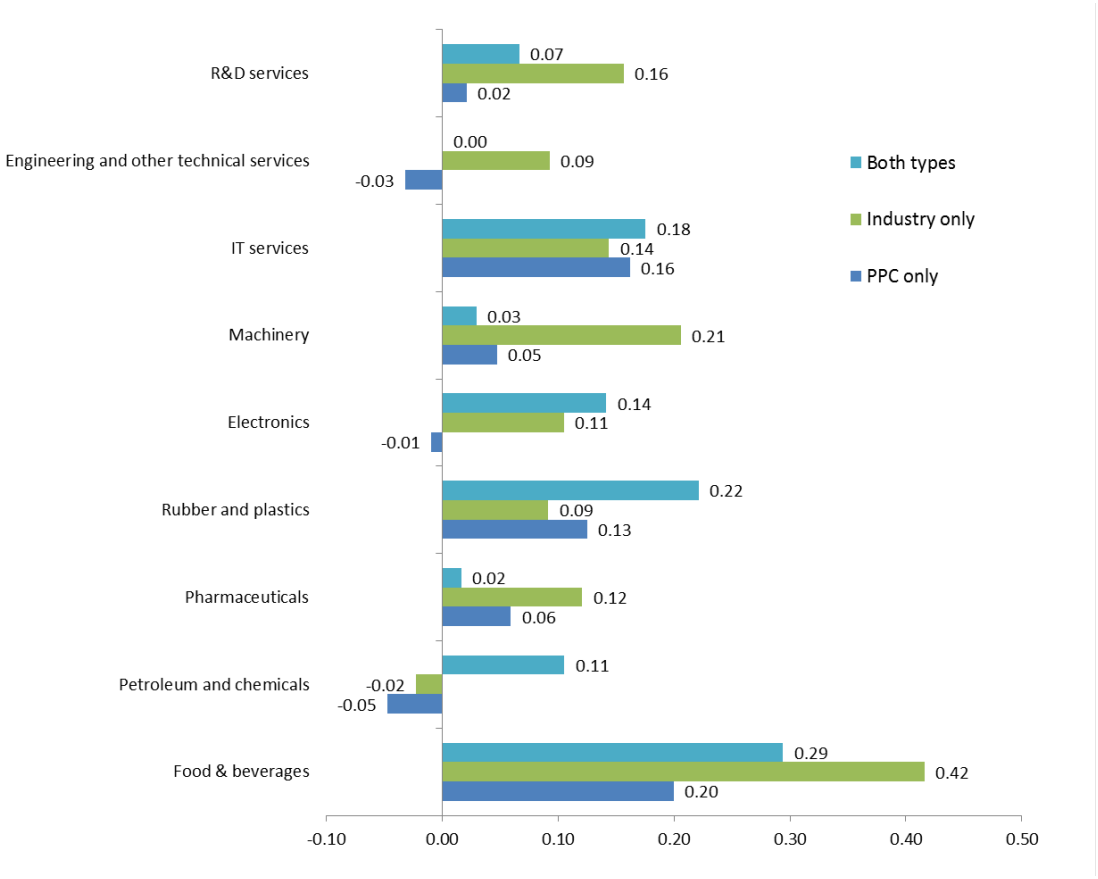
Model	OLS	Mixed effects		Mixed effects		Mixed effects	
VARIABLES	Coeff. (p-value)	Coeff. (p-value)	Estimate Std.Err. (95% CI)	Coeff. (p-value)	Estimate Std.Err. (95% CI)	Coeff. (p-value)	Estimate Std.Err. (95% CI)
Log Capital per employee	0.038*** (0.000)	0.037*** (0.000)		0.039*** (0.000)		0.037*** (0.000)	
Log employees	0.026*** (0.000)	0.026*** (0.000)		0.020*** (0.000)		0.0247*** (0.000)	
Share employees with PhD	-0.350*** (0.000)	-0.326*** (0.000)		-0.258*** (0.000)		-0.347*** (0.000)	
Exports (dummy)	0.171*** (0.000)	0.171*** (0.000)		0.169*** (0.000)		0.170*** (0.000)	
Industry-only publication (t-2 tot)	0.139*** (0.000)	0.146*** (0.008)	0.135 0.061 (0.056-0.327)	0.157*** (0.005)	0.139 0.061 (0.059-0.327)		
Public-private collaboration only (t-2 to t)	0.060*** (0.000)	0.058 (0.108)	0.094 0.029 (0.051-0.174)	0.072* (0.061)	0.101 0.031 (0.056-0.182)		
Both types of publication (t-2 to t)	0.097*** (0.000)	0.117*** (0.005)	0.108 0.037 (0.055-0.210)	0.136*** (0.001)	0.108 0.037 (0.055-0.211)		
Industry-only publication (t-4 tot)						0.158*** (0.000)	0.106 0.053 (0.040-0.281)
Public-private collaboration only (t-4 to t)						0.050 (0.162)	0.093 0.028 (0.051-0.169)
Both types of publication (t-4 to t)						0.135*** (0.003)	0.121 0.038 (0.066-0.223)
Constant	5.321*** (0.000)	5.987*** (0.000)	0.162 0.039 (0.102-0.258)	5.987*** (0.000)	0.155 0.037 (0.097-0.247)	5.993*** (0.000)	0.161 0.038 (0.101-0.257)
Observations	37,469	37,469		37,076		37,469	
R-squared	0.124						
LR test vs. linear model (chi2 / p-value)		1423(0.000)		1201(0.000)		1424(0.000)	
Number of groups		9		9		9	

