University of Sussex

A University of Sussex DPhil thesis

Available online via Sussex Research Online:

http://sro.sussex.ac.uk/

This thesis is protected by copyright which belongs to the author.

This thesis cannot be reproduced or quoted extensively from without first obtaining permission in writing from the Author

The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the Author

When referring to this work, full bibliographic details including the author, title, awarding institution and date of the thesis must be given

Please visit Sussex Research Online for more information and further details

ORGANISING THE SOCIO-ECONOMIC RELEVANCE OF UNIVERSITY RESEARCH: THE CASE OF NANOMATERIALS RESEARCH IN TAIWAN

MIN-HUA TSAI

A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy

SPRU - Science and Technology Policy Research,
School of Business, Management and Economics, University of Sussex

April, 2013

Declaration

I hereby declare that this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.

Signature:……………………………………..

Acknowledgements

UNIVERSITY OF SUSSEX

MIN-HUA TSAI, THE DEGREE OF DOCTOR OF PHILOSOPHY

ORGANISING THE SOCIO-ECONOMIC RELEVANCE OF UNIVERSITY RESEARCH: THE CASE OF NANOMATERIALS RESEARCH IN TAIWAN

SUMMARY

This thesis is concerned with academics' behaviour when organising research aimed at being relevant. More specifically, this study combines a sociological approach and an extensive bibliometric analysis, investigating the relationships between scientists' perceptions of relevance, their research behaviours and their publishing activities in terms of organising nanomaterials research in Taiwan. By introducing a resource-based concept of the notion of relevance from a scientist's perspective, it contributes to intellectual debates on changes to knowledge production and the relationship between scientific excellence and socio-economic relevance.

The study finds that the ways nanomaterials scientists perceive and organise their research, specifically in terms of research orientation, industry involvement and interdisciplinary collaboration, are not entirely oriented towards socio-economic concerns. Scientists tend to adapt to the demand for relevance by demonstrating potential research applications and forming interdisciplinary collaborations. Nevertheless, they are more persistent in terms of not having industry involved in the research process. Balancing adaptation and persistence reflects scientists' concerns with securing financial, intellectual and symbolic resources in order to establish their academic credibility.

The bibliometric analysis broadly confirms the qualitative results findings, showing an increasing trend towards publishing in applied and targeted basic journals, and towards interdisciplinary collaboration. Yet, the proportion of university-industry papers has been rather stable over time. While our interviews suggest that senior scientists tend to consider interdisciplinary collaboration as a way to facilitate application, the bibliometric analysis shows that interdisciplinary co-authored papers tend to be more basic and receive more citations. The analysis also finds that junior scientists tend to feel more pressure to achieve a strong academic performance, thereby pushing them away from activities concerning achieving the envisioned socio-economic relevance of their research. Given the ambiguous notion of relevance and the inconsistency of policy practices, this thesis suggests that the real pressure is more to do with the demand for excellence than for relevance.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Introduction

This study aims to gain a better understanding of scientists' behaviour when organising research that aims to be relevant. Specifically, we investigate the relationships between academics' perceptions, research behaviours and publishing activities in terms of organising 'relevance' in their research processes.

The objectives are to identify scientists' behavioural patterns in response to the relevance of university research, highlight the factors underlying patterns and demonstrate the effects on their publishing activities. This chapter provides an overview and presents the structure of this thesis.

1.1 Background of this study

University research is increasingly seen as a strategic resource to ensure a country's economic competitiveness and help solve urgent societal problems. At the same time, constraints on governmental budgets have resulted in pressures for greater accountability of public expenditure. These conditions have reshaped policy frameworks, thereby exerting a certain influence on how scientists conduct research in the changing research environment. Early examples are the Brooks Report (Organisation for Economic Co-operation and Development [OECD], 1971) and the Rothschild Report (Her Majesty's Stationery Office [HMSO], 1971), both of which called for a more responsive mode of research and for scientists to address societal needs. In a recent seminar held by a high-level expert group in the European Commission (European Commission [EC], 2010), the question of how best to organise research to meet socio-economic needs remained a central issue in the policy agenda. Many discussions concerning this question assume that scientists often do not make

their research relevant to socio-economic needs "because they do not perceive benefits from doing so" (*ibid*., p.18). Over the three decades since the Brooks Report was published, our understanding of scientists' behaviour in addressing the socio-economic relevance of science remains limited. Instead of looking at the problem from the angle of policy practitioners, this study provides an alternative perspective on the notion of relevance at the level of individual scientists.

The research problem of how scientists perceive and organise research aimed at being relevant emerges from a number of studies claiming that science systems have gone through a dynamic transformation. For instance, literature on national innovation systems (Edquist, 1997; Nelson, 1993) and the Triple Helix model (Etzkowitz & Leydesdorff, 2000) argues that universities tend to have strong linkages and interactions with other institutional actors to enhance innovative activities. 'Mode 2' research is reported to be carried out in the context of application and tends to involve more 'transdisciplinary' collaborations (Gibbons et al., 1994). In the new research environment, the quality of science cannot be judged solely by its scientific merits, with an extended peer community needing to be included in the quality control process (Funtowicz & Ravetz, 1993). These studies appear to suggest that science is best organised in a number of interrelated strands - that is, the research is application oriented, stakeholders are involved and there is interdisciplinary collaboration[1] - so that it might help achieve the desired socio-economic outcomes. Following this line of thought, we should assume corresponding behaviour at the level of individual scientists who shape changes to the science system.

However, as Chapter 2 will show, the above approaches of organising research aimed at relevance appear not so straightforward. Firstly, policy notions such as

---

[1] The term 'interdisciplinarity' being used throughout this study usually refers to a general concept, unless otherwise specified, covering a wide range of collaborations and interactions among scientists.

relevance and interdisciplinarity are rather ambiguous and their common vision might be only partly shared. This ambiguity creates both incentives and tensions between policy makers and scientists. Secondly, while the arguments for the transformation of science extend our understanding of the interaction between universities and other institutional actors, they tend to overlook the diversity of scientific disciplines within universities. Thirdly, the rationale for policy practices aimed at promoting relevance appears to be based on a questionable assumption that the government maintains control and scientists generally comply to fulfil the expected goals.

