BACKGROUND REPORT

INTERDISCIPLINARY RESEARCH IS KEY TO SOLVING SOCIETY´S PROBLEMS

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PREFACE

All over Europe there is a wish to promote research and innovation that can help address major societal concerns, or "grand challenges" as called in the EU Framework Programme for Research and Innovation, Horizon 2020. The communication from the European Commission on Horizon 2020 stresses that those challenges require that we bring together resources and knowledge from different fields, technologies and scientific disciplines. We need to be better at getting the so-called "hard" sciences – the natural and technical sciences – and the so-called "soft sciences" – the social sciences and the humanities (or SSH, for short) – to work together.

The reason is fairly simple: good solutions to important problems – whether that is in industry or larger societal problems – are rarely found within a single discipline; instead, solving complex, real-life problems generally requires bringing together insights from multiple disciplines. Thus, one of the success criterions for Horizon 2020 is to promote and effectively support interdisciplinary research.

But what is interdisciplinary research? Even though the societal importance of interdisciplinary research is widely recognized, there is relatively little knowledge about the nature of interdisciplinary research. We need to be able to answer questions such as: how much research is carried out as interdisciplinary research? And if you engage in interdisciplinary research does that require something else than monodisicplinary research? What are the barriers? And what incentives do we need, if we want to proceed in this direction? We need knowledge so we can identify the measures that will support research that tackles these grand societal challenges.

Therefore, DEA has carried out a study of interdisciplinary research. By case illustration we have looked at the correlation between interdisciplinary research and productivity, impact and cooperation and we have produced new knowledge to identify barriers and possibilities for interdisciplinary research. The study shows that while Danish research overall has high productivity and impact in all three case illustrations there is a potential for greater interdisciplinarity in the three chosen fields.

The main conclusions in this study is evidence of a positive and significant relationship between interdisciplinarity and impact. In order words, the more interdisciplinary a publication is, the higher the level of impact it is likely to have. Thus, at least in the three research fields examined, interdisciplinary publications appear to be rewarded, and not penalized, in terms of scientific performance.

Enjoy the reading!

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1 PURPOSE

"WITHOUT KNOWLEDGE FROM SEVERAL ACADEMIC DISCIPLINES, IMPORTANT PROBLEMS IN CONTEMPORARY SOCIETY CANNOT BE SOLVED." (BUANES AND JENTOFT 2009)

Even though the importance of interdisciplinary research is widely acknowledged, relatively little is known about how public policies should be designed to effectively promote it. This is in large part due to the difficulties associated with defining and measuring interdisciplinary research.[1]

To develop effective policies to stimulate interdisciplinary research, we need better insight into how much interdisciplinary research actually occurs or how public policies can best support it – and this calls for reliable, systematic means of identifying and measuring it.

The aim is to stimulate the debate on how Horizon 2020 and other large research programs should be designed with a view to encouraging and supporting interdisciplinary research collaboration.

AIMS OF THE STUDY

- To call for more evidence-based use of public funds to promote interdisciplinary research.
- To provide more general insights into the challenges associated with promoting greater interdisciplinarity in research.
- To explore the usefulness of a new bibliometric method for assessing the interdisciplinarity of research.

We therefore explore the usefulness of a new method for measuring the interdisciplinarity of research. The method, which was developed in academia and uses bibliometric data (that is, data on scientific publications), is applied in case studies of three selected research fields: genetically modified foods, metabolism and obesity, and renewable energy.

1.1 WHAT IS INTERDISCIPLINARY RESEARCH?

Problems whose solutions cannot be identified from within a single discipline calls for inputs from a number of different disciplines (Buanes and Jentoft 2009). The actual level of interdisciplinarity of research can, however, be difficult to define, notably since boundaries between disciplines are fluid. What one researcher perceives as a research field, for example, another researcher may see as a subset of a larger field (Huutoniemi et al. 2010).

Interestingly, the notion of a scientific "discipline" has only been in common use for about a century (Klein 1996). During the nineteenth and twentieth century, science diversified into a series of specialized areas, resulting in the formation of disciplines that gradually grew more robust and their members more isolated from one another (Wagner et al. 2011).

[1] *For more detailed discussions of challenges and approaches to the measurement of interdisciplinarity in research, see e.g. Huutoniemi et al. 2010; Porter et al. 2006; Roessner and Perreault 2007; Wagner et al. 2011. For publications stressing the need for further research on interdisciplinarity in the sciences, see e.g. The National Academies 2005; Wagner et al. 2011.*

During the 1970s, calls from policymakers for greater and more short-term relevance in science and an increased recognition of the value of problem solving in engineering and other applied sciences lead to a growing problem orientation in scientific research (e.g. Kline 1995; Schmidt 2008). This in turn spurred interest in interdisciplinary research as a means of uniting scientific disciplines.

The first international conference on interdisciplinary research was held in 1970; since then, interdisciplinary research has been the subject of a growing research field of its own within the social sciences (Klein 2008). Nonetheless, academic researchers have yet to fully shed light on the complex social and cognitive processes that make for successful interdisciplinary research (e.g. The National Academies 2005; Wagner et al. 2011).

WHY IS INTERDISCIPLINARY RESEARCH IMPORTANT?

Nissani (1997) makes a case for interdisciplinary research based on the following 10 arguments:

1. Creativity often requires interdisciplinary knowledge.
2. Immigrants often make important contributions to their new field.
3. Disciplinarians often commit errors which can be best detected by people familiar with two or more disciplines.
4. Some worthwhile topics of research fall in the interstices among the traditional disciplines.
5. Many intellectual, social, and practical problems require interdisciplinary approaches.
6. Interdisciplinary knowledge and research serve to remind us of the unity-of-knowledge ideal.
7. Interdisciplinarians enjoy greater flexibility in their research.
8. More so than narrow disciplinarians, interdisciplinarians often treat themselves to the intellectual equivalent of traveling in new lands.
9. Interdisciplinarians may help breach communication gaps in the modern academy, thereby helping to mobilize its enormous intellectual resources in the cause of greater social rationality and justice.
10. By bridging fragmented disciplines, interdisciplinarians might play a role in the defense of academic freedom.

Source: Nissani 1997.

WHAT IS A SCIENTIFIC DISCIPLINE?

A scientific discipline can be defined as a community of researchers with a shared set of methods and assumptions that they apply to formulate and solve problems within a particular knowledge domain.

Definition inspired by Darden and Maull 1977.

AN EXAMPLE OF INTERDISCIPLINARY COLLABORATION THAT SPANS THE HARD AND SOFT SCIENCES

The Danish Centre for Bioethics and Risk Assessment (CeBRA) is committed to performing interdisciplinary research, where ethical issues are studied in connection with biological research within food production, biotechnology and animal sciences. The centre is organized as a partnership between parts of the University of Copenhagen, Aarhus University, and the Technical University of Denmark. Research undertaken is performed at the host universities, based on external grants, but CeBRA facilitates an interdisciplinary approach across universities and disciplines. The research performed at CeBRA makes a substantial input to both the scientific study of and the public debate on bioethics.

The director of the centre, Professor Peter Sandøe, is a strong advocate for interdisciplinary work and is one of the main drivers behind the interdisciplinary research center. In relation to his work, Sandøe stresses that we must understand technical issues in the context of our society in order to understand exactly what challenges we are facing and how these can be solved.

This calls for interdisciplinary work, where the humanities and social sciences can link the work of the natural and technical sciences. Biological discoveries and inventions involve both opportunities and risks for society; and a wide perspective is therefore needed in to conceptualize these opportunities and risks.

According to Sandøe, scientists should involve themselves in the public debate as informed citizens, but often stay out of it precisely because they are scientists and – for some – because they fear criticism or interference in their work.

1.2 DISTINGUISHING BETWEEN INTERDISCIPLINARY AND MULTI-DISCIPLINARY RESEARCH

Research that spans multiple disciplines comes in many forms. In its simplest forms, researchers can "borrow" insights or methods from other disciplines to enrich or guide their own research. In its more extreme forms, disciplines can converge and result in the formation of entirely new disciplines and professional research communities.

While research projects often involve scientists from multiple disciplines, this therefore does not necessarily mean that the research in the project is truly interdisciplinary. There is an important distinction between multidisciplinarity and interdisciplinarity (see e.g. Huutoniemi et al. 2010).

In **interdisciplinary research**, insights and methods from different scientific disciplines are integrated and used to investigate a jointly defined research problem through a joint research effort. By contrast, in **multidisciplinary research**, related research problems are investigated from different disciplines. The extent to which researchers from the different disciplines communicate with and draw inspiration from each other may differ, but there is no real integration of insights and methods from the participating disciplines.

Another important difference between multidisciplinary and interdisciplinary research, which is illustrated in the figure below, is their effect on the research fields they bring together. According to a report from the National Academies (2005), in multidisciplinary collaboration, researchers from different disciplines work on a common problem and split apart unchanged once their task has been accomplished. Interdisciplinary collaboration, however, has the potential to forge new research fields or disciplines.

1.3 APPROACHES TO MEASURING INTERDISCIPLINARITY

Widening interest in interdisciplinary research has made both research funding agencies and academic scholars concerned with how to define, operationalize and measure interdisciplinarity in research; however, despite decades of work on the subject, there is as of yet no agreement on how interdisciplinarity should be measured in practice (Huutoniemi et al. 2010).

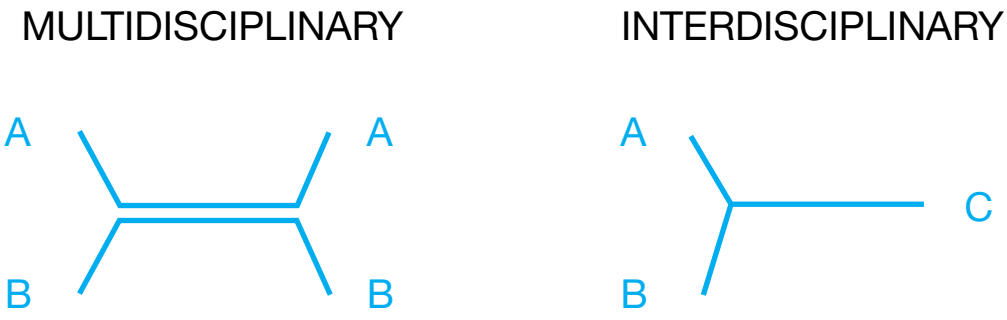
An often used approach to measuring interdisciplinarity in policy analyses and evaluations is to use collaboration between research environments as a proxy for interdisciplinary collaboration. If for instance a research project includes participants from a Department of Biology, a Department of Chemistry, and a Department of Psychology, this is said to indicate interdisciplinary research collaboration.

The main disadvantage of this indicator is that it does not allow for any distinction between multi- and interdisciplinarity: there is no way of determining whether there has been any real integration of research insights or methods from the participating disciplines.

Moreover, research environments that are listed as participants in the same research project, e.g. on a grant application, do not necessarily collaborate with each other. In some cases, researchers from different research environments may apply for funding together to increase their chances of obtaining funding without any real intention of

FIGURE 1: The difference between multi- and interdisciplinary research

Source: The National Academies, 2005



collaborating closely together if the funding be granted. In other cases, the participants may intend to collaborate but actual cooperation is hindered by practical difficulties in engaging in interdisciplinary research. Neither of these types of situations can be identified using the aforementioned method.