Dependent variable: Log(value-added per employee). Time and industry dummies included in all regressions. P-values in parentheses. *** p<0.01, ** p<0.05, * p<0.1

To give an idea of the differences that are suggested by this model, figure 4.4 shows total effects for both types of publication for individual industries. The largest total effects are found in Food and beverages, Machinery and Rubber and plastics. Interestingly, these are also the industry groups with the lowest knowledge intensity. This could suggest that the opportunities for distinguishing firms' R&D and innovation activities from other firms are larger within these industries; i.e. that firms with publication activity 'stand out' more prominently in industries with low knowledge intensity. However, coefficient estimates are also relatively large within Electronics and IT services, both of which have higher knowledge intensity.

IT services also stands out in having similar coefficients across the three types of publications, ranging from 0.14 to 0.18. Differences are much larger in all other industry groups.

Figure 4.4. Total effects for each type of publication by industry



The industries for which total effects are highest for industry-only publications are Food and beverages, Machinery, Pharmaceuticals, Engineering, and R&D services. However, for three of these groups (Food and beverages, Pharmaceuticals and R&D services), industry-only publications account for 10% or less of all firm observations. Shares are larger within Machinery, where the role for industry-only publications would appear to be larger.

For Engineering, industry-only publications are essentially the only type of publication where estimated coefficients are positive, despite the fact that this only characterizes a small share of the firms with publications. It is not clear what lies behind this result, but one possibility could be that there are differences in these firms' characteristics that we are not able to observe based on the data available here.

Coefficient estimates are highest for both types of publications within Electronics, Rubber and plastics, Petroleum and chemicals, and IT services. Within Electronics, both average firm size and knowledge intensity are similar for the three publication types.

The results of this mixed levels analysis illustrate that there are fairly large differences across industries, both in publication activity and in the relation between publication and productivity. However, the analysis is unable to identify the specific causes behind this diversity. A number of open questions still remain concerning the factors behind firms' choice between industry-only publications and publishing in collaboration with public research, which are likely very dependent on the characteristics of individual firms.

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APPENDIX

This appendix provides a more detailed description of the matching approach used in section 4 and the results of the matching analysis.

A1.1 Nearest-Neighbor matching procedure

As noted in section 4, the specific propensity score matching approach used in the analysis is called "Nearest-Neighbor Matching". A description of the approach used in given in Table A1.

Table A1. Description of the Nearest-Neighbor Matching procedure used in the analysis.

1) Specify and estimate a probit model of the probability of receiving a grant to obtain propensity scores $\hat{P}(X)$:

$$\Pr(Y = 1|X) = G(\beta_0 + \beta_j X_j)$$

2) Restrict the sample to include only individuals within the common support area (where individuals with the same characteristics have a positive probability of being both treated (grantee) or non-treated (rejected applicant))
3) Each treatment (receipt of grant) is paired with the non-treated that has the closest propensity score. We require first, however, exact matches according to research council and age group. The difference between propensity scores for treatments and matched controls must be within 0.0001; otherwise they are excluded from the sample, thus eliminating poor matches. Moreover, matching is performed without replacement; i.e. non-treated cannot be matched with more than one treated individual.
4) Applying the matched sample, the average treatment effect on the treated is estimated. As matching with replacement biases the *t*-statistics we correct the standard errors for the appearance of repeated observations by bootstrapping.