In summary, earlier studies on changing science systems usually address the process of knowledge production at the macro level and regard universities as a homogeneous entity. A better understanding of the social organisation of science from a scientist's perspective may help to fill the knowledge gap concerning the discrepancy between normative requirements at the macro level and actual research practices at the micro level. In this respect, this thesis aims to contribute to the intellectual debate on changing knowledge production.

Several studies investigate how scientists respond to the changing context of research using different approaches (Bercovitz & Feldman, 2008; Calvert, 2001; Gulbrandsen, 2005; Hessels, 2010; Hessels et al., 2011; Laudel, 2006; Leisyte, 2007; Morris, 2000, 2003; Morris & Rip, 2006). Even at a disciplinary level, they highlight the diversity of scientists' perceptions and reactions towards the research environment. In general, scientists do not fully embrace those changes that may affect their research practices. They tend to pursue different strategies in different circumstances. These studies argue that the 'old' routines and norms of research practices remain persistent to a large extent. The existing literature thus challenges the view of a global transformation to the science system and suggests that we should look at how scientists' motives and behaviour co-evolve with the institutional environment for a better understanding of the

changes of knowledge production.

An investigation from a scientist's perspective helps provide insights into the effects of promoting relevance on scientists' research practices, which remains a heated issue of intellectual debate. Specifically, there are reservations about whether the quest for greater scientific relevance might undermine scientific work, thereby leading researchers to pursue applied and short-term research (Florida & Cohen, 1999; Geuna, 2001). In addition, industry involvement may direct the scientists' research agendas (Blumenthal et al., 1996). These studies concern the effect of pursuing 'relevance' on changing research content, which might be detrimental to scientific development in the long run. Nonetheless, other studies argue that relevance can be an integral part of scientific research and that this does not necessarily come at the expense of scientific understanding (Rip, 1997; Stokes, 1997).

A vast amount of empirical evidence is based on the relationship between publications and entrepreneurial activities, often arriving at different conclusions (see the review by Larsen, 2011). While previous studies tend to show a positive relationship between the volume of publications and patents, the effects of different entrepreneurial activities on the research nature and on the scientific impact remain mixed.

This study aims to advance our knowledge in this respect by linking scientists' research behaviours to their publishing activities. Scholarly publications not only serve as a main research output but also, to certain extent, reveal the result of formal interaction and communication between scientists and other actors (Borgman, 1990). The comprehensive information contained in a bibliography helps provide an alternative perspective on the social organisation of research. Previous studies tend to focus on the relationship between different research outputs, such as patents and publications, but seldom investigate research behaviour revealed in bibliometric records.

Furthermore, this thesis provides new evidence in an emerging scientific area (nanomaterials research) and from a particular national context (in Taiwan), both of which are under-explored in previous research. Extensive studies related to this research subject have been conducted in the USA and some European countries. Nonetheless, rarely have they been carried out in other national contexts. Although the changing landscape of science systems seems to have been a feature if not in all, then in many countries, the organisational structure of science, institutional set-ups and the cognitive culture of science remain historically and socially rooted in individual countries. Further research into the social organisation of science in different national contexts is needed to provide a stronger basis for theoretical arguments.

Given the above background, this study is expected to fill a knowledge gap concerning the social organisation of research in a changing research environment from a scientist's perspective.

1.2 Research questions, objectives and theoretical concerns

The central research question of the thesis is: How should we understand the socio-economic relevance of research in terms of scientists' perceptions, research behaviours and publishing activities? We assume that scientists' behaviours are not entirely independent from the institutional context. Scientists' actions are partly affected by their perceptions of the research environment. In turn, their research behaviour will reshape the knowledge production structure. The unit of analysis is scientists at universities. More specifically, this study asks the following two questions:

1 How do university scientists perceive and organise research that aims to be relevant?

2 What is the relationship between scientists' research behaviours and publishing activities?

The objectives of the first research question are to identify the behavioural patterns used to organise relevant research and highlight those factors underlying the various patterns. The objectives of the second research question are to establish the relationship between scientists' research behaviours and their scientific performance, and then triangulate those findings with the first research question. As such, this thesis aims to gain a better understanding of scientists' research behaviours when dealing with the notion of relevance during the research process.

It is worth noting that there are two research behaviour levels put forward in this study. At a more explicit level, we focus on three major approaches of organising research that is usually aimed at being relevant in terms of research orientation, industry involvement and interdisciplinary collaboration (Böhme et al., 1983; Böhme et al., 1976; EC, 2005; Gibbons et al., 1994; Irvine & Martin, 1984; Stokes, 1997; Ziman, 1994). At a more implicit level, we identify the patterns of adaptive and persistent behaviour underlying scientists' responses to the three criteria for organising relevant research.

We examine the research question from a resource-based perspective by developing a conceptual framework, which combines the theoretical lenses from boundary work (Gieryn, 1983), principal-agent theory (Braun & Guston, 2003; Guston, 1996; van der Meulen, 1998) and the credibility cycle (Latour & Woolgar, 1979). As we addressed in Chapter 2, the central idea is that the notion of relevance is very much concerned with mobilising resources among government, industry and scientists. Government mainly mobilises financial resources towards areas that are of socio-economic importance and delegates scientists to fulfil its policy objectives. University scientists depend on external resources to achieve their own research purposes whilst retaining their autonomy. Industry is increasingly regarded as an important actor for scientists to obtain external resources and legitimise their public funding. Organising relevant research assumes that scientists have to re-negotiate resources with other actors.

Nonetheless, existing studies show that scientists perceive changes to the institutional environment differently, with their actual research practices not necessarily affected significantly (Calvert, 2001; Leisyte, 2007). The above three theories provide different aspects of scientists' behaviour in the exchange of resources. In what follows, we briefly introduce the perspectives of the three theories that are relevant to this study.

Boundary work points to the ambiguous notion of science, which allows academics to draw a line between science and non-science, and between different disciplines by attributing selective characteristics of science for different purposes. Previous research suggests that the ambiguous feature of relevance has served as a boundary concept (Scott, 2004). Examining what features scientists select in terms of organising relevant research helps understand scientists' interests or struggles in response to the demand for the research to be relevant.