To provide better insight into the actual degree and nature of interdisciplinary collaboration, surveys or interviews may be used to collect information from the participants in a research project. However, respondents often have different subjective understandings of "interdisciplinary research" that may influence their answers. Moreover, there is a risk that participants will act strategically and describe their collaboration as more interdisciplinary than it actually was. Last but not least, survey and interview methods are very time-consuming, particularly if the aim is to provide a reliable and comparable assessment of the level of interdisciplinarity in a large number of research projects.

A growing part of research concerns the use of scientometric techniques to assess interdisciplinarity in research based on e.g. publication data, patent data or research proposals. While scientometric methods also have shortcomings (see e.g. Huutoniemi et al. 2010), they also provide a systematic means of assessing the degree of interdisciplinarity of a given piece of research or group of researchers.

2 OUR APPROACH

2.1 DATA AND METHODS

We use data on scientific publications to explore the actual degree of interdisciplinarity in research within three selected research fields. The methodology applied in this study consists of four main parts, which are described in the following.

1. Collection of all Danish publications published during the period 2000-2011 (both years included) in journals indexed in the bibliometric database Thomson Reuters Web of Science.[2] Publications were considered to be Danish if they were written by at least one author affiliated with a Danish research institution or company.

2. Analysis of Danish research in an international perspective. The total set of Danish publications was compared to scientific publications from the 20 leading OECD countries in each field, on three dimensions:

- **Productivity:** how many articles they published, i.e. how much they contributed to the international research front.
- **Impact:** how often their articles had been cited, i.e. how great an overall impact they had made on the research front.
- **Interdisciplinarity:** the level of interdisciplinarity of each of their articles, calculated as described in more detail below.

3. Analysis of the degree and role of interdisciplinarity in the Danish research fields through further analysis of the bibliometric data combined with interviews with selected researchers from the public sector and from industry. Respondents were identified in the bibliometric analysis and selected based on high levels of interdisciplinarity and/or impact, and approximately six interviews with researchers in Denmark and abroad were conducted in connection with each case study.

4. Analysis of the relationship between interdisciplinarity and other key aspects of academic research, notably scientific impact and collaboration with industry, using multivariate statistical analysis. If there is a significant relationship between interdisciplinarity and key aspects of scientific performance, this is likely to affect academic researchers' incentives to engage in interdisciplinary research and must therefore be taken into account in the design of public policy to promote interdisciplinarity.

The results of the analysis of Danish research in an international perspective and of analysis of the degree and role of interdisciplinarity in the Danish research fields examined are presented in the case studies described in chapters 4 to 6 of this report.

The data, methods and results of the regression analysis to investigate the relationship between interdisciplinarity and other key aspects of academic research are presented in chapter 7.

2.2 THE INTERDISCIPLINARITY INDEX

During the last decade, academic researchers have developed a number of different methods for assessing the level of interdisciplinarity in research (for a review, see Leydesdorff and Rafols 2011). In recent years, academics have focused on one particular approach, which allows for the systematic assessment of the degree of interdisciplinarity in a body of research using an "interdisciplinarity index" (developed by Porter et al. 2007, Alkærsig 2011 and Rafols et al. 2012).

[2] *Publications were retrieved from Thomson Reuters Web of Science, one of the two major databases used for bibliometric studies, along with the Elsevier owned Scopus. Differences between the two databases are limited and mainly center on the number of journals covered, particularly in the social science and humanities. Several recent studies (e.g. Leydesdorff et al. 2010; Archambault et al. 2009) however conclude that the bibliometric indicators derived from the two databases differ only in extreme cases, e.g. research fields with very few publications or few citations.*

The interdisciplinarity index is based on an analysis of publications in international peer-reviewed scientific journals. Such publications are public researchers' main channel for dissemination of their research; as a result, analyzing the entire population of scientific publications within a given research field yields a comprehensive picture of research activities in that field.

The method was originally developed to gauge how interdisciplinary a body of research is, and later refined to measure interdisciplinarity in publications of individual researchers. We have adapted the method for the use in this study by elaborating on the context in which the index is used, to allow for the analysis of larger sets of publications, for instance all publications from a given country or research institution.

Essentially, the method determines the degree of interdisciplinarity of a particular publication (and thus of the research presented in that publication) based on the scientific disciplines that it cites.[3] Any scientific publication cites a number of other publications, for example because it builds on previous research described in these articles. Citations are also used to position a publication in the overall academic debate within a field, and to frame its contribution vis-à-vis other scholars.

The method is based on the assumption that research, which is truly interdisciplinary, will, at least to some extent, cite the disciplines that it builds on. We would therefore expect an interdisciplinary publication to cite more disciplines (and to cite them to a greater extent) than a publication, which is written entirely within a specific scientific discipline.

The "interdisciplinarity index" assigns a score to either a single publication or to a group of publications. The value of the score lies in the range between 0 and 1, where 0 indicates monodisciplinarity, and 1 a high level of interdisciplinarity.

The interdisciplinary index is based on three equally weighted dimensions:

- **The degree of variation** in the disciplines cited, that is, the number of disciplines that an article cites. An article that cites many disciplines is considered to be more interdisciplinary than one that cites few disciplines.
- **The balance** between disciplines cited, that is, the relative proportions of the disciplines cited. An article where e.g. two disciplines are cited an equal number of times is considered to be more interdisciplinary than an article, which cites one discipline 90 percent of the time and the other discipline 10 percent of the time.
- **The cognitive distance** between disciplines, that is, how often they are cited together. For example, there is a greater cognitive distance between the natural sciences and the humanities than between the natural sciences and the medical sciences.

CITATIONS AS AN INDICATOR OF SCIENTIFIC IMPACT AND INTERDISCIPLINARITY

We measure interdisciplinarity using citations in scientific publications. A citation is a reference to the prior research that a given article draws and builds upon. Citations play an important role in scientific publications because they allow researchers to indicate what prior work their own research builds upon, to position their work in the literature, and to thus communicate their contribution to the research front. Citations are therefore often used as indicators of the scientific impact that a publication has, that is, its impact on the research community.

Citations from a scientific publication thus provide valuable information about the research that the publication builds on. The interdisciplinarity index exploits this by examining which journals a publication cites. All scientific journals are specialized within certain disciplines and can therefore be categorized based on the disciplines that they cover. By analyzing which journals a publication cites, we can therefore extrapolate information about which disciplines the research presented in the publication builds upon.

We thus exploit the fact that a scientific publication can refer to research within the same discipline or to other closely or distantly related disciplines. An article in a physics journal that only refers to articles in other physics journals would for example be characterized as a monodisciplinary article. Meanwhile, an article in a physics journal that refers to articles in technical or social science journals would be a multi- or interdisciplinary article.

[3] *The Web of Science database assigns all journals that it indexes to a set of subject areas based on the general theme of the journal, i.e. based on the scientific disciplines that they cover; we use these categories to identify the disciplines that a given publication refers to, based on the journals that it cites. This classification of journals consists of approximately 250 "subject areas" across the socalled "hard" and "soft" sciences. A journal can be categorized according to up to five different subject areas such as e.g. Biochemistry & Molecular Biology, Computer Science and Mathematics. We use the classification of a journal as a proxy for the classification of the publications that appear in that journal.*

Cognitive distance is determined through an analysis of the total number of citations between two journals and the disciplines that they cover within a given period. The distance is thus reversely proportional to the number of citations; as such, two journals that rarely cite each other will be characterized by a great cognitive distance. The interdisciplinarity index is based on the sum of all cognitive distances for the citations from a given publication to the various journals that it cites.

This last dimension, cognitive distance, is based on the idea that the rarer it is for two disciplines to be cited in the same paper, the more groundbreaking (or, rather, "disciplinebreaking") the research that connects them must be. Thus, an article that cites two disciplines, which are normally rarely cited together, is considered more interdisciplinary than one, which cites disciplines that are often cited in the same articles.

The notion of cognitive distance is based on the recognition that there are large differences in concepts, tools and methods from one research discipline to the next. Key nuances in the interdisciplinarity index emerge because of the greater cognitive distance between e.g. English and mathematics as compared to the distance between e.g. astrophysics and geophysics.[4]

The interdisciplinarity index is given by the average of the cognitive distances between any given subject area for the sample of publications assigned to the country or organization researched. The average value is in the final index weighed by the frequency of the occurrence of the subject areas within the data sample. This is done to ensure that the effect of single subject area publications generating high-distance measures are diminished, which otherwise would cause false positive effect of high interdisciplinarity.

The index is designed in such a way that the average values are general low, which is caused by the high number of different subject areas assigned to each publication. The fact that more than 30 percent of the publication in the sample appear in journals which have three or more subject areas assigned to them pushes the index towards the low numbers.

2.3 THE THREE CASE STUDY RESEARCH FIELDS

Using this index, we can approximate the degree of interdisciplinarity in all publications from a given scientist, a given research environment or within a given research field. In this project, we focus on three research fields: renewable energy, genetically modified foods and metabolism and obesity research.

These research fields were selected because they all carry high relevance for the grand societal challenges that Horizon 2020 will focus on (see European Commission 2011 for more information). Moreover, all were expected (at least potentially) to have a substantial degree of interdisciplinary research, both within and across the hard and soft sciences.

In our search for publications from the three research fields, each field was defined by a set of keywords representing fundamental technologies, concepts and methods. Keywords were carefully selected based on our general knowledge of the areas and by consulting recent technology reviews of the three fields. The resulting search strings do not allow us to capture all research conducted within each field; rather, the search strings have been developed in a careful, iterative process so as to minimize the number of publications with only limited relevance to the selected fields that is captured in the analysis.

Thus, the aim of the bibliometric data collection was to ensure as comprehensive as possible a coverage of publications in each of the three selected research fields while limiting "noise" from other fields.

THE THREE CASE STUDY RESEARCH FIELDS

Genetically modified foods: Genetically modified foods are based on plants or animals, where DNA has been modified through genetic engineering in order to enhance desirable characteristics e.g. to enable the greater, more effective production of crops. They are relevant for the Horizon 2020 challenge on *food security, sustainable agriculture, marine and maritime research and the bio-economy.*

Metabolism and obesity: Research on metabolism studies how the body metabolises food, and how proper nutrition and exercise can contribute to healthy living. Obesity is a growing problem in many parts of the world and associated with a number of chronic conditions e.g. diabetes and cardiovascular diseases. This field of research is therefore important to address the Horizon 2020 challenge regarding *health, demographic change and wellbeing.*

Renewable energy: This research field aims to develop sustainable sources of energy (e.g. solar or wind energy) that can replace fossil fuel technology. Research on renewable energy will help to address the Horizon 2020 challenge to provide *secure, clean and efficient energy.*

[4] *Cognitive distance is determined through an analysis of the total number of citations between two journals and the disciplines that they cover within a given period. The distance is thus reversely proportional to the number of citations; as such, two journals that rarely cite each other will be characterized by a great cognitive distance. The interdisciplinarity index is based on the sum of all cognitive distances for the citations from a given publication to the various journals that it cites.*

3 MAIN FINDINGS

3.1 DANISH RESEARCH HAS HIGH OVERALL PRODUCTIVITY AND IMPACT

The three case studies indicate that Danish research in all three fields has **high productivity** relative to the size of the population. Denmark is the most productive country worldwide, measured on the number of scientific publications per capita, in all three case study areas. In other words, considering the size of the country, Denmark makes a substantial *contribution* to international research.