A1.2 Control group and matching variables

The matched control group is taken from a large pool of firms with ten or more employees. We start with the full sample yearly observations for all Danish firms with ten employees or more and impose the following restrictions on the sample. First, all firm observations in NACE 2-digit industries with no publishing firms are removed. Second, we remove firm observations with low knowledge intensity. Some firms with publications do not have employees with a PhD. For these, we would like to ensure that they are matched with firms that conduct R&D.

Hence, the control group is restricted to firm observations that either have a positive share of employees with a PhD or have conducted R&D over the period, based on data from the R&D survey. Finally, for both firms with and without publications, we remove extreme values for value-added per employee. All observations with negative value-added are removed, as are observations with value-added per employee in excess of 10 mn DKK.

Following Caliendo & Kopeinig (2008) we include variables that are reasonable and available. Further, the specification is evaluated on basis of the matching quality. In order to ensure comparability between groups, the matched sample should be balanced according to all specified matching variables.

R&D expenditures or R&D intensity would have been a highly relevant variable to use in this matching exercise. However, due to data limitations we have chosen not to include it. R&D data is from the R&D and Innovation survey, which is based on a random sample. Hence, this means that many R&D active firms may have only been included in the survey sample for one or two years, or not at all in some cases. Only the largest firms (250 employees or larger in the early part of the period, later changed to 100 employees or larger) are included in the survey on a regular basis. In order to avoid severe loss of observations, we rely instead on education data to construct measures of firms' knowledge intensity.

We use linked employer-employee data to construct two measures of firms' knowledge intensity based on employees' education level: the share of employees with a master's degree or higher, and the share of employees with a PhD. Note, however, that this data is only available for employees that have received their education in a Danish institution. Hence, foreign-educated PhDs are not included in this data. We unfortunately do not have a method available to measure the number of foreign PhDs, though despite this shortcoming, the data provides a valuable

measure of firms' knowledge intensity. The share of PhDs is included in the propensity score model while an exact match among 10 classes according the share of all knowledge intensive employees was imposed. This method ensured balance for both measures in actual shares.

We explored both the inclusion of both measures of knowledge intensity (shares of employees with a PhD and shares with a maste'rs degree or higher) directly into the propensity and an alternative method of requiring an exact match on intervals of these two variables. Requiring an exact match for intervals provided a much better match on all variables (in particular for the knowledge intensity variables). One percentage point intervals were used for the share of PhDs (ie. 0-1%, 1-2%, etc.) and ten percentage point intervals for the share with master's degree or higher (ie. 0-10% and so on).

We also include a measure of capital intensity in terms of physical capital per employee. This variable was though found not to have a significant impact on the propensity score and its inclusion adversely affected the matching precision of the other variables, in particular knowledge intensity. Hence, we instead include a simpler, ordinal measure of capital intensity, with a value of 1 for low capital intensity (under 1 mn DKK) and high capital intensity (1 mn DKK or more). This variable is significant in the propensity score without reducing precision of the other matching variables.

Firm size is measured using four size classes, 10 to 49 employees, 50 to 249, 250-499 and 500 or more employees. A potential drawback from this method is the possibility of large variation in number employees for the largest size class. However, we argue that this does not reduce the quality of matches, as value-added per employee does not appear to be correlated with the number of employees. For example the correlation of value-added per employee and number employees is only 0.003 for all firms and -0.008 for firms with 250 employees or more.

Firm structure and markets can vary considerably across industries; hence we want to ensure that firms are matched within the same type of industry. However, restricting to each individual NACE 2-digit industry proves to be too restrictive given the need to match with other variables. We have thus grouped into 15 larger industrial groupings. An exact match according to industrial groups is required.

The year of the observation is important due to business cycle fluctuations. The model specification worked best by including the year in the propensity score as opposed to imposing an exact match. Imposing an exact match for both year and industry proved too restrictive, resulting in a poor match according to knowledge intensity, while including year in the propensity score allowed for a balanced match for both year and the knowledge intensity measures.

International orientation can be an important factor in differentiating firms. To account for this, we use a simple indicator of whether firms have had exports in either period t-2 or t-1.

A1.3. Probit model and testing for balance in the matched sample

To illustrate the approach, we describe here in greater detail the procedure for public-private publications compared to no publication. Thereafter, we present the results of all five comparisons.