Principal-agent theory suggests that the relationship between funding body and scientists mainly concerns the problem of delegation. From a government perspective, the conflict of goals and information asymmetry creates adverse selection and moral hazard problems. From a scientist's perspective, these problems in turn provide a space that enables a scientist to fit in with policy requirements in order to secure external resources. In other words, scientists will adapt to policy requirements to a certain extent, depending on how serious the non-compliance penalties are perceived to be (Morris, 2003). The seriousness may lie in the degree of credibility a scientist possesses, with the concept of the credibility cycle addressed in the following.

The credibility cycle assumes that the cycle of converting financial resources into recognition, which in turn attracts more resources, is a common feature influencing the behaviour of a scientist. Scientists have to accumulate credits in order to build up credibility and thus may not easily shift their research subjects and practices. In other words, their research behaviour is path-dependent, a behaviour which implies that

scientists may be motivated by their own interests, regardless of external pressure, if their credibility is already secured.

Moreover, the credibility cycle also suggests that scientists not only need financial and material resources (e.g. money, research facilities and available data) but also need human resources and symbolic resources (e.g. recognition and status) that help to reinforce scientists' investment in their credibility (Braun, 1998; Knorr-Cetina, 1982; Latour & Woolgar, 1979). The extent to which scientists engage in relevant research depends on the types of resources embedded in the 'relevant' activities that help to establish their credibility.

Based on the insights of the theories, we expect that scientists' behaviours in response to the relevance of research might be better understood as the interplay between their concern with credibility and the resources they can obtain from the perceived environment.

1.3 Rationale for studying nanomaterials research

This thesis focuses on nanomaterials research conducted by university scientists in Taiwan as the empirical foundation. Following suggestions in existing literature, we have selected nanomaterials research for a number of reasons. First, an investigation at the research field level, rather than an entire science system, seems more appropriate as section 1.1 argued. Second, the chosen field is one that is widely expected to achieve certain ultimate goals that are of socio-economic importance. Third, the university plays a crucial role in research relevance being achieved. Fourth, the site of investigation should be of policy significance in a specific national context.

We consider that nanotechnology research is a 'strong case' for organising relevant research. Nanotechnology research has attracted widespread attention and substantial investment around the world since the late 1980s. It is widely recognised as visionary

research that has the potential to "have a substantial impact on industry and on our standard of living by improving healthcare, environment and economy" (National Science and Technology Council, 2000, p. 27). Taiwan is no exception. Nanotechnology research has been one of the top priorities funded by the government in recent years. Since the launch of the National Science and Technology Programme for Nanoscience and Nanotechnology (hereafter the "Nano Programme") in 2003, it has been the largest National Programme[2] supported by the government and has funded scientists in a wide range of disciplinary backgrounds. This study narrows down the focus to nanomaterials research. Chapter 3 addresses how the sample of scientists was selected. Chapter 4 introduces the policy background and institutional arrangements around nanotechnology research in Taiwan, with the analysis suggesting that nanomaterials research is an appropriate case for the empirical focus of this study.

1.4 Significance of the research topic

There is potentially both practical and theoretical significance to this study. The investigation of how university scientists organise their research may help improve policy-makers' understanding of the dynamic structure of science systems, thereby enabling them to formulate more effective policies. Pavitt's (1991) analysis of the economic usefulness of basic research suggests that many policies tend to involve a misconceived attempt to seek more direct and obvious benefits from basic research. In addition, theories for developing greater socio-economic relevance of science have been mainly developed in the US context. Therefore, Pavitt suggests that further research is needed to fill a gap in empirical knowledge about "the structure, efficiency and dynamics of national systems of basic research" (Pavitt, 1991, p. 117). He further

---

[2] Up to 2011, at a time when the National Energy Programme received most government financial support.

suggests that those attempting to apply the US model in other national contexts should "consult local practising scientists and users beforehand" (Pavitt, 2001, p. 775). This study at the level of individual scientists is expected to yield a more realistic view of the policy implications.

In particular, our study suggests that distinguishing between 'relevance' and 'impact,' as well as conceptualising the notion of relevance, provides a guiding framework, thereby enabling policy-makers to better understand the problems of how best to organise research to ensure the relevance of science. Policy discourse tends to use the notions of relevance and impact interchangeably without providing a clear definition. Evaluation practices usually focus on whether public funding has achieved the anticipated socio-economic outcomes, such as solving the problems of climate change or enhancing economic competitiveness. Nevertheless, there remain conceptual and methodological problems concerning how to measure relevance effectively. As a result, many policy level discussions assume that scientists do not usually fulfil the envisaged socio-economic relevance of their scientific research. This study points to the problem of exchanging resources among scientists, government and industry under the current institutional environment, a perspective that may help policy-makers think about how to design a more effective incentive structure.

The theoretical significance of this study is that the subject in question is expected to contribute to the intellectual debate about a changing science system and its implications for the relationship between scientific excellence and relevance. Specifically, this study complements current knowledge about a changing science system by focusing on the level of individual scientists, a perspective that has so far received limited attention. As shown in section 1.1, the central arguments for a changing science system tend to leave the organisation of science as a 'black box', where inputs and outputs are identified and the internal mechanisms remain unknown.

Several studies highlight the social organisation of science as an important perspective if one is to gain a better understanding of the changing science system, with existing empirical research remaining limited. Hessels and van Lente (2008) review the thesis of 'Mode 2' and related notions, arguing that further empirical research into related questions concerning new forms of knowledge production should take into account the heterogeneity of scientific fields and national contexts.

1.5 Thesis structure

The thesis consists of seven chapters. After the introduction in Chapter 1, Chapter 2 reviews notions related to the socio-economic relevance of science and proposes a conceptual framework for this study. We show how the notions of relevance and impact have been widely used at different dimensions, foci and levels of analysis in science policy studies and practices. The analysis suggests that it is necessary to distinguish between the notions of relevance and impact to gain a better understanding of what exactly the relevance of research means and what problems lie behind the notion. To problematise the notion of relevance, the analysis identifies three major approaches of organising research towards socio-economic relevance - that is, research orientation, industry involvement and interdisciplinary collaboration - and examines the issues used to justify the relevance of research. The analysis underlines the social organisation of science as an important perspective to investigate the subject in question. We argue that the notion of relevance is very much a resource-based concept. We then develop a conceptual framework to investigate the relationships between scientists' perceptions, research behaviours and publishing activities in terms of organising relevant research. Based on the theoretical foundations of boundary work, principal-agent theory and credibility cycle, we regard scientists' behaviours in response to the policy requirements for relevance as a way of exchanging resources.