The case studies also reveal that Danish research has **high scientific impact**, meaning that it makes a significant *difference* on the international research front.

The level of impact varies, however, across research fields. For example, Danish research has a significantly higher impact in metabolism and obesity research and research on renewable energy than in research on genetically modified foods.

3.2 THERE IS A POTENTIAL FOR GREATER INTERDISCIPLINARITY IN DANISH RESEARCH

The level of interdisciplinarity in all three research fields is on par with or below the international level for all fields. This, combined with the results of our case studies, suggests that there is a potential to increase the level of interdisciplinarity in Danish research.

SCIENTIFIC IMPACT OF DANISH RESEARCH

Genetically modified foods: Denmark is ranked no. 18 out of 20 OECD countries

No. 1: USA (47.8 citations per publication)
No. 2: Italy (37.5 citations)
No. 3: England (36.2 citations)
No. 4: Germany (32.6 citations)
No. 5: The Netherlands (30.5 citations)
...
No. 18: Denmark (14.7 citations)

Metabolism and obesity: Denmark is ranked no. 4 out of 20 OECD countries

No. 1: Finland (37.5 citations per publication)
No. 2: USA (28.5 citations)
No. 3: Sweden (28.0 citations)
No. 4: Denmark (25.7 citations)
No. 5: England (24.9 citations)

Renewable energy: Denmark is ranked no. 2 out of 20 OECD countries

No. 1: USA (19.4 citations per publication)
No. 2: Denmark (18.1 citations)
No. 3: The Netherlands (17.2 citations)
No. 4: Switzerland (17.1 citations)
No. 5: Germany (15.8 citations)

Based on publication data from Thomson Reuters Web of Science 2000-2011 (both years included).

Among our three research fields, this is especially the case for research on genetically modified foods and on renewable energy.

The case studies indicate that discipline-spanning research in the three research fields is predominantly multidisciplinary rather than interdisciplinary. The potential for greater cross-cutting research therefore appears to lie in strengthening the degree of interaction among scientific disciplines.

The case studies indicated that Denmark has good overall conditions for interdisciplinary research. Several Danish research funders provide grants for large, interdisciplinary research projects. For instance the Council for Strategic Research explicitly wishes to promote interdisciplinarity, while the Danish National Advanced Technology Foundation promotes problem-oriented research collaboration between universities and industry.

DANISH INTERDISCIPLINARITY SCORE[5]

Genetically modified foods: Denmark is ranked no. 20 out of 20 OECD countries (score: 0.12)

No. 1: South Korea (0.19)
No. 2: Japan (0.18)
No. 3: France (0.18)
No. 4: Italy (0.17)
No. 5: Spain (0.17)

Metabolism and obesity: Denmark is ranked no. 8 out of 20 OECD countries (score: 0.12)

No. 1: Japan (0.13)
No. 2: Switzerland (0.13)
No. 3: Finland (0.13)
No. 4: England (0.13)
No. 5: USA (0.13)

Renewable energy: Denmark is ranked no. 14 out of 20 OECD countries (score: 0.16)

No. 1: South Korea (0.18)
No. 2: Taiwan (0.17)
No. 3: China (0.17)
No. 4: Italy (0.17)
No. 5: France (0.17)

Based on publication data from Thomson Reuters Web of Science 2000-2011 (both years included).

The explanation for why some researchers chose not to engage in interdisciplinary research must therefore be found elsewhere. In fact, interdisciplinary research is associated with significant barriers that must be overcome, including structural barriers but also cultural and cognitive barriers; the latter two are the most difficult to mitigate (Buanes and Jentoft 2009).

The case studies suggest several barriers to interdisciplinarity that may influence researchers to choose mono- or multidisciplinary research over interdisciplinary ventures. The rest of this section describes the most important of these barriers.

> *"Any interdisciplinary approach will inevitably challenge, or be challenged by the regulative, cognitive and normative dimensions of established disciplines. Crossing disciplinary boundaries involves breaking rules, as well as questioning paradigms and norms, which are often considered to be inappropriate. It is therefore to be expected that those who do so will be met by some form of sanction. There is a risk, for example that your proposal or article will be rejected or that you will not to be promoted."*
>
> *Buanes and Jentoft, 2009*

Interdisciplinary research is uncertain and resourcedemanding

Engaging in integrative research involving several disciplines requires participants to first establish a common "language" and research method that enables them to work jointly while exploiting the potential from cross-fertilization between their disciplines. This process can be very demanding in terms of the time and energy that researchers must invest in it. Moreover, its outcomes are highly uncertain, as interdisciplinary projects often break new ground and are therefore associated with a high level of risk. This may lead researchers to opt for more accessible research projects with a higher likelihood of success.

Interdisciplinary research can be more difficult to publish in prestigious journals

The case studies also lend support to an often mentioned barrier to interdisciplinarity, namely that the results of interdisciplinary research are more difficult to publish in prestigious academic journals because these journals are generally focused on specific disciplines. They may also lack the necessary breadth of disciplines among

[5] *The method in its current version tends to yield interdisciplinarity scores that are both quite low and lie within a relatively small range. This limitation is recognized in the academic literature, and efforts are underway to remedy it, for example by performing separate analyses on the three dimensions (variation, balance and distance) that are used in the calculation of the interdisciplinarity index. Nonetheless, we still find the method useful in drawing out differences in degrees of interdisciplinarity that can provide the starting point for more indepth research.*

their external reviewers to satisfactorily assess the quality of interdisciplinary submissions. Journals like *Nature* and *Science* are therefore exceptions to the rule. Respondents, however, also indicate that the ability to publish interdisciplinary work in high-impact journals differs greatly across research fields and is not always an impediment to interdisciplinarity.

The value of interdisciplinarity is unclear

According to respondents, many researchers do not see the value of interdisciplinarity over multidisciplinary research and therefore lack incentive to overcome the barriers associated with interdisciplinary research projects.

Research problems are defined within disciplines rather than based on societal challenges

The case studies also suggest that the reason many researchers do not see the value of interdisciplinarity may be that they are content to address research issues within their own disciplines. In contrast, researchers that take an interest in broader societal problems appear more open to interdisciplinary approaches.

Disciplines often operate with a basic set of assumptions and research methods that affect their research focus

Moreover, disciplines are prone to "fads", i.e. popular topics that influence the current research agenda. Research problems that are defined within a particularly disciplinary context therefore often have a very different nature than applied research problems that are based on societal challenges. The latter tend to be much more complex and require inputs from several different disciplines.

3.3 THERE IS SUBSTANTIAL COLLABORATION BETWEEN THE HARD AND SOFT SCIENCES – BUT MUCH OF IT IS MULTI-DISCIPLINARY RATHER THAN INTERDISCIPLINARY

As indicated by table 1, just three percent of all Danish publications identified from the three research areas are SSH publications, defined as publications with one or more authors from SSH university departments and faculties.[6] A large proportion of these publications, however, are co-authored with researchers from technical and/or natural science departments and faculties. For research on genetically modified foods and renewable energy, approximately one third of all SSH publications are co-authored with the hard sciences, while this is true for almost all SSH publications in metabolism and obesity research. These results should be taken with a grain of salt, as they are based on an analysis of just 39 publications. Nonetheless, they indicate that there is substantial interaction between the hard and soft sciences in the three research areas examined.

The qualitative case studies also indicate, however, that this interaction is often multidisciplinary rather than interdisciplinary, and that the degree of interdisciplinary collaboration falls the further apart two disciplines are. The case studies suggest a number of factors that may explain why researchers find it challenging to bridge SSH research with research on the natural and technical sciences; these factors are described in the following.

TABLE 1: SSH publications in each of the three case study research areas

Source: DAMVAD, 2012

	Total no. of Danish publications in the field	No. of these publications that are SSH publications (pct. of all Danish articles)	No. of these SSH publications that are co-authored with the hard sciences (pct. of all SSH articles)
Genetically modified foods	186	19 (10 pct.)	7 (37 pct.)
Metabolism and obesity	738	9 (one pct.)	8 (89 pct.)
Renewable energy	312	11 (four pct.)	3 (27 pct.)
Total	**1,236**	**39 (three pct.)**	**18 (46 pct.)**

[6] *The relatively low proportion of SSH research may be partly explained by the fact that SSH researchers publish fewer scientific articles than their counterparts in the natural and technical sciences. As mentioned in a previous footnote, the results may also be affected by the fact that data was collected from Thomson Reuters Web of Science. This database has generally been preferred in studies that span a broad range of disciplines and sciences, while Elsevier's Scopus – the other leading bibliometric database – has had better coverage of the SSH. As explained earlier, these differences have been reduced in recent years, as both databases have made efforts to overcome their shortcomings. Nonetheless, it should be noted that SSH research may be underestimated in our study.*

EXAMPLES OF SSH RESEARCH FROM THE THREE CASES

Genetically modified foods:
- Bioethics (e.g. examined from a philosophical or business perspective)
- Food economics; health economics
- Customer relations in the food sector
- Environmental impact

Metabolism and obesity:
- Philosophy
- Economics and psychology
- Firms' efforts to increase employee health

Renewable energy:
- Economics and management
- Environmental studies
- Environmental regulation in municipalities

Based on an analysis of publication data from Thomson Reuters Web of Science 2000-2011 (both years included).

Lack of contact to potential collaborators

Universities and academic research communities are largely organized based on traditional academic disciplines. This creates limited opportunities to meet researchers from other communities. As a result, researchers also lack insight into research topics in other fields which makes it more difficult to identify promising areas for interdisciplinary research.

Few obvious points of collaboration

When researchers from different disciplines share research interests, they often focus on very different aspects of these interest areas. This makes it more challenging to identify research problems of common interest. In some research areas, this is far easier; for example, study of the development of the market for electric cars requires both technical insight into the production of cars and the development of the necessary infrastructure and economic insight into the costs of acquiring and maintaining an electric vehicle. When joint research interests are harder to come by, the likelihood of entering into collaboration decreases.

Lack of incentive to collaborate

Many of the barriers related to interdisciplinary research collaboration increase with the distance between disciplines, including for example the development of a common language and research methodology. Moreover, interdisciplinary research can be difficult to publish in high-impact journals. Several respondents also pointed out that interdisciplinary research requires participants to choose a clear publication strategy early on (including which journals to target) to increase the chances that publications will be suitable for and accepted by good journals. Overcoming barriers like this requires a significant investment of time and resources on the part of researchers, which occurs at the detriment of other activities, e.g. pursuing more accessible research and publications within the researchers' own fields.

Cultural barriers

According to respondents, many researchers do not see the value of interdisciplinary collaboration. Particularly in some areas of SSH research, interdisciplinary research is perceived as less prestigious, and the demand for applied, problem-oriented research is lower than in many hard sciences.

In extension of this, the case studies suggest that, for some researchers, a barrier to interdisciplinary research lies within a lack of sufficient insight into different methodological approaches and recognition of their respective contributions to research.

Social science and humanities research often becomes an "appendix"

When social science and humanities are incorporated into multidisciplinary research projects, they are often brought in as an "add on", or as an independent project within the main project. This is in large part due to the difficult, time-consuming and uncertain nature of integrative research. Moreover, SSH researchers are often not closely involved in the preliminary formulation of the research problem that defines the joint project.