Table A2 shows the results of the probit regression that is used to construct the propensity score. The dependent variable here is a dummy variable for whether the firm has co-authored a publication with a public research institution within the last three years (t-2 to t). As can be seen from the table, all variables are positively and significantly related to the propensity for public-private publications. The regression sample includes yearly observations both for firms with a public-private publication in the last three years and firms without a publication in the last three years. The sample includes in all 51,896 observations, 2,437 with a public-private publication and 49,136 without a publication.

Of the 2,437 observations with a public-private publication, 1,109 were outside the common support (the estimated propensity to have a public-private publication was too high, or too close to 100%) and were removed from the analysis.

Table A2. Results of probit regression where public-private publication in last 3 years is the treatment variable

Dependent var.: Public-private publication in last 3 years (dummy variable)	Coeff.	Std.Err.	P-value
Year	0.024	0.002	0.000
Capital intensity class	0.425	0.028	0.000
Size class	0.411	0.011	0.000
Exports	0.214	0.023	0.000
Constant	-51.884	4.758	0.000
Number of obs	51,896		
LR chi2(4)	2085.19		0.000
Pseudo R2	0.106		

The remaining 1,328 observations were matched with observations without a publication. Each observation was matched with that observation which had the closest propensity score. Though, in addition, it was required that observations were only matched with other observations from the same industry. A key criterion for the quality of the resulting matched sample is that firms with and without a public-private publication are fully comparable in terms of the variables used in the procedure. Table A3 below shows results of the probit estimations for each of the five comparisons while table A4 shows mean values of key variables for the matched samples.

Table A3. Results of probit regression for the five matching analyses

Treatment group		**Control group population**	
Publication during time t-2 to t		**No publication during time t-2 to t**	
Variable	Coeff.	Std.Err.	P-value
Year	0.022	0.002	0.000
Capital intensity class	0.417	0.027	0.000
Size class	0.410	0.011	0.000
Exports	0.255	0.022	0.000
Constant	-48.829	4.465	0.000
Publication involving public-private collaboration during time t-2 to t		**No publication during time t-2 to t**	
Variable	Coeff.	Std.Err.	P-value
Year	0.024	0.002	0.000
Capital intensity class	0.425	0.028	0.000
Size class	0.411	0.011	0.000
Exports	0.214	0.023	0.000
Constant	-51.884	4.758	0.000

Both publication involving public-private collaboration and industry-only publication during time t-2 to t		**Publication, but not both publication involving public-private collaboration and industry-only publication during time t-2 to t**	
Variable	Coeff.	Std.Err.	P-value
Year	0.004	0.006	0.478
Capital intensity class	0.304	0.059	0.000
Size class	0.259	0.022	0.000
Exports	0.033	0.064	0.606
Constant	-9.965	11.620	0.391
Publication involving public-private collaboration during time t-2 to t		**Publication but no public-private collaboration during time t-2 to t**	
Variable	Coeff.	Std.Err.	P-value
Year	0.020	0.007	0.002
Capital intensity class	0.127	0.072	0.077
Size class	0.092	0.026	0.000
Exports	-0.322	0.077	0.000
Constant	-40.104	13.404	0.003
Publication involving international public-private collaboration during time t-2 to t		**Publication, but no publication involving international public-private collaboration during time t-2 to t**	
Variable	Coeff.	Std.Err.	P-value
Year	0.026	0.006	0.000
Capital intensity class	0.336	0.059	0.000
Size class	0.102	0.022	0.000
Exports	-0.160	0.061	0.009
Constant	-52.706	11.342	0.000

Table A4. Comparison of mean values for treated and control groups in the matched sample