Chapter 3 presents the research design and methodology. It initially identifies the key elements in the research design before explaining why a combination of qualitative interviews and bibliometric methods have been chosen to investigate the research questions. The research procedure is elaborated, including the collection, processing and analysis of the data, from the interviews and bibliometric work respectively. Finally, the chapter addresses the methodological limitations.

Chapter 4 describes the policy context in Taiwan, focusing on the role of university research and its relationship with societal and economic needs. The aim is to present how the notion of relevance has evolved alongside the socio-political context and what major policy practices have been implemented. The chapter starts by tracing the changing rationale for university funding over the past six decades in Taiwan and presents the policy actions initiated by the government under different socio-political contexts. It then focuses on the public funding of nanotechnology research as an empirical case study under the current policy context. Our analysis suggests that university research, as a direct source of industrial development, has become the rationale for public funding during the past decade. The initiative of the large-scale funding of nanotechnology research is appropriate for use as the empirical case study for this study.

Chapters 5 and 6 present the empirical results of this study. Chapter 5 elaborates on scientists' perceptions and research behaviours in terms of research orientation, industry involvement and interdisciplinary collaboration. The evidence is mainly based on 34 scientist interviews, with supplementary data taken from their curriculum vitaes. We will show that scientists interpret the notion of relevance and the related research practices variously. Their research behaviour tends to be influenced by a number of personal factors and the institutional environment they perceive. How scientists respond to the relevance of research reveals their concerns with securing financial, symbolic and

human capital in order to establish academic credibility. As a result, their research behaviour may not be entirely oriented towards making their research relevant.

Chapter 6 presents evidence from a bibliometric analysis of 6172 SCI (Science Citation Index) papers produced by 331 nanomaterials scientists in Taiwan. It deals with the relationship between scientists' research behaviour and their scientific performance. The chapter analyses the overall pattern and then compares scientists with different levels of seniority. The bibliometric analysis generally accords with our interview data, showing that research behaviour differs between junior and senior scientists, and that collaboration with heterogeneous organisations, except for that with industrial sectors, does not negatively affect the citation impact.

Chapter 7 presents the conclusion of this thesis. It first synthesises the empirical findings and then discusses what we have learnt about scientists' behaviour when dealing with the notion of relevance. We argue that the institutional environment does not co-evolve with the demand for relevance. While there has been a trend towards applied and targeted basic research, and towards interdisciplinary collaboration, the institutional division of labour and disciplinary boundaries remain clear. Moreover, policy practices targeting the achieving of relevance are inconsistent. These circumstances encourage scientists to adapt to policy requirements in certain ways but to persist in maintaining the independence of their research practices. We conclude that scientists' behaviours are influenced more by the pressure for excellence than with relevance. The theoretical contributions and policy implications are then presented. This chapter concludes with a discussion of the generalisation of the results of this study and suggestions for future research directions.

Chapter 2

Literature Review and Conceptual Framework

The purpose of this chapter is to shed light on notions related to the relevance of science, thereby developing the conceptual framework of this study. Although there has been an increasing emphasis on the socio-economic relevance of publicly funded research, the notion and the underlying assumptions have not been critically analysed. This chapter will discuss several concepts in relation to the following questions: (1) What do we mean by the relevance of research? (2) How has research tended to be organised in order to achieve relevance? (3) How can we measure relevance? Reviewing the literature with regard to these questions will provide helpful insights into the analytical dimensions of the conceptual framework that guides the data collection and analysis of this study.

This chapter consists of four sections. Section 2.1 addresses the conceptual distinctions between the notions of relevance and the impact in terms of the timing (ex-ante versus ex-post) and focus of policy actions (research process versus research exploitation). It then examines several schools of thought that argue for a social orientation of science. We argue that, compared to the result-based concept of impact, the term 'relevance' is very much a resource-based concept, with its related activities tending to occur in the knowledge production process.

Section 2.2 identifies the major approaches of organising research that are expected to produce relevant knowledge for socio-economic needs. The literature review shows that organising research towards socio-economic purposes tends to suggest that firstly external goals are the driving force behind scientific research, secondly that there is user or industry involvement in the research process and third interdisciplinary collaboration is often used. We find that these criteria seem not particularly straightforward and

require further understanding. The ambiguity of the notion of relevance raises questions about whether and how scientists orient their research behaviour towards achieving socio-economic relevance and the consequences on their publishing activities.

Section 2.3 reviews studies on how relevance and impact are usually measured. The review shows several conceptual and methodological issues that make measuring 'relevance' problematic. We then focus on the debates at the level of individual scientists, specifically examining the effects of promoting relevance on scientists' research behaviour and their publishing activities. The review shows that scientists' responses to the changing research environment are rather diverse, with the empirical studies challenging the view of the global transformation of the science system.

On the basis of the literature review, section 2.4 provides a conceptual framework for this study. It addresses the key elements that make up the framework and then proposes a resource-based perspective by combining boundary work, principal-agent theory and the credibility cycle to investigate the research problem under the framework.

2.1 Understanding the notions of relevance and impact

This section clarifies the notions of relevance and impact that have been widely used in policy practices. It mainly draws from literature related to research evaluation (Martin, 1996; OECD, 2002a; Polt & Rojo, 2002) and on the changing relationship between science and society (e.g. Böhme et al., 1983; Böhme et al., 1976; Etzkowitz & Leydesdorff, 2000; Gibbons et al., 1994; Ziman, 1994). Although the notions of relevance and impact are often used interchangeably in research evaluations, the analysis shows that these two terms appear to be conceptually distinctive. The clarification of the notions help us obtain a better understanding of the rationale for promoting relevant research.