Necessity is the mother of invention

Finally, the case studies and interviews also indicated that because of the aforementioned barriers to interdisciplinary collaboration between the hard and soft sciences, such collaboration often occurs because researchers have no other viable options to pursue. For instance, one respondent from the humanities explains that very little public or private funding is available in his field of research. He therefore approaches potential collaborators from the natural and technical sciences because of their access to funding. On a similar note, researchers working with animal models in clinical research are often open to working with ethics researchers because of public concerns regarding animal welfare.

3.4 INDUSTRY PRODUCES BOTH HIGH IMPACT AND HIGHLY INTERDISCIPLINARY RESEARCH – BUT NOT AT THE SAME TIME

Eight percent of all the Danish publications identified from the three research areas were firm publications, defined as publications with one or more authors from private Danish companies.

As indicated by table 2, these firm publications have – on average – both higher impact and a higher degree of interdisciplinarity than the total set of publications. It is not surprising that firms engage in interdisciplinary research, as they need to gather and synthesize inputs and methods from all relevant scientific disciplines in order to develop new products and solve concrete, practical problems. Industry research has, however, traditionally been associated with lower levels of scientific impact, as firms tend to do research on more applied issues, which generally receive fewer citations (and therefore has lower impact) than basic research. Contrary to expectations, the firms in all three of the research fields have produced high impact research. A more detailed examination of the publication suggests that firms produce high impact research when they collaborate with leading national or international research environments.

However, further analysis of the data shows that there is no significant correlation between publications where firm publications have a high scientific impact and those where they have high degrees of interdisciplinarity: in other words, they either publish high impact research or interdisciplinary research.

Closer inspection of the bibliometric data also reveals that applied research institutions (e.g. government research institutions), like private firms, exhibit a high degree of interdisciplinarity, although they generally speaking have relatively few publications and low scientific impact.

Moreover, we find that while the level of scientific impact differs greatly for research from the various Danish universities, the universities have lower overall levels of interdisciplinarity. This is not surprising, as universities have a responsibility to maintain and develop strong disciplinary research and are, to a large extent, organized into research units based on scientific disciplines rather than societal challenges.

In addition, a key rationale for the public funding of universities is that these institutions are both able to and responsible for ensuring the long-term development of specialized knowledge and research methods within given disciplines that interdisciplinary research can build on.

Our findings also suggest, however, that part of the explanation for the lower relative level of interdisciplinarity

TABLE 2: Firm publications vs. publications in each of the three case study research areas

Source: DAMVAD, 2012

	Total no. of Danish publications in the field	Average no. of citations per publication	Average interdisciplinarity score
Genetically modified foods			
Firm publications only	18	11.90	0.15
All Danish publications	186	10.45	0.14
Metabolism and obesity			
Firm publications only	32	28.90	0.13
All Danish publications	738	23.00	0.12
Renewable energy			
Firm publications only	46	18.39	0.16
All Danish publications	312	12.28	0.14
Total			
Firm publications only	96	19.75	0.15
All Danish publications	1,236	15.24	0.13

in universities' research lies in aforementioned barriers to interdisciplinarity, e.g. that interdisciplinary research is uncertain, resource-demanding and can be difficult to publish in prestigious academic journals. This indicates that there is potential to stimulate greater interdisciplinarity in Danish universities, at least within the three research fields examined in the case studies, if these barriers are mitigated.

However, the case studies indicate that firms that engage in collaboration with universities are often not involved early on in the design of interdisciplinary research projects, but included after the main research problem has been formulated. This implies that their inputs are not fully exploited. In the worst cases, this can mean that companies become symbolic or peripheral participants in the projects, much like social science and humanities research risks becoming an appendix in projects defined primarily from the vantage point of the natural or technical sciences.

Our findings suggest that greater collaboration between universities and applied research institutions and/or companies may also stimulate more problem-oriented research and thereby potentially more interdisciplinary collaboration. The qualitative studies indicate, however, that this requires that the collaborative research is problem-oriented in nature and that applied research institutions and firms are involved from the very beginning of the project, including especially in the initial definition of the research problem, to ensure that their particular insights are brought to bear on the foundation for the joint research project.

3.5 INTERDISCIPLINARITY IS GOOD FOR IMPACT, BUT ONLY WITHIN THE HARD SCIENCES

Part of the study included a multivariate regression analysis that allowed us to analyze the relationship between interdisciplinarity and other key aspects of academic research, notably scientific impact and collaboration with industry. This is based on the idea that if there is a significant relationship between interdisciplinarity and key aspects of scientific performance, this is likely to affect academic researchers' incentives to engage in interdisciplinary research and must therefore be taken into account in the design of public policy to promote interdisciplinarity.

In general, we find evidence of a positive and significant relationship between interdisciplinarity and impact. In other words, the more interdisciplinary a publication is, the higher the level of impact it is likely to have. Thus, at least in the three research fields examined, interdisciplinary publications appear to be rewarded, and not penalized, in terms of their scientific performance.

Moreover, having one or more authors from the social sciences and humanities was associated with a lower impact. This is likely to be explained by the fact that the soft sciences generally receive fewer citations than the hard sciences. It does, however, have implications for the researchers seeking to publish results from collaboration between the hard and soft science: if they publish in social science and humanities journals, this is likely to have a negative effect on the scientific impact of any natural or technical scientists that collaborate with them.

In contrast, having one or more authors from private industry did not have any significant effect on the scientific impact of an article.

Publications that have both a high interdisciplinarity score and at least one author from the social sciences and humanities or from industry are associated with lower levels of scientific impact.

These findings indicate that there are substantial disincentives for university researchers to engage in interdisciplinary research collaboration with SSH or firm researchers or, in other words, precisely the type of interdisciplinarity that is aimed for in Horizon 2020.

Please refer to chapter 7 of this report for a full description of the results of the regression analysis.

KEY FINDINGS OF THE REGRESSION ANALYSIS

- A positive and significant relationship between interdisciplinarity and impact.
- Having one or more authors from the social sciences and humanities on a publication was associated with a lower impact.
- Having one or more authors from private industry did not have any effect on the scientific impact of an article.
- For interdisciplinary publications, having a co-author from the SSH or from industry was associated with lower scientific impact.

4 CASE STUDY: RESEARCH ON GENETICALLY MODIFIED FOODS

4.1 DANISH RESEARCH IN AN INTERNATIONAL PERSPECTIVE

Denmark is the most productive country worldwide, measured on the number of scientific publications per capita, in the field of research on genetically modified (GM) foods (cf. table 3). Denmark lags behind many of the 20 leading OECD countries in the field, however, when measured on the levels of interdisciplinarity and scientific impact, where Denmark is ranked, respectively, at number 20 and 18 (cf. tables 4 and 5).

TABLE 3: Scientific productivity within research on genetically modified foods, adjusted for population size

Source: DAMVAD, 2012, based on data from Web of Science. Population data derived from The CIA World Factbook

Rank	Country	Total no. of publications	Population (in millions)	No. of publications per million inhabitants
1	Denmark	186	5	37
2	Scotland	136	5	27
3	New Zealand	101	4	25
4	Switzerland	195	8	24
5	Netherlands	340	17	20
6	Belgium	166	10	17
7	England	730	52	14
8	Australia	278	22	13
9	Sweden	111	9	12
10	Canada	411	34	12
11	Germany	721	81	9
12	USA	2,651	314	8
13	France	530	66	8
14	Italy	381	61	6
15	Spain	245	47	5
16	South Korea	202	49	4
17	Japan	465	127	4
18	Brazil	140	206	1
19	China	536	1,343	0
20	India	160	1,205	0

TABLE 4: Scientific impact within research on genetically modified foods

Source: DAMVAD, 2012, based on data from Web of Science

Rank	Country	Total no. of publications	Total no. of citations	No. of citations per publication
1	USA	2,651	126,690	47.8
2	Italy	381	14,300	37.5
3	England	730	26,453	36,2
4	Germany	721	23,479	32.6
5	Netherlands	340	10,370	30.5
6	Japan	465	13,902	29.9
7	Switzerland	195	5,414	27.8
8	Scotland	136	3,716	27.3
9	France	530	14,396	27.2
10	Belgium	166	4,424	26.7
11	Australia	278	7,319	26,3
12	Canada	411	10,560	25,7
13	Sweden	111	2,697	24.3
14	New Zealand	101	2,289	22.7
15	Spain	245	5,337	21,8
16	South Korea	202	3,846	19.0
17	China	536	8,409	15.7
18	**Denmark**	**186**	**2,743**	**14.7**
19	Brazil	140	1,935	13.8
20	India	160	2,066	12.9

TABLE 5: Score on the interdisciplinary index within research on genetically modified foods

Source: DAMVAD, 2012, based on data from Web of Science

Rank	Country	Interdisciplinarity score
1	South Korea	0.19
2	Japan	0.18
3	France	0.18
4	Italy	0.17
5	Spain	0.17
6	China	0.17
7	Germany	0.17
8	USA	0.17
9	Belgium	0.16
10	Scotland	0.16
11	Sweden	0.16
12	Switzerland	0.16
13	Canada	0.16
14	India	0.16
15	Brazil	0.15
16	England	0.15
17	Netherlands	0.15
18	Australia	0.14
19	New Zealand	0.14
20	**Denmark**	**0.12**

4.2 A CLOSER LOOK AT THE DANISH RESEARCH COMMUNITY

The organization that has contributed the most (measured by volume of publications) to Danish research on genetically modified foods over the past decade is the University of Copenhagen, which has authored or co-authored 62 (that is, a third) of the 186 articles within the field. Aarhus University and the Technical University of Denmark are the second and third most significant contributors and, of these, the latter has received the highest average number of citations per article within the field, notably 23.9 citations per publications.

As a whole, private firms also constitute an important source of research in this field. These firms include large companies such as Chr. Hansen A/S, Novozymes and Danisco Biotechnology as well as a range of small and medium sized enterprises. With four publications, Chr. Hansen A/S has the most publications among the companies; with an average impact of 18,5 citations per article, the company also has an above average impact within the research field.

FIRMS THAT HAVE CONTRIBUTED TO PUBLISHED RESEARCH ON GENETICALLY MODIFIED FOODS

Alpharma
Bioneer
Chr. Hansen A/S
Danisco Biotechnology
Fluxome Sciences
LEO Pharma
Novozymes
NsGene Pipeline Biotech
Pixiegene
Rheoscience
Sejet Plant Breeding

All the major Danish contributors to research on genetically modified foods have equivalent average levels of interdisciplinarity.

A series of other research actors have also contributed to the field, but with less than ten publications in Web of Science indexed journals during the period of study.