Treatment group		**Control group population**	
Publication during time t-2 to t		**No publication during time t-2 to t**	
Variable	Treated	Control	p>|t|
pscore	0.106	0.104	0.508
Capital intensity	2636.3	1796.5	0.131
Capital intensity class	1.135	1.173	0.003
Number employees	509.8	229.7	0.000
Size class	3.980	3.939	0.288
year	2006.4	2006.2	0.096
Industry group	41.8	41.8	1.000
Share Masters	0.227	0.221	0.380
Share Phd	0.026	0.025	0.749
Publication involving public-private collaboration during time t-2 to t		**No publication during time t-2 to t**	
Variable	Treated	Control	p>|t|
pscore	0.095	0.092	0.397
Capital intensity	2936.7	1662.0	0.053
Capital intensity class	1.132	1.175	0.002
Number employees	562.8	233.0	0.000
Size class	3.999	3.953	0.296
year	2006.6	2006.0	0.000
Industry group	41.2	41.2	1.000
Share Masters	0.227	0.221	0.403
Share Phd	0.028	0.027	0.764
Both publication involving public-private collaboration and industry-only publication during time t-2 to t		**Publication, but not both publication involving public-private collaboration and industry-only publication during time t-2 to t**	
Variable	Treated	Control	p>|t|
pscore	0.511	0.505	0.157
Capital intensity	3195.9	2551.9	0.556
Capital intensity class	1.139	1.150	0.590
Number employees	756.6	472.4	0.000
Size class	4.326	4.226	0.135
year	2006.8	2006.2	0.005
Industry group	44.6	44.6	1.000
Share Masters	0.227	0.224	0.827
Share Phd	0.045	0.044	0.883

Publication involving public-private collaboration during time t-2 to t		**Publication but no public-private collaboration during time t-2 to t**	
Variable	Treated	Control	p>|t|
pscore	0.835	0.833	0.110
Capital intensity	1997.8	1993.8	0.993
Capital intensity class	1.143	1.208	0.000
Number employees	849.8	830.5	0.790
Size class	4.500	4.501	0.984
year	2006.9	2005.6	0.000
Industry group	44.8	44.8	1.000
Share Masters	0.191	0.187	0.662
Share Phd	0.023	0.022	0.921
Publication involving international public-private collaboration during time t-2 to t		**Publication, but no publication involving international public-private collaboration during time t-2 to t**	
Variable	Treated	Control	p>|t|
pscore	0.416	0.411	0.526
Capital intensity	3761.3	5307.7	0.144
Capital intensity class	1.207	1.226	0.377
Number employees	790.6	427.9	0.000
Size class	4.278	4.259	0.767
year	2006.9	2004.0	0.000
Industry group	45.3	45.3	1.000
Share Masters	0.265	0.263	0.886
Share Phd	0.059	0.058	0.913

Table A5 shows the full results of the matching analysis. The table shows mean values of outcome variables both for the treatment and control groups, and both for the matched and unmatched samples. Table A5 also shows the results of t-tests for the matched sample of whether mean values for the treated and control group are significantly different from each other. Two outcome variables are examined in the analysis, value-added per employee and the two-year change in value-added per employee.

Table A5. Results of the matching analysis – comparison of mean values for value-added per employee and changes in value-added per employee for the matched samples.

Variable	Sample	Treated	Controls	Difference	S.E.	P-value
		Publication	No publication			
Value_added per employee	Unmatched	561.50	492.79	68.71	9.50	7.23
	Matched	573.23	492.80	80.43	14.57	5.52
2 year difference in value-added per employee	Unmatched	69.55	8.44	61.11	37.25	1.64
	Matched	49.25	17.63	31.61	24.63	1.28
		Public-private publication	No publication			
Value_added per employee	Unmatched	567.81	492.79	75.02	8.72	8.60
	Matched	573.05	503.92	69.13	14.12	4.90
2 year difference in value-added per employee	Unmatched	69.80	8.44	61.36	34.13	1.80
	Matched	52.56	21.87	30.70	16.37	1.88
		Public-private publication	Industry publication			
Value_added per employee	Unmatched	561.50	599.49	-37.99	24.69	-1.54
	Matched	608.67	615.88	-7.21	60.64	-0.12
2 year difference in value-added per employee	Unmatched	69.55	71.09	-1.54	27.07	-0.06
	Matched	48.68	108.66	-59.98	41.31	-1.45
		Both public-private and industry publication	Other publication			
Value_added per employee	Unmatched	579.78	559.98	19.80	18.80	1.05
	Matched	558.75	525.98	32.76	43.88	0.75
2 year difference in value-added per employee	Unmatched	67.08	71.62	-4.55	20.30	-0.22
	Matched	64.23	19.39	44.84	48.34	0.93
		International public-private publication	Other publication			
Value_added per employee	Unmatched	570.00	565.53	4.47	18.40	0.24
	Matched	570.43	549.59	20.84	32.18	0.65
2 year difference in value-added per employee	Unmatched	76.96	62.04	14.93	19.91	0.75
	Matched	49.30	48.28	1.01	33.92	0.03