2.1.1 Distinguishing between relevance and impact

Compared to the notion of relevance, impact appears to be more widely used in evaluation practices. It usually refers to the effects of policy intervention at different levels and with different foci. For example, the *RTD Evaluation Toolbox* published by the European Commission in 2002 provides a conceptual framework for knowledge measurement covering input, output, outcome and impact indicators. Outcome refers to "the initial impacts of the intervention providing the reason for the programme," while impact refers to "the long-term socio-economic changes the intervention brings about" (Polt & Rojo, 2002, p. 17). In addition, the notion of impact usually contains a range of aspects in which policy makers and stakeholders may be interested. Traditionally, research impact has focused on scientific merit and quality, and on the contributions to scientific progress (Martin, 1996). With increasing policy concerns about the socio-economic contributions of publicly funded research, many attempts to understand the impact of research place more emphasis on the non-academic context, such as economic, social, environmental, political and cultural aspects (Kanninen & Lemola, 2006; Molas-Gallart et al., 2000; Pavitt, 1991; Salter et al., 2000; Salter & Martin, 2001). The focus of the aspects depends on the expected achievements of policy intervention.

Although the notions of relevance and impact have been used interchangeably in evaluation practices, there are certain conceptual distinctions between the two. Firstly, relevance usually refers to *ex-ante* appraisal, while impact refers to *ex-post* evaluation. As van der Meulen and Rip state (2000, p. 12):

> "*Relevance*: starting from a proposed, ongoing or concluded research project or programme, one enquires into its actual and envisaged linkages and promises. Relevance is particularly important in *ex ante* evaluations, but the promises should be checked in *ex post* evaluation.
>
> *Impact*: the uptake of research (and the effects of such uptake), often as a combination of results of several projects, earlier findings, and experience of practitioners, can be studied as such, but for *ex post* evaluation, attribution to

specific research projects and actions is necessary."

The above framework suggests that the notion of relevance is a resource-based concept and that of impact a result-based concept. As a forward-looking category, the term 'relevance' implies an expectation that research will realise potential promises in the future. Given this assumption, resources are mobilised to organisations and actors most likely to fulfil the research expectations. In practice, the OECD defines five general criteria - relevance, efficiency, effectiveness, impacts and sustainability - as the basis for evaluation and performance management. Relevance is a measure of "the extent to which the objectives of a development intervention are consistent with beneficiaries' requirements, country needs, global priorities and partners' and donors' policies" (OECD, 2002b, p. 32). The assessment of relevance tends to serve as a frame of reference for funding decisions.[3]

A second distinction, and related to the first, concerns policy practices in terms of *process* and *results*. The quest for socio-economic relevance tends to take place throughout the entire knowledge production process. In policy practice, foresight activities have been widely used to help identify research priorities that will meet societal and economic needs (Martin & Johnston, 1999). Moreover, many policy discourses and research initiatives in European countries seek to identify user communities and potential impacts as the justification for funding research (Davenport et al., 2003; Shove & Rip, 2000; Wickham & Collins, 2006)**.** In the USA, the National Science Foundation (NSF) has changed its review criteria for assessing research proposals since 1997 and now asks scientists to identify the likely broader impacts of their research (Holbrook, 2005). Compared with the policy designs for relevance, those for impacts usually concern facilitating the exploitation of research results. For example,

---

[3] It is worth noting that there is a trend towards the linkage between performance measures and resource allocation in government budgeting (OECD, 2007).

a variety of initiatives related to technology transfer and the commercialisation of research have been widely used to translate publicly funded research into economic growth.

Despite the distinctions between relevance and impact, the two notions, to some extent, are related. As we have seen, the relevance of research seems to have to do more with the *production* than the *utilisation* of knowledge. Weingart (2008) notes that "the control is gradually moved upwards from intervening at the stage of implementation of knowledge to that of the production of new knowledge" (p.143). Ferné (1995, pp. 18-19) also maintains that:

> "In all industrial countries, governments have tended to shift, in recent years, to indirect actions intended to promote the development of a trade-oriented research environment….This focus has been accompanied by gradual re-direction of the public research support towards new types of programmes, in order to channel efforts onto areas of greater economic relevance….The development of a 'system of exploitation of research results' is thus coupled with the transformation of the research system into a 'system for the production of exploitable results.'"

The shift in focus towards the knowledge production process began with the debate about the negative consequences of technological progress on society in the 1960s (Gibbons et al., 1994; Weingart, 2008). Along with the increasingly competitive environment, the constraints on public expenditure and the adoption of new public management by governments (see Dunleavy & Hood, 1994), the demands for greater accountability and the participation of extra-academic groups in science have been strengthened since the 1960s.[4]

---

[4] A number of studies indicate the beginning of the trend towards linking science to societal and economic needs in different countries and in different time periods (e.g. Brooks, 1996; Elzinga, 1997; Irvine & Martin, 1984; Martin, 2003; Rip, 1997), ranging from the early 1960s to the late 1980s. This trend has become quite widespread since 1990 (Maclean et al., 1998).

This trend assumes that effective controls in upstream activities ensure the production of 'relevant knowledge', thereby helping to meet socio-economic needs. The phenomenon of placing greater emphasis on the relevance of research implies a changing science system that re-defines the interaction between science and society (Guston & Keniston, 1994). The next section examines the different schools of thought of the changing science systems.

2.1.2 Examining the arguments for the social orientation of science

Although we have distinguished the notions of relevance and impact, what the nature of 'relevant knowledge' is and how such knowledge is usually formed in order to fulfil the socio-economic needs remains unclear. This section considers these aspects by introducing three perspectives concerning the social orientation of science. The first two schools of thought focus on the internal and external factors of scientific development at a macro or disciplinary level, with the third one focusing on the role of expectations in achieving social relevance to a scientific-technological field. We then focus on empirical studies at the level of individual scientists.

Internal perspective on scientific development

The first group of studies concern an internal perspective of scientific development. In the 1970s, the German Starnberg authors (Böhme et al., 1983; Böhme et al., 1976) developed the model of finalisation in science, suggesting that the external goals of science are intrinsically integrated into a discipline and serve as a guideline for scientific progress when a discipline reaches the stage of its theoretical maturity. Based on the case studies of several scientific disciplines, the finalisation thesis argues that the social orientation of science is a historical process and will be eventually determined by scientific advancement. In addition, the authors of the finalisation thesis maintain that

"a finalized science is more than 'applied science' because it has an independently extended theoretical framework worked out for specific problems within the mature science's object domain" (Schroyer, 1984, p. 717). Along with the theoretical evolution of science, individual scientists tend to take into account the goal of solving social problems as a natural process when conducting scientific research.

The finalisation thesis raised heated debates in the 1970s, with criticisms concerned with the lack of clarity and criteria for the maturity stage and the structure of internal orientation (Pfetsch, 1979). Nevertheless, as noted by Pfetsch (1979), the discussions were more about its political implications for the autonomy and integrity of the scientific community than its scientific inquiry.