TABLE 6: Danish organisations that contribute to research on genetically foods

Source: DAMVAD, 2012, based on data from Web of Science

Organization	No. of publications	Total no. of citiitions	No. of citiitions per publications	Interdisciplin-arity score
University of Copenhagen	62	736	11.9	0.14
Aarhus University	42	725	17.3	0.13
Technical University of Denmark	32	764	23.9	0.15
Private firms	18	215	11.9	0.15
University of Copenhagen Hospital	8	81	10.1	0.09
University of Southern Denmark	7	41	5.9	0.14
Odense University Hospital	5	39	7.8	0.11
Aarhus University Hospital	3	13	4.3	0.18
National research laboratories*	2	89	44.5	0.25
Danish Hydraulic Institute	1	33	33.0	0.10
Copenhagen Business School	1	3	3.0	0.02
University of Aalborg	1	0	0.0	0.13
Danish Agricultural Advisory Services	1	3	3.0	0.19
Technological Institute	1	1	1.0	0.20

* *Includes SSI, The National Institute for Health Data and Disease Control, and The Kennedy Center, National Research Center for Genetics, Visual Impairment and Mental Retardation.*

4.3 KEY FINDINGS FROM THE CASE STUDY

Interdisciplinary research primarily occurs among closely related disciplines

The bibliometric analysis shows that interdisciplinary research primarily occurs within the natural and technical sciences. A small subset of research in the field is, however, based on collaboration between the natural and technical sciences on the one hand and social sciences and humanities on the other; this research primarily concerns ethical issues related to GM foods. In fact, ethics are such a significant topic in research on GM foods that interdisciplinary research groups and committees have been established, including for example the aforementioned Centre for Bioethics and Risk Assessment (CeBRA). On a related note, the Nordic Committee on Bioethics promotes Nordic cooperation and exchange between relevant parties within bioethics. The Committee is funded by the Nordic Council of Ministers and organizes events and publishes publications within bioethics. Another example of research collaboration that spans the soft and hard sciences can be seen in the box below.

THE LINK BETWEEN GENETICS AND THE HISTORY OF SCIENCE

Thomas G. Jensen, is a professor and head of the Department of Biomedicine at Aarhus University. He leads a group which explores how the scientific field of genetics has evolved historically. The objective is to map the field of research in order to prevent knowledge in the field from being lost over time. The team is interdisciplinary, as it consists of both scientific historians and scientists within the field of genetics.

Across the various disciplines in the field, there is consensus that research on GM foods requires simultaneous breadth and depth. "Breadth" refers to the importance of engaging in boundary-crossing research that integrates relevant elements from various disciplines. Meanwhile, "depth" refers to the need for strong monodisciplinary knowledge and research methods. In other words, respondents argue that good interdisciplinary research comes from researchers with a solid grounding in their respective disciplines.

There is funding for interdisciplinary research – but reviewer panels should be interdisciplinary

Adequate funding appears to be available for interdisciplinary research in GM foods, both in Denmark and in the EU. However, it is stressed that the panels that review interdisciplinary research applications should themselves have an interdisciplinary background that enables them to fully assess the potential value and quality of interdisciplinary applications.

Academic barriers to interdisciplinarity

When it comes to GM foods, it can be difficult to get interdisciplinary work published in more prestigious journals, as these are often focused on a particular discipline. According to Professor Peter Sandøe, this has the unfortunate effect that "many good researchers will not be motivated to engage seriously in interdisciplinary research."

Some respondents also noted, however, that journals seem to be able to renew themselves and that it is likely that interdisciplinary research will, over time, gain a better foothold within the more prestigious journals.

Nonetheless, some respondents from the field have experienced that interdisciplinary work is not as highly recognized by peers as monodisciplinary research. Such barriers can lead researchers to choose monodisciplinary research projects over interdisciplinary ones.

Facilitating interdisciplinary research

The respondents made several suggestions as to how interdisciplinary research can successfully be undertaken. The most experienced respondents within interdisciplinary research emphasized the importance of creating an environment where scientists can speak openly with each other. *"To foster such environments, there must be mutual trust among the participants, or else scientists may not feel comfortable speaking openly in the forum, as they can feel intimidated by scientists from other disciplines,"* explains Kate Millar, Dr and Director of the Centre for Applied Bioethics at University of Nottingham. She emphasizes that it takes time to build the spaces needed for fruitful interdisciplinary research to take place.

She emphasizes that it takes time to build the spaces needed for fruitful interdisciplinary research to take place.

Professor Peter Sandøe explains how the personal commitment of the individual team members to interdisciplinarity is crucial: *"It requires determination and will from all partners in the project for interdisciplinary research to succeed. If these elements are present, it can be very exciting and work well. Unfortunately, it is often seen that from the start intentions are good, but that later in the process in the light of limited resources timewise the planned interdisciplinary papers end up never getting published."*

Companies promote problemoriented, interdisciplinary research

The bibliometric analysis indicated that scientific publications, which were authored or co-authored by researchers from industry generally have significant scientific impact. Moreover, industry publications also had a higher overall level of interdisciplinarity, compared to all Danish publications in the field.

The case study indicates that this may be because companies engage in research of a more problemoriented, applied character: they take as their point of departure not a given discipline but a specific problem that needs to be solved.

A respondent from Chr. Hansen A/S explained that due to the highly critical public debate on GM foods in the late 1990s, they chose to rethink their research efforts to provide the basis for a more informed (and open) public opinion towards GM foods. In its own words, the company therefore performs research using GM methods not for product development, but for knowledge development, which implies that their research within GM food facilitates a means to better natural food products.

Also, the organization of companies can have a significant impact on their ability to undertake interdisciplinary research, as they are most often organized according to business areas. This may foster more work across disciplines than at traditional research institutions, which are organized according to disciplines. Moreover, firms do not have to stay as "true" to the methods and assumptions of a given discipline as academic researchers often must in order to get published in prestigious journals.

Most of the research conducted in the industry is undertaken in collaboration with scientists from universities or other public research institutions. Thus, there seems to be a strong relationship between companies and public research institutions within research on GM foods, and public scientists also reported that companies play an important role in the GM foods research community.

Companies in the industry contribute to scientific publications and conferences for several reasons. This interaction provides firms with a platform for engaging with the research community and thus for potential collaboration. This interaction can go both ways: companies contact academic researchers that they identified in their search for interesting publications, but companies are also approached by public scientists based on their scientific publications.

Interestingly, the companies also publish their papers as a way to perform quality control of their research, based on the citations and responses that they receive within the research community. Furthermore, scientific publications also often opens the door for companies to academic conferences, which provide firms with both a platform on which to present their activities and results and with an opportunity to engage with the research community and identify possible future research collaborators.

INTERDISCIPLINARY ORGANIZATIONAL STRUCTURE AT CHR. HANSEN A/S

Chr. Hansen A/S produces bioscience based ingredients for the food, health and animal feed industries. Research and development activities at Chr. Hansen A/S are most often performed in teams with representation from many different disciplines. Projects can both be multi-and interdisciplinary, depending on the objectives of the individual project.

Eric Johansen, Associate Vice President of Science at Chr. Hansen A/S, explains that an interdisciplinary approach is an integral part of the company's approach to innovation. R&D projects can for example include microbiologists, bioanalysts and experts on robot technology. Moreover, business experts are always involved in order to strengthen the business case in a project; they therefore need to understand the "language" of the other, "hard science" disciplines, which is often a challenge.

5 CASE STUDY: RESEARCH ON METABOLISM AND OBESITY

5.1 DANISH RESEARCH IN AN INTERNATIONAL PERSPECTIVE

Overall, metabolism and obesity are areas in which Danish research is doing very well. Denmark is the most productive country measured on the number of scientific publications, corrected for the number of inhabitants (cf. table 7). In addition, Danish research has the fourth highest impact of the leading 20 OECD countries in this field of research (cf. table 8).

Furthermore, Danish research on metabolism and obesity comes in as number eight when ranked on its level of interdisciplinarity (cf. table 9). However, it should be noted that all the 20 OECD countries score very similar levels of interdisciplinarity, ranging from 0.12 to just 0.13 on a scale from 0 to 1.

TABLE 7: Scientific productivity within research on metabolism and obesity, adjusted for population size

Source: DAMVAD, 2012, based on data from Web of Science. Population data derived from The CIA World Factbook

Rank	Country	Total no. of publications	Population (in millions)	No. of publications per million inhabitants
1	**Denmark**	**738**	**5**	**147.6**
2	Finland	441	5	82.2
3	Sweden	604	9	67.1
4	Norway	304	5	60.8
5	Australia	830	22	37.7
6	Switzerland	265	8	33.1
7	Netherlands	526	17	30.9
8	Canada	883	34	26.0
9	England	1,283	52	24.7
10	Greece	266	11	24.2
11	USA	6,834	314	21.8
12	Italy	848	61	13.9
13	Spain	638	47	13.6
14	Germany	861	81	10.6
15	France	647	66	9.8
16	Japan	601	127	4.7
17	South Korea	229	49	4.7
18	Turkey	220	80	2.8
19	Brazil	433	206	2.1
20	China	354	1,343	0.3

TABLE 8: Scientific impact within research on metabolism and obesity

Source: DAMVAD, 2012, based on data from Web of Science

Rank	Country	Total no. of publications	Total no. of citations	No. of citations per publication
1	Finland	411	15,407	37.5
2	USA	6,834	194,902	28.5
3	Sweden	604	16,921	28.0
4	**Denmark**	**738**	**18,495**	**25.7**
5	England	1,283	31,982	24.9
6	France	647	15,821	24.5
7	Netherlands	526	11,474	21.8
8	Canada	883	18,703	21.2
9	Italy	848	17,903	21.1
10	Australia	830	17,396	21.0
11	Norway	304	6,167	20,.3
12	Greece	266	5,285	19.9
13	Switzerland	265	5,156	19.5
14	Germany	861	16,033	18.6
15	Spain	638	10,771	16.9
16	Japan	601	8,566	14.3
17	China	354	4,925	13.9
18	Brazil	433	4,207	9.7
19	South Korea	229	2,091	9.1
20	Turkey	220	1,753	8.0

TABLE 9: Score on the interdisciplinarity index within research on metabolism and obesity

Source: DAMVAD, 2012, based on data from Web of Science

Rank	Country	Interdisciplinarity index
1	Japan	0.13
2	Switzerland	0.13
3	Finland	0.13
4	England	0.13
5	USA	0.13
6	Spain	0.13
7	Germany	0.13
8	**Denmark**	**0.12**
9	Canada	0.12
10	France	0.12
11	Greece	0.12
12	Australia	0.12
13	China	0.12
14	Turkey	0.12
15	South Korea	0.12
16	Netherlands	0.12
17	Italy	0.12
18	Sweden	0.12
19	Brazil	0.12
20	Norway	0.12

5.2 A CLOSER LOOK AT THE DANISH RESEARCH COMMUNITY

The organizations that have contributed the most (measured by volume of publications) to Danish research on obesity and metabolism over the past decade are hospitals and university hospitals, the University of Copenhagen and other research institutions.

University hospitals include 10 Danish university hospitals; the university hospital associated with the University of Copenhagen has authored 101 of the 262 university hospital publications. Another significant contributor, the Aarhus University Hospital, has published 82 publications in the field during the period of study.

It is interesting to note that Hvidovre University Hospital has contributed with 6,1 percent (16) of the university hospital publications in the field, but accounts for 20,5 percent (1.308) of the citations, averaging 81,75 citations per publication.

Research performed at 19 other (i.e. non-university) hospitals generally has a high impact. For example, Aalborg Hospital has published nine articles with an average of 63,2 citations, which is more than double the average number of citations to publications authored or co-authored by industry.

TABLE 10: Danish organizations that contribute to research on metabolism and obesity

Source: DAMVAD, 2012, based on data from Web of Science

Organization	No. of publications	Total no. of citiitions	No. of citiitions per publications	Interdisciplinarity score
University hospitals	261	6,375	24.3	0.12
University of Copenhagen	137	3,650	26.1	0.13
Other research institutions*	113	3,048	27.0	0.11
Hospitals	72	2,207	30.7	0.13
University of Southern Denmark	60	1,005	16.0	0.11
Aarhus University	44	1,045	22.2	0.12
Private firms	32	925	28.9	0.13
National research laboratories**	11	151	13.7	0v12
Technical University of Denmark	7	56	8.0	0.10
Aalborg University	1	33	33.0	0.09

** Incl.: Danish Cancer Society, the Hagedorn Research Institute, the Steno Diabetes Center, Team Denmark and WHO.*

** Incl.: National Institute of Occupational Health, National Research Centre for the Working Environment and SSI, The National Institute for Health Data and Disease Control.*

Private firms also make a contribution to research in this field. These firms are however dominated by Novo Nordisk, which has generated approximately half of the company publications identified in this study. Publications by Novo Nordisk have an average of 31,1 citations per article, which is higher than the average number of citations per publication within the research field.

Publications by hospitals and private firms have the highest average impact, along with publications from the University of Copenhagen. Moreover, these organizations also have the highest average degree of interdisciplinarity.

FIRMS THAT HAVE CONTRIBUTED TO PUBLISHED RESEARCH ON METABOLISM AND OBESITY

Center for Clinical & Basic Research
Cyncron
H. Lundbeck
Jørgensen Clinic for Plastic Surgery
Kobenhavns Praktiserende Laegers Lab.
Medical Center Charlottenlund
NeuroSearch
Nordic Bioscience
Novo Nordisk
Nutri Pharma
Rheoscience
Sven Bittmann Clinic for Plastic Surgery

5.3 KEY FINDINGS FROM THE CASE STUDY

Long tradition of combining disciplines when aiming to address obesity-related challenges

Research within metabolism and obesity has a long tradition of combining disciplines. The very nature of the research field motivates an interdisciplinary approach, as it has become evident that, in order to fight obesity, a change in human behavior and wellbeing is as important as getting the right kind of medical advice and treatment.

The recognition that multiple disciplines are required to fight obesity is hence a common and widespread perception within the research field, and has been so for several years. Thus, it is emphasized that a significant amount of collaboration occurs across the hard and soft sciences. However, collaboration among closely related disciplines is still most common.

Professor Arne Astrup, head of the Department of Human Nutrition, Copenhagen University, explains that *"If we wish to understand what causes obesity to occur, and to get better at treating and preventing obesity, it is necessary to have participation from a great variety of disciplines across the wet and dry sciences. The importance of translating scientific results into dietary guidelines that will actually be of relevance to the individual person has been crucial to the research within obesity. In obesity research, we also collaborate with the kitchens at hospitals and with celebrity chefs such as Claus Meyer to invent dishes that are pleasant to eat at the same time as they are in accordance with a specific diet. Hence, we have come to the conclusion that if we wish to cure obesity, we need to collaborate across different disciplines and professional backgrounds."*

Industry and hospitals play an important role

The bibliometric analysis has revealed that companies have both a high degree of interdisciplinarity and a high impact in their publications. The role of companies in research differs, ranging from providing inputs to academic research to actively contributing to driving the research forward.

A "Novo Nordisk effect" is apparent in this case study. The company participates in almost half of all publications in the field that are co-authored by Danish firms. Novo Nordisk participates in a substantial amount of research with a broader perspective than merely the development and testing of new drugs. Novo Nordisk also supports basic (mostly interdisciplinary) research related to obesity and diabetes. This has helped build strong links to universities and other research institutions, and thus stimulated the participation of Novo Nordisk in various academic research projects within obesity.

Like industry, hospitals have a high degree of interdisciplinarity and high impact in their publications in this field. In their organizational structure, hospitals are predisposed to interdisciplinarity, as they are often organized around themes (such as obesity) and with multiple disciplines represented within each of those themes.

Moreover, Claus Dethlefsen, Department of Clinical Medicine and Cardiology, Aalborg Hospital, argues that, because clinical research results may lead to changes in clinical practice, *"Compared to universities, hospitals have a different culture regarding the publication of research. There is a greater focus on the quality and reliability of the published results. There seems to be more patience to reach robust results, than what is predominant at universities."*

Interdisciplinarity and academic prestige

Overall, academics researchers experience that interdisciplinary research creates better research, thus enhancing their ability to publish in the prestigious journals. It is stressed that medical journals are often concentrated on a topic (such as obesity or diabetes), which makes it easier to combine different methods and disciplines.

Moreover, the importance of such combination seems to be increasing. A substantial number of key journals are enthusiastic about interdisciplinary research that cuts through "old perceptions", as put by one respondent. However, interdisciplinary research places great demand on dissemination as methods and results must be communicated beyond the individual discipline and without the presumption of prior knowledge among the audience.

Different disciplinary traditions tend, however, to constitute barriers to publication of interdisciplinary research results. As it is not always possible or desirable to target interdisciplinary journals, scientists have to choose which journals to publish early on, in the research process, so that they may target their research and make it more palatable for the chosen journal. In addition to this, there are different traditions for crediting authors across the disciplines, which may also pose a minor challenge to the publication of interdisciplinary research.

Interdisciplinary obesity platforms are catalysts for interdisciplinary research

Within research on metabolism and obesity, it is evident that strong research platforms play an important role as an enabler of research across disciplines. Examples of such platforms include The Novo Nordisk Foundation Center for Basic Metabolic Research based at the University of Copenhagen, a Nordic Center of Excellence Program on Food, Nutrition and Health financed by Nordforsk, and the OPUS Center based at the University of Copenhagen with financial support from the Nordea Foundation. These platforms provide an opportunity for scientists, hospitals and industry to meet around a common theme, but across disciplines. This serves as a point of departure for future projects on metabolism and obesity research that combine different perspectives and disciplines in order to solve a common problem.

Marianne Uhre Jakobsen, Associate Professor at the Department of Public Health, Aarhus University, states that *"It is important for research to have a platform concentrated on common research questions with the participation from a variety of different disciplines. A platform fosters new research ideas when there is openness among the participating parties and there is a broad representation of disciplines from different institutions. If interdisciplinarity should be further enhanced, common platforms is the way forward."*

6 CASE STUDY: RESEARCH ON RENEWABLE ENERGY

Denmark holds a strong position within research on renewable energy, measured both on the number of scientific publications per capita and scientific impact, where Denmark ranks first and second, respectively, among the 20 leading OECD countries in the research field (cf. tables 11 and 12). Denmark ranks somewhat lower on the degree of interdisciplinarity, namely at no. 14 (cf. table 13).

TABLE 11: Scientific productivity within research on renewable energy, adjusted for population size

Source: DAMVAD, 2012, based on data from Web of Science. Population data derived from The CIA World Factbook

Rank	Country	Total no. of publications	Population (in millions)	No. of publications per million inhabitants
1	**Denmark**	**312**	**5**	**62.4**
2	Sweden	395	9	43.9
3	Switzerland	220	8	27.5
4	Greece	276	11	25.1
5	Netherlands	319	17	18.8
6	Canada	614	34	18.1
7	Australia	374	22	17.0
8	England	801	52	15.4
9	Taiwan	259	23	11.3
10	Spain	513	47	10.9
11	USA	3,316	314	10.6
12	Germany	812	81	10.0
13	Italy	541	61	8.9
14	Turkey	691	80	8.6
15	France	459	66	7.0
16	South Korea	306	49	6,2
17	Japan	514	127	4.0
18	Brazil	389	206	1.9
19	China	989	1,343	0.7
20	India	672	1,205	0.6

TABLE 12: Scientific impact within research on renewable energy

Source: DAMVAD, 2012, based on data from Web of Science

Rank	Country	Total no. of publications	Total no. of citations	No. of citations per publication
1	USA	3,316	64,297	19.4
2	**Denmark**	**312**	**5,419**	**17.4**
3	Netherlands	319	5,472	17.2
4	Switzerland	220	3,757	17.1
5	Germany	812	12,861	15.8
6	England	801	12,373	15.4
7	Turkey	691	9,571	13.9
8	Sweden	395	5,341	13.5
9	Australia	374	5,028	13.4
10	France	459	5,990	13.1
11	Canada	614	7,945	12.9
12	India	672	8,110	12.1
13	Italy	541	6,518	12.0
14	Japan	514	6,121	11.9
15	Spain	513	5,523	10.8
16	Greece	276	2,683	9.7
17	China	989	8,514	8.6
18	Taiwan	259	2,035	7.9
19	Brazil	389	2,966	7.6
20	South Korea	306	1,985	6.5

TABLE 13: Score on the interdisciplinarity index within research on renewable energy

Source: DAMVAD, 2012, based on data from Web of Science

Rank	Country	Interdisciplinarity index
1	South Korea	0.18
2	Taiwan	0.17
3	China	0.17
4	Italy	0.17
5	France	0.17
6	Switzerland	0.17
7	Spain	0.17
8	Turkey	0.17
9	Japan	0.16
10	Greece	0.16
11	Canada	0.16
12	USA	0.16
13	Australia	0.16
14	**Denmark**	**0.16**
15	England	0.16
16	Sweden	0.16
17	Germany	0.16
18	India	0.15
19	Brazil	0.15
20	Netherlands	0.15

6.1 A CLOSER LOOK AT THE DANISH RESEARCH COMMUNITY

The organizations that have contributed the most (measured by volume of publications) to Danish research on renewable energy over the past decade are the Technical University of Denmark, Aalborg University and Aarhus University.

Private firms are also an important contributor to this research field, having authored or co-authored 14 percent of all publications identified in this study. This relatively high degree of private involvement in scientific publications emphasizes the important role that firms play in the research community within renewable sources of energy. Publications by private firms are moreover distributed across a wide range of companies, illustrating that this research fields covers a number of different subfields, ranging from biofuels to solar energy to fuel cell technology.

It is interesting to note that Haldor Topsøe has contributed to five publications which have, however, received a total of 409 citations (or an average of 81.8 citations per publication). This high level of impact is partly due to the fact that Haldor Topsøe is a significant contributor to basic nanotechnological research (and basic research generally receives more citations than applied research).

TABLE 14: Danish organizations that contribute to research on renewable energy

Source: DAMVAD, 2012, based on data from Web of Science

Organization	No. of publications	Total no. of cititions	No. of cititions per publications	Interdisciplinarity score
Technical University of Denmark	91	1,735	19.1	0.14
Aalborg University	72	1,450	20.1	0.15
Private firms	45	846	18.8	0.16
Aarhus University	41	464	11.3	0.16
University of Copenhagen	23	513	22.3	0.15
Other research institutions*	14	284	20.3	0.15
University of Southern Denmark	8	40	5.0	0.15
Roskilde University	6	28	4.7	0.12
National research laboratories**	5	36	7.2	0.11
Hospitals	4	16	4.0	0.16
Copenhagen Business School	3	7	2.3	0.14

** Incl.: Danish Institute for Government Research AKF, Danish Institute for International Studies, Danish Meteorological Institute, Danish Research Center for Organic Farming, European Environmental Agency, Geological Survey of Denmark and Greenland - GEUS, Nordic Agency for Development and Ecology (NORDECO) a.o.*

*** Incl.: National Institute of Occupational Health and National Research Centre for the Working Environment.*

FIRMS THAT HAVE CONTRIBUTED TO PUBLISHED RESEARCH ON RENEWABLE ENERGY

AgroTech
Alfa Laval
Arla Foods
Bolding & Burchard
Copenhagen Energy
COWI
Danish Power Systems
Det Norske Veritas
DONG Energy
Elkraft Syst
EMD International
Energinet Dk
Geographic Resource Analysis & Science
Haldor Topsøe Research Labs.
Inbicon
IRD Fuel Cells
Kemira Miljø
Novo Nordisk
Novozymes
PlanEnergi
Rambøll
Topsøe Fuel Cell
Vestas
Wave Draon

6.2 KEY FINDINGS FROM THE CASE STUDY

The high productivity and impact of Danish renewable energy research is the combined result of many years of scientific research, a persistent political focus on renewable energy, and companies' continuous research and development efforts.