Institutional perspective on scientific development

In contrast, several science-policy studies provide an institutional perspective on the transformation of science, emphasising external factors as the major driving force for a changing relationship between science and society. Notions, such as Mode-2 knowledge production (Gibbons et al., 1994), systems of innovation (Edquist, 1997; Lundvall, 1992; Nelson, 1993), the Triple Helix model (Etzkowitz & Leydesdorff, 1998, 2000) and 'entrepreneurial university' (Etzkowitz, 1998, 2003; Etzkowitz et al., 2000), have attempted to address the reorganisation of the relationship between university, industry and government in response to a world of growing scientific and technological competition. Rather than discussing every issue and criticism stated in these studies, this section focuses on the rationale for the linkage between science and the socio-economic concerns relevant to this study.

While systems of innovation and the Triple Helix model focus on different perspectives,[5] they both place significant emphasis on interactions between institutional actors as the main source of innovation. For example, Lundvall (1992) stresses that different forms of interactive learning tend to create a stock of economically useful knowledge. Private firms may explore academic knowledge in order to obtain inputs for the innovation process. Even if the aims and directions of basic research are less responsive to economic concerns, academic scientists will be somewhat oriented towards non-academic users. Since systems approaches tend to focus on the role of firms in the innovation process and regard academic knowledge as one element of the institutional infrastructure, they shed little light on the changing characteristics within science systems.

The Triple Helix model (Etzkowitz & Leydesdorff, 1998, 2000) points to an emerging overlay of networks that reconfigure the relationship between universities, industries and government agencies in response to knowledge-based innovation. In this model, the concept of the 'entrepreneurial university' arises from an interplay of shifts in funding patterns, intellectual property reform and scientists' perceptions of new opportunities (Etzkowitz, 1989; Etzkowitz et al., 2008). As a result, academic scientists are undergoing cognitive changes of norms in a way that 'capitalisation of knowledge' can be integrated into 'extension of knowledge' (Etzkowitz, 1998). According to the distinction between relevance and impact identified in section 2.1.1, the Triple Helix model and notion of entrepreneurial university focus more on the exploitation of research results, such as setting up different forms of technology-transfer mechanisms, than on organisation of the research process.

---

[5] The systems of innovation approach regards firms as playing a leading role in innovation, while the Triple Helix thesis emphasises the 'third mission' of universities (in addition to teaching and research) as crucial activities that contribute to economic development.

The Mode-2 thesis (Gibbons et al., 1994) addresses a number of characteristics about the changing nature of the research process. According to the thesis, Mode-2 knowledge is more socially oriented, transdisciplinary and reflexive. Moreover, such knowledge tends to involve a variety of organisations, with quality control needing to be extended to incorporate non-scientific criteria. While the Mode-2 thesis has been rather influential since being published, it has also given rise many intellectual debates due to its lack of a theoretical foundation and supporting empirical evidence (Hessels & van Lente, 2008).

One of the main deficiencies in the institutional perspective of changing science systems is that they seem to assume that transformation occurs across the entire science system without considering the diversity among different disciplines. Weingart (1997) argues that Mode-2 knowledge production may be applicable to certain sections in the research system but cannot be generalised as a whole.

The role of expectations in shaping the relevance of research

Given the emergence of scientific-technological fields as a strategic resource to achieve economic competitiveness, a group of studies focus on the role of expectations in fulfilling the social reality of these new fields (Borup et al., 2006; Rip, 1997; van Lente & Rip, 1998). Earlier research had the specific context of the 1980s, a time when the notion of 'strategic science' was widely acknowledged as a promising category of science in the UK. Using a case-study approach focusing on membrane technology, Van Lente and Rip (1998) address how strategic research as a rhetorical entity turns out to shape the specific expectations of a new field. They propose a promise-requirement cycle to elaborate the socio-cognitive dynamics of interaction between scientists, industrialists and policy makers. They argue that "future shape and promises are as important as the actual production of artefacts and validation of knowledge claims" in a

strategic oriented field (*ibid*., p.245).

While the three schools of thought point to different foci concerning the social orientation of science, they suggest that the demand for the relevance of research is more concerned with the interaction between institutional actors than the nature of research. It is worth noting that these studies are mainly descriptive and focus on different levels of analysis. Their arguments imply that scientists' research practices might be subject to funding policy considerations and interaction with non-academic actors. In addition, the motivations of scientists and the research environment they perceive also affect how they interact with other actors. As addressed above, one main issue arising from the finalisation thesis concerns scientific autonomy and integrity. In what follows, we look at how individual scientists react to changes in the research environment.

Empirical studies at the level of individual scientists

A number of studies have emerged to address the diverse responses of scientists to the changing context since the last decade or so (Calvert, 2001; Gulbrandsen, 2005; Hessels, 2010; Hessels et al., 2009; Laudel, 2006; Leisyte, 2007; Morris, 2000, 2003; Morris & Rip, 2006; O'Brien & Toms, 2008; Scott, 2004; Shove & Rip, 2000). These studies contribute to our knowledge about the institutional factors that govern research aimed at being relevant, the meaning and position of relevance in scientific practices, the tensions in the interaction between funding bodies and scientists, and scientists' strategies in response to the changes. Their findings show the dynamics of change in the institutional context perceived by scientists, thereby exerting a certain influence on scientists' behaviour to varying degrees.

These studies provide an alternative perspective on the assertion of a changing science system by looking at scientists' responses with regard to their interaction under

a specific context. A consensus of their findings is that institutional changes and the effects on research practices vary in different disciplines. Thus, they challenge some of the views concerning the changing science system at a macro level.

Several insights can be drawn from previous research. First, while the demand for relevance is not a new phenomenon, the notion of relevance is contextually dependent on the changes of a specific socio-political environment over time. Second, the relationship between funding administration and scientists in negotiating the relevance of science seems to not have stablised yet, although the governing environment has shifted towards greater demand for relevance of research. One main reason for this is concerned with the inconsistent policy instruments used to promote 'relevance'. The other reason is that the traditional norms and research practices are still prevalent in the scientific community. Third, the behaviour of scientists is not fully aligned with the external requirements. The changing institutional environment indeed exerts a certain influence on scientists' behaviour. Nonetheless, the effects on their daily practices and on the nature of research vary extensively.