Interdisciplinarity plays a key role – but mainly among closely related disciplines

The bibliometric analysis has indicated a relatively low degree of interdisciplinarity in research within renewable energy. However, interdisciplinarity is seen as a prerequisite for energy research and hence practiced among scientists. This is based on the perception that nature and society are not organized according to disciplines, and a combination of technologies is therefore needed to get the right understanding and provide new perspectives and solutions for the renewable use of energy. An example of this is research on how electric cars can be used as storage for excess energy using battery technology in a way which is both economically sound and in tune with consumers' needs and preferences.

Solving energy problems requires combining different disciplines, though energy research mostly combines closely related disciplines, particularly within the technical sciences. However, the study has also identified examples of research projects that involve the SSH, notably economics.

Professor Gert Tinggaard Svendsen, Department of Political Science, Aarhus University, explains that *"A hot topic within energy research is climate policy, especially regarding the use of renewable energy as an alternative to fossil fuels. This kind of research requires a strong combination of technical insights into the scope of the new technologies, their economic forecasts, and an understanding of how the political system operates. Thus it is hard not to work in this field without taking an interdisciplinary approach."*

Understanding the interplay between the technological developments within renewable energy and viable business models, for instance in relation to electric cars and solar cells, is becoming increasingly important and calls for an interdisciplinary approach.

Interdisciplinarity and academic prestige

A closer look at the bibliometric analysis reveals that the publications that have the highest degree of interdisciplinarity do not have the highest impact. Some respondents suggested that established journals have not yet fully adapted to interdisciplinary articles and thus recognized their value to the research field. In fact, the case study indicates that interdisciplinary energy research can have difficulties getting accepted in established journals, which often have a more monodisciplinary focus. Thus, interdisciplinary articles often get published in newer journals that tend to have a more outspoken focus on interdisciplinary research but also lower scientific impact.

Some respondents noted that more established journals occasionally experiment with interdisciplinary articles, for example in special issues; however, interdisciplinary articles often do not transcend to the regular issues.

The role of industry research

The bibliometric analysis also showed that a substantial number of companies contribute to research on renewable energy. The study revealed that energy research tends to be more applied than basic in nature, which may explain why industry research plays a significant role. Collaboration on research projects is to a great extent initiated by companies that bring a specific idea or research problem to academic scientists as a starting point for collaboration. Conferences and other less formal networks – where ideas are shared and future projects find their way – also provide important points of contact between industry and academia.

The bibliometric analysis also revealed that industry research generally has a high degree of interdisciplinarity compared to university research; which may be explained by the fact that companies are driven by a need to solve specific problems, which forces them to combine inputs from a variety of sources and disciplines.

Interviews also suggest that much private energy research is undertaken in collaboration with public research institutions, and that these collaborations also tend to be problemoriented and therefore need an interdisciplinary approach. The collaborations are moreover driven by strong ties between industry and university researchers that result partly from the fact that industry researchers often maintain an affiliation with the university where they did their research training.

7 ANALYSIS OF THE RELATIONSHIP BETWEEN INTERDISCIPLINARITY AND IMPACT

This chapter presents the results of a regression analysis that investigates the relationship between interdisciplinarity and other key aspects of academic research, notably scientific impact and collaboration with industry.

The motivation for this analysis is that if there is a significant relationship between interdisciplinarity and key aspects of scientific performance, then this is likely to affect academic researchers' incentives to engage in interdisciplinary research and must therefore be taken into account in the design of public policy to promote interdisciplinarity.

The analysis is based on the bibliometric data collected as described in chapter 2 of this report. The unit of analysis is publications, i.e. Danish articles identified in the three selected research fields.

The data set included 1,236 publications authored by at least one Danish scientist during the period 2000 to 2011. Publications had to have at least one reference to another publication in a Web of Science indexed journal in order to be included in the regression analysis.[8]

A total of 739 observations (i.e. publications) were included in the model and distributed across the three research areas as follows:

- Genetically modified foods: 186 publications of which we could identify 122 unique publications with at least one reference to other publications in Web of Science indexed journals.
- Metabolism and obesity: 738 of which we could identify 369 unique publications with at least one reference to other publications in Web of Science indexed journals.
- Renewable energy: 312 publications of which we could identify 262 unique publications with at least one reference to other publications in Web of Science indexed journals.

The relationship between scientific impact and the level of interdisciplinarity of a research article was modeled collectively for the three research areas in order to ensure that the number of observations is sufficiently high to allow for a robust analysis.

7.1 VARIABLES

The dependent variable is the ***scientific impact*** [Impact] of publications as indicated by the number of citations in scientific journals indexed in Web of Science to these publications.

The **independent variable** is the ***level of interdisciplinarity*** [Interdisciplinarity] of each publication, as indicated by its score on the interdisciplinarity index.

We also include a number of control variables. To control for the effect of differences in citation patterns (and therefore impact) across different research areas, we include ***a dummy variable for each of the three research areas*** *[Genetically modified foods, Obesity and metabolism, and Renewable energy].* Moreover, we control for the ***number of authors*** *[No. of authors]* and the ***age of the publication*** *[Age of publication],* as publications that have more authors and that are older tend to have

[8] *This is because such references are central to the calculation of the interdisciplinarity index, since the measure of cognitive distance between subjects area requires publications to be in Web of Science indexed journals (that have been assigned subject areas).*

high citation numbers. Finally, we include a control for the ***number of subject areas*** *[No. of subject areas]* assigned to the scientific journal in which a given publication appeared. These subject areas are included to account for the potential bias that a high number of subject areas might result in a higher interdisciplinarity score.

We also include ***a dummy variable identifying SSH publications*** *[SSH-Authors],* i.e. articles that have been authored by at least one researcher from the social sciences or humanities. The identification of authors from the social sciences and humanities was based on the institutional and department affiliation of the authors.

Finally, the model includes ***a dummy variable identifying industry publications*** *[Firm-Authors]*, i.e. articles that have been authored by at least one researcher from Danish companies. Firm authors were identified based on their affiliation with a company name and address.

7.2 DESCRIPTIVE STATISTICS

Tables 15 and 16 present the descriptive statistics on the variables included in the model and the results of an initial correlation analysis of the variables.

TABLE 15: Descriptive statistics

Source: DAMVAD, 2012

Variable	Obs.	Mean	Standard deviation	Min.	Max.
Interdisciplinarity	739	0.13	0.06	0	0.34
Impact	739	21.14	40.36	0	392
No. of authors	739	5.13	7.69	1	104
Age of publication	739	4.59	3.15	0	12
No. of subject areas	739	2.63	1.78	1	12

Variable	Percentage of total population	Obs.
Genetically modified foods	16.51 pct.	(122)
Metabolism and obesity	49.80 pct.	(369)
Renewable Energy	33.69 pct.	(249)
SSH-Authors	5.41 pct.	(40)
Firm-Authors	11.37 pct.	(84)

TABLE 16: Results of the Pearson correlation

Source: DAMVAD, 2012, N.B. Pearson correlation scores marked by (**) indicates significance at least at the five percent level

		Impact	Interdi-scipli-narity	No. of authors	Age of publica-tion	No. of subject areas	Geneti-cally modified foods	Metabo-lism and obesity	Renew-able energy	Firm-Authors
		1	2	3	4	5	6	7	8	9
Impact	1									
Interdisciplinarity	2	0.0523								
No. of authors	3	0.0694	-0.0846**							
Age of publication	4	0.391**	-0.0578	-0.1305**						
No. of subject areas	5	-0.0329	0.1068**	0.1423**	-0.0734**					
Genetically modified foods	6	-0.0408	0.0587	-0.1116**	0.2444	-0.0161				
Metabolism and obesity	7	0.0865**	-0.1963**	0.3183**	-0.0029	0.0239	-0.4431**			
Renewable energy	8	-0.0595	0.1616**	-0.2492**	-0.1888**	-0.0126	-1.0266**	-0.0126**		
Firm-Authors	9	-0.0036	0.072	-0.0679	0.0309	0.1688**	0.0362	-0.1354**	0.1148**	
SSH-Authors	10	-0.0344	-0.1183**	-0.0638	0.0211	0.0534	0.1998**	-0.1308**	-0.0185	-0.0479

Model specification

Since the dependent variable is a count variable, a negative binomial regression model was chosen. Subsequent tests for fit of fitted model to either a binomial or a regular poisson distribution showed a significant fit between the observed distribution and the binomial distribution. In order to handle issues regarding multicollinearity when modeling the effect of different author affiliations, a natural logarithmic transformation is made for the independent variable, the level of interdisciplinarity. Moreover, all modeling is performed using the STATA robust options to handle heteroscedasity. Finally, models have tested negative for collinearity.

Results

Table 17 shows the results of a series of models exploring the relationship between interdisciplinarity and scientific impact while controlling for the research area and a set of basic control variables that are likely to influence the level of interdisciplinarity.

Model 1 forms the baseline model for the subsequent models and shows that the level of impact for a given article is positively and significantly influenced by the level of interdisciplinarity. As expected, it also shows that the age of the publication and the number of authors both have a positive and significant effect on the impact of an article.

Model 2 shows a significant positive effect of the research area of metabolism and obesity on the impact of the publication. This suggests that publications in metabolism and obesity research may generally score higher impact than publications from the other two research fields. The opposite case holds true for publications on genetically modified foods, which are significantly and negatively associated with article impact. There is no significant relationship between being from the field of research on renewable energy and the overall impact of a publication.

TABLE 17: Analysis of the relationship between interdisciplinarity and impact

*Source: DAMVAD, 2012, N.B. Levels of significance: * p<0.1, ** p<0.05, *** p<0.01*

	Model 1	Model 2	Model 3	Model 4
Interdisciplinarity score	3.275***	3.772***	3.537***	3.133***
	[0.940]	[0.942]	[0.927]	[0.942]
Metabolism and obesity		0.256**		
		[0.118]		
Genetically modified foods			-0.629***	
			[0.129]	
Renewable energy				0.086
				[0.123]
No. of authors	0.033***	0.026***	0.031***	0.035***
	[0.010]	[0.010]	[0.009]	[0.010]
Age of publication	0.350***	0.349***	0.366***	0.352***
	[0.022]	[0.022]	[0.021]	[0.022]
No. of subject areas	-0.020	-0.018	-0.022	-0.021
	[0.031]	[0.030]	[0.030]	[0.032]
Constant	0.475**	0.312	0.469**	0.447**
	[0.202]	[0.210]	[0.196]	[0.209]
lnalpha Constant	0.365***	0.356***	0.333***	0.364***
	[0.061]	[0.060]	[0.061]	[0.061]
Pseudo LL	-2701.933	-2698.697	-2690.763	-2701.600
No. of observations	740	740	740	740
Wald-Chi2	277.0895***	282.9694***	316.2172***	278.7576***

Table 18 shows the results of a series of models examining the relationship between interdisciplinarity and scientific impact, when a dummy for the presence of authors from either the SSH or industry is included.

The analysis indicates that having one or more authors from the SSH is negatively and significantly associated with impact (Model 3), while there is no effect on impact from having industry authors on a publications (Model 2). Testing for the effect of interacting the two kind of authors with the level of interdisciplinarity reveals that for publications that both have a high level of interdisciplinarity and one or more SSH authors on the team are penalized with a negative effect on impact (Model 4). The model also shows that even when controlling for the influence of SSH authors, interdisciplinarity is still positively and significantly associated with impact (Model 4).

For firm affiliated authors, the picture is similar: the interaction of high interdisciplinarity and the presence of one or more industry authors has significant and negative effect on the impact of an article. Moreover, when controlling for firmaffiliated authors, we still find that the level of interdisciplinarity is significantly and positively associated with the scientific impact of an article (Model 2).

TABLE 18: Analysis of the relationship between interdisciplinarity and impact – with interaction effects

*Source: DAMVAD, 2012, N.B. Levels of significance: * p<0.1, ** p<0.05, *** p<0.01*

	Model 1	Model 2	Model 3	Model 4
Ln (Interdisciplinarity)	0.443***	**0.494*** **	0.413***	**0.438*** **
	[0.105]	[0.110]	[0.107]	[0.108]
No. of authors	0.033***	0.033***	0.032***	0.032***
	[0.010]	[0.010]	[0.010]	[0.010]
Age of publication	0.349***	0.349***	0.351***	0.347***
	[0.022]	[0.022]	[0.022]	[0.022]
No. of subject areas	-0.022	-0.021	-0.019	-0.018
	[0.033]	[0.034]	[0.031]	[0.031]
Firm-Authors	0.059	**-1.007**		
	[0.169]	[0.645]		
Ln(Interdisciplinarity)*Firm-Author		-0.502*		
		[0.289]		
SSH-Authors			**-0.475****	-2.447**
			[0.225]	[1.203]
Ln(Interdisciplinarity)*SSH-Author				**-0.794**
				[0.496]
Constant	1.856***	1.961***	1.807***	1.877***
	[0.260]	[0.266]	[0.261]	[0.264]
Lnalpha constant	0.359***	0.354***	0.352***	0.349***
	[0.062]	[0.063]	[0.061]	[0.061]
Pseudo LL	-2682.428	-2680.954	-2680.178	-2678.886
No of Obs	736	736	736	736
Wald-Chi2	272.4169***	273.9707***	286.1051***	291.3326***

8 RECOMMENDATIONS

In conclusion, interdisciplinary research does not occur to the extent that society would like it to occur, because a number of barriers make it less attractive for academic researchers and companies to engage in.

First, both the process and the outcomes of interdisciplinary research are highly uncertain, because interdisciplinarity involves venturing into unchartered territory. This makes it less attractive both to firms that seek a financial return on their investments in research, and to academic researchers, whose scarce time and resources must be spent efficiently, for instance generating scientific publications.

Second, interdisciplinary research requires the development of a common "language" and common research methods that allow the participants to engage in joint research. It also requires representatives of all participating disciplines to be involved in the initial definition of the research problem and design of the research project. Such collaboration is both time-consuming and demanding.

Third, it can be difficult to find collaborators, as researchers typically have strong professional ties within their own disciplines, but not to other disciplines. Thus, researchers often lack both insight and networks into other research fields, which makes it difficult to identify and establish interdisciplinary collaboration.

However, our findings that interdisciplinary publications are likely to have higher scientific impact also suggest that there are strong incentives toward interdisciplinarity that can help outweigh the uncertainty and costs associated with boundary-spanning research.

Nonetheless, because of these aforementioned barriers, public policies that encourage and support interdisciplinary research are necessary to ensure that a societally desirable level of interdisciplinary research occurs. This is especially true for interdisciplinary research that spans the hard and soft sciences.

It is important to stress, however, that interdisciplinarity is a mean to an end, and not an end itself. Policies to stimulate interdisciplinary research must therefore be designed to mitigate barriers to interdisciplinarity where greater interdisciplinary research collaboration can help address major societal challenges without having negative unintended effects on the direction or quality of academic research.

Public programs that encourage interdisciplinary research that does not add value or that do not take barriers to interdisciplinary research into consideration are likely to lead to "symbolic" interdisciplinarity alone, i.e. projects which are interdisciplinary on paper but not in practice.

In addition, our case studies indicate that there is a division of labor in interdisciplinary research among various actors in the research system, notably among universities and firms but also hospitals and applied research institutions. The universities are more monodisciplinary in their nature because they have a responsibility for ensuring development of specialized knowledge. The firms, hospitals and applied research institutions are more interdisciplinary because the research produced there are more problem-oriented. To effectively promote interdisciplinary research, public policy must consider and support this division of labor – or seek to alter it, in those cases, where the lack of interdisciplinarity is due to a lack of resources, willingness or incentives to engage in it.

For example, our study suggests that collaboration with industry can promote greater problemorientation in academic research, provided that firms are brought to bear on the definition of joint research problems, goals and methods at the start of the collaboration.

Moreover, good interdisciplinary research builds on strong disciplinary foundations. Thus, interdisciplinary research is an important supplement (and not an alternative) to research, which is anchored in specific scientific disciplines.

In view of the substantial barriers to interdisciplinary research relative to multidisciplinary research – and the penalties that it may involve for particularly university scientists – it is also important to make a careful assessment of the circumstances under which interdisciplinarity will contribute significant value added for society, for example as compared to multidisciplinary research.

Finally, the case studies pointed to a number of key barriers to interdisciplinary research. They also suggested a number of possible means of overcoming these barriers; the most important of these potential remedies are described in table 19.

REFLECTIONS ON THE METHODOLOGY

The bibliometric method for measuring interdisciplinarity that was investigated in this study is interesting, because it presents an opportunity to explore the degree of interdisciplinarity in research in different fields and different sets of actors in the research community. It is however presented as possible supplement to, and not a substitute for, other means of assessing multi- or interdisciplinarity in research.

Some limitations of the approach should be noted. First, the method only captures interdisciplinary collaboration, which results in publications. However, researchers rarely engage in research that does not generate publications.

Second, the method in its current version tends to yield interdisciplinarity scores that are both quite low and lie within a relatively small range. This limitation is recognized in the academic literature, and efforts are underway to remedy it, for example by performing separate analyses on the three dimensions (variation, balance and distance) that are used in the calculation of the interdisciplinarity index. Nonetheless, we still find the method useful in drawing out differences in degrees of interdisciplinarity that can provide the starting point for more indepth research.

Finally, it should be noted that the research fields were defined based on existing insight into the three case study research areas and recent review of research within these fields, and not by a panel of experts. Thus, our data collection may have underestimated the total number of Danish publications in the three fields in our effort to limit "noise" from other research fields captured in the search.

TABLE 19: Overview of key barriers to interdisciplinarity and suggestions for how to deal with them

Source: DAMVAD and DEA, 2012

BARRIERS TO INTERDISCIPLINARITY	POSSIBLE REMEDIES
Researchers underestimate the difficulties and the investment of time and resources involved in developing a "common language" and a joint set of research tools, which are necessary for interdisciplinary research.	Interdisciplinary research projects should be large and long enough to allow for the development of a "common ground". Part of the funding should be reserved for the pursuit of new research avenues or challenges that were not anticipated at the outset of the collaboration. Funding should include possibilities for research stays or other forms of colocation (either temporary or for the duration of the project). However, co-location should not be forced.
There is a high degree of uncertainty regarding the outcomes of interdisciplinary projects. This may lead researchers to pursue mono- or multidisciplinary projects that are less risky and over which the researchers have more control.	Provide funding for pilot projects, i.e. small projects that allow researchers to explore the usefulness of an interdisciplinary venture on a small scale before committing to larger, longer projects. This could for example be achieved on a test scale through student projects (e.g. Masters' theses).
Researchers tend to define research problems within their own disciplines and not in terms of broad societal challenges. This limits the need for interdisciplinary collaboration.	Encourage collaboration between discipline-oriented university researchers and problem-oriented researchers e.g. industry and/or applied research institutions. Define research centres that are focused on specific problems rather than traditional disciplines, and rethink the traditional faculty structure of the universities to respond to the call for excellence in interdisciplinary research. Post calls for solutions to societal challenges or prizes for the best interdisciplinary approaches to important societal challenges.
Many researchers lack personal networks to other disciplines and therefore have limited knowledge of potential collaborators and their research.	Promote networking across disciplines, e.g. by bringing a broad set of researchers together to discuss specific societal challenges. Such networking should however involve researchers that have a strong academic performance within their discipline, as good interdisciplinary research rests on strong disciplinary foundations.
Projects that start out with the intention of being interdisciplinary turn out to be multidisciplinary, in large part because the contributions of the various disciplines were not properly integrated at the start of the project.	Require interdisciplinary projects to involve all participants in joint identification of the research problem and the research approach from the outset. This is especially important for research that involves firms and for "hard science" projects that involve SSH researchers.

APPENDIX 1.
LIST OF INTERVIEW RESPONDENTS

RESEARCH ON GENETICALLY MODIFIED FOODS

- Thomas G. Jensen, Head of Department, Department of Biomedicince, Aarhus University (Academia)
- Jens B. Nielsen, Professor, Novo Nordisk Foundation Center for Biosustainability, Technical University of Denmark (Academia)
- Peter Sandøe, Professor, Institute of Food and Resource Economics and Department of Large Animal Sciences, University of Copenhagen (Academia)
- Eric Johansen, Associate Vice President - Science, Chr. Hansen A/S (Industry)
- Kate Millar, Director of the Centre for Applied Bioethics, School of Biosciences, University of Nottingham, United Kingdom (Academia)

OBESITY AND METABOLISM RESEARCH

- Arne Astrup, Head of Department, Department of Human Nutrition, University of Copenhagen (Academia)
- Claus Dethlefsen, Research Associate Professor, Department of Clinical Medicine, Aarhus University Hospital (Aalborg) (Academia)
- Marianne Uhre Jakobsen, Associate Professor, Department of Public Health, Aarhus University (Academia)
- Anne Tjønneland, Head of Research, Kost, Gener og Miljø, Danish Cancer Society (Non-profit organization)
- Mads F. Rasmussen, Head of Clinical Development and Research – Diabetes, Novo Nordisk (Industry)
- Inez de Beaufort, Professor, Department of Medical Ethics and Philosophy of Medicine, Erasmus MC (Medical Center), The Netherlands (Academia)

RESEARCH ON RENEWABLE ENERGY

- Mogens Bjerg Mogensen, Research Professor, Department of Energy Conversion and Storage, Technical University of Denmark (Academia)
- Tjalfe Poulsen, Associate Professor, Department of Biotechnology, Chemistry and Environmental Engineering, Aalborg University (Academia)
- Morten Rask, Associate Professor, Department of Business Administration, Aarhus University (Academia)
- Gert Tinggaard Svendsen, Professor, Department of Political Science and Government, Aarhus University (Academia)
- Anders N. Andersen, Head of Energy Systems Department, EMD International (Industry)
- Jens Rostrup-Nielsen, Head of Research, Haldor Topsøe (Industry)
- Arild Underdal, Professor, Department of Political Science, University of Oslo, Norway (Academia)

APPENDIX 2.
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DEA is a political independent think tank committed to create growth and to attract foreign investments in Denmark through in-depth knowledge on education, research and innovation.

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