Given the diversity of the scientific community and the complexity of institutional arrangements in different national contexts, existing studies leave several questions for further investigation, such as: How can we gain a better understanding of scientists' behaviour and their underlying considerations in organising relevant research? How do personal and institutional factors interact with each other, thereby exhibiting certain influence on scientists' behaviour? What does the notion of relevance and its practices entail for scientists and for their research? This study aims to advance our knowledge on scientists' behaviour in dealing with the notion of relevance.

2.1.3 Summary: justifying the focus of this study

The previous two sections distinguish between the notions of relevance and impact, and examine the arguments for the social orientation of science from different theoretical perspectives. The analysis shows that, in practice, the meanings of relevance and impact have been used interchangeably at different dimensions, foci and levels of analysis. Nonetheless, the two notions are conceptually distinctive. We suggest that the notion of relevance is a resource-based concept, when compared to that of impact. We thus argue that one must carefully distinguish these two terms before further examining issues related to relevance.

The review of the arguments for the social orientation of science suggests that we should take into account the diversity of a science system if we wish to ascertain a better understanding of the notion of relevance. Systems approaches tend to focus on a rather higher level of analysis and appear to shed little light on the process of scientific knowledge production. Although the Mode-2 thesis encompasses a wide variety of features to depict knowledge production, existing research suggests that we should investigate these features individually rather than regard Mode-2 knowledge as an overarching framework (Hessels & van Lente, 2008). In addition, the focus on individual scientists provides us with another perspective to understand how scientists might react to the socio-economic relevance of science. The following section addresses the three major approaches of organising research that is expected to ensure the socio-economic relevance of research.

2.2 Organising relevance in the research process

On the basis of literature in science-policy research (EC, 2005; Gibbons et al., 1994; Irvine & Martin, 1984; Stokes, 1997), sociological studies of science (Böhme et

al., 1976; Funtowicz & Ravetz, 1993; Ziman, 1994) and actual policy practices, we identify three major approaches of organising research that are usually aimed at fulfilling the socio-economic relevance of research. They are: (1) external goals as the driving force behind scientific research, (2) users being involved in the research process and (3) interdisciplinary collaboration. We assume that these three aspects are the most direct approaches that scientists tend to organise and manage their research in the current funding environment, even though governments might introduce other policy instruments to ensure the relevance of research, such as foresight activities (Martin & Johnston, 1999) and the mechanisms of quality control (Funtowicz & Ravetz, 1993). We consider them to be the institutional factors that exert an influence on scientists' research practices. For example, technological priorities and review criteria may affect scientists' research agenda in order to secure research grants. This section investigates these concepts and the debated issues.

2.2.1 External goals as the driving force behind scientific research

The first criterion for organising relevant research is that scientific knowledge tends to be directed more by external goals toward solving economic, political and social problems than by the internal logic of scientific inquiry. This criterion has two main features. First, the distinction between basic research and applied research is rather blurred (Gibbons et al., 1994; Irvine & Martin, 1984; Stokes, 1997). Second, scientists tend to internalise the quest for relevance, thereby being guided by multiple goals (Böhme et al., 1976; Rip, 2002). Each feature will be discussed below.

Traditionally, two main types of research – basic and applied – have been considered in a linear way and treated as opposing in terms of the goals: pursuing knowledge for its own sake or for practical applications (Bush, 1945; OECD, 1994, 2002). The goals of research have been the rationale for institutional arrangements of

science and technology for over a century (Stokes, 1997). At a time of success in defence-related research and in medical research during the Second World War, the basic-applied dichotomy was reinforced by Vannevar Bush (1945), who claims that basic research, which is performed "without thought of practical ends" (*ibid*., p.18), will often lead to industrial progress and hence benefit the public. Although Bush's view has been quite influential in science policy, the linear relationship between basic and applied research has been criticised for its oversimplification and its neglect of demand-side factors (see, for example, Brooks, 1994; Kline & Rosenberg, 1986; Rosenberg & Nelson, 1994).

Since the 1970s, a number of studies have recognised that the goals of understanding and application are often complementary rather than mutually exclusive, thereby coining different terms to describe the phenomenon. For example, Gibbons et al. (1994) suggest that 'Mode 2' research takes place in the context of application, which is shaped by the interactions between the fundamental and the applied. By considering both the goals for understanding and for use, Stokes (1997) proposes the term 'use-inspired basic research' or Pasteur's Quadrant, a category that Stokes acknowledges as somewhat equivalent to 'strategic research' proposed by Irvine and Martin (1984). More recently, an expert group in a report to the European Commission proposed the term 'frontier research' in order to reflect a closer connection between basic and applied research (EC, 2005). Like the notion of basic research proposed by Vannevar Bush (1945), these alternative terms embrace an idea that scientific knowledge is essential for yielding socio-economic benefits. Yet, the studies proposing these notions reject the linear model of fulfilling the benefits.

The goal of addressing non-scientific problems gives rise to a question concerning who sets the goals. Sociological literature suggests that relevance can be internalised by scientists (Böhme et al., 1976; Rip, 1997, 2002). Rip (1997) addresses the development

of chemistry in the late 1800s as an example of how relevance is built into the paradigm of scientific research. The internalisation of 'relevance' is a result of self-reinforcing interaction between scientists and industrialists. 'Industry,' as an ideograph, plays the role of an abstract sponsor and guides research agendas. Rip suggests that scientists' interactions on government R&D programmes should be analysed using this socio-cognitive approach. In addition, Stokes (1997) argues that, by recognising Pasteur's Quadrant as not an either-or logic with regard to basic and applied research, the conflict over research goals between scientists and their sponsors will diminish. However, Stokes also acknowledges that different actors may have different interpretations of a given research project.

In policy practices, the research goal of addressing socio-economic needs is not always well articulated. The notion of relevance is an important rationale for policy makers to justify public funding support (Irvine & Martin, 1984; Stokes, 1997). However, it is rather ambiguous about who defines the goal of relevance and which issues should be addressed among various societal problems (EC, 2010). Policy practices tend to assume that government maintains control and that scientists generally comply with government, thereby achieving common goals between policy-makers and scientists. The requirement for external relevance thus challenges the legitimacy and autonomy of science (Pfetsch, 1979). Empirically, the balance between the goals of relevance and scientific integrity remains an important issue. The existing literature shows that the notions of basic and applied research are still alive and meaningful at the level of individual scientists (Calvert, 2001; Gulbrandsen & Kyvik, 2010; Gulbrandsen & Langfeldt, 2004). The studies suggest that the traditional divisions of labour and the conventional mode of research inquiries remain largely in existence.

2.2.2 User involvement in the research process

A second criterion denoting the relevance of research is emphasis on identifying a user community and on users' roles in the whole research process. Traditionally, scientists communicate with their peers who share similar research interests by circulating publications, exchanging correspondence, or organising research collaboration, thereby obtaining recognition from their peers (Hagstrom, 1965). Thus, the main audience of academic research is a group of peers informally bound as an 'invisible college' (Crane, 1972; Price, 1963). With the increasing demands for socio-economic relevance of research and seeking additional sources of funds, a key strategy in policy practice is to make research relevant to potential users beyond scientific communities (Davenport et al., 2003; Rappert, 1997; Shove & Rip, 2000; Wickham & Collins, 2006). The notion of users thus incorporates industries, the public sector, non-profit organisations and citizens at large. In the UK, for example, the 1993 White Paper – *Realising Our Potential* – highlighted the various user communities of each Research Council, with communities including different industries together with universities and cognate government bodies (HMSO, 1993). Since then, the UK Economic and Social Research Council (ESRC), for the first time, has placed emphasis on meeting the needs of the user community in its thematic priorities (ESRC, 1995; Rappert, 1997). Identifying potential research users outside scientific communities appears to be an important justification for funding decisions.

In addition to identifying user communities, several analysts suggest that the involvement of users in the whole research process helps ensure the relevance of research. Such involvement may take different forms at different stages of the research process. For example, the relevant stakeholders can be involved in the process of priority-setting (Martin & Johnston, 1999), funding negotiation (Davenport et al., 2003), conduct of research (Wickham & Collins, 2006) and peer review (Funtowicz & Ravetz,

1993; Scott, 2007). These phenomena indicate that users not only utilise the research results but can also play a more active role in the knowledge production process.

In practice, user involvement in the research process is not always so straightforward. Firstly, the notion of users has a symbolic function and tends to serve as an abstract actor demonstrating the relevance of research (Rip, 1997; Shove & Rip, 2000). Ideological interpretations by different groups may raise the problem of the mismatching of the intended goals among different actors. Shove and Rip (2000) find that, while a funding agency may refer to user-supporters and user-collaborators in its mission statement, researchers tend to denote their users in a more generic form, partly real and partly imagined. The advisory group of a research project usually serves as the mediators or user representatives of research, rather than the actual users (Davenport et al., 2003). Shove and Rip (2000) argue that the ambiguous role of users often causes the problem that researchers tend to "concentrate on nominating potential users but pay less attention to the process of use" (p.179). The authors suggest that funders and scientists need to articulate the role and nature of users for a more effective user-researcher relationship. The study also shows that the criterion of user involvement has a certain degree of ambiguity, leaving room for interpretation and negotiation.

Moreover, meeting users' needs may entail the problem about what constitutes a proper researcher-user relationship. Consider the university-industry relationship as an example. Since government should fund research that private firms will not support to maximise wider social benefits (Nelson, 1959), there is a dilemma concerning getting closer to industrial users while not being too specifically relevant to any particular one. One concern related to this dilemma is that short-term research may substitute for long-term and risky research in a university (Feller et al., 2002; Geuna, 2001). Industry involvement may influence scientists' research agenda (Blumenthal et al., 1996). Consequently, the goal of developing fundamental knowledge that is of national

importance may not be fulfilled.

2.2.3 Interdisciplinary collaboration

The third criterion is that research aimed at solving socio-economic problems tends to be organised in an interdisciplinary manner. Since the 1960s, interdisciplinarity and other related concepts have been widely proposed without reaching a consensus on their definitions and operationalisation in practice (Huutoniemi et al., 2010). This section initially briefly reviews the history of interdisciplinarity and its evolution towards the modern concept. After that, the review focuses on how interdisciplinarity has been generally defined, before discussing the problems of organising interdisciplinary collaboration.

In the book *Interdisciplinarity: History, Theory, & Practice*, Klein (1990) introduces the history of interdisciplinarity and explores the evolution of the concept by analysing unity and diversity discourses. Although the term interdisciplinarity emerged in the twentieth century, the roots of the underpinning idea can be traced back to Plato, who advocated pursuing a unified science. By the late Middle Ages, the term 'discipline' emerged in response to the external demand for specialised knowledge. As noted by Klein (1990), the growth of professionalisation and the institutionalisation of science accelerated movement away from synthesised knowledge. A historical review of the notion of interdisciplinarity suggests that the issue of interdisciplinarity has long focused on the unification and specialisation of knowledge.

Klein (1990) continues to suggest that the modern connotation of disciplinarity is a product of the nineteenth century and driven by a number of internal and external forces. The Second World War facilitated cooperative work among physicists and chemists for military purposes. In addition, mission-oriented projects have played an important role in shaping the current definition of interdisciplinarity (Klein, 1990). Perhaps the most

representative case is the Manhattan Project, a cooperative effort among scientists from different disciplines to develop an atomic bomb. With this success in the Second World War, the postwar decades have highlighted a remarkable era of interdisciplinarity. The discussions in previous studies have surrounded both research and teaching in the knowledge production process (e.g. Klein, 1990; OECD, 1972). The following will focus on how interdisciplinary research is usually defined.

A number of studies suggest different terms related to interdisciplinarity, such as multidisciplinarity, transdisciplinarity, pluridisciplinarity or supradisciplinarity (Balsiger, 2004; Huutoniemi et al., 2010; Klein, 1990; OECD, 1972). Existing literature tends to distinguish multidisciplinarity from interdisciplinarity in terms of whether research is carried out with the integration of other research fields. Rossini and Porter (1979) use the analogies of a patchwork quilt and a tapestry to describe the difference between multidisciplinary and interdisciplinary research. Klein (1990) shares a similar idea, pointing out that multidisciplinary research is "essentially additive, not integrative" (p. 56). Disciplinary researchers undertook their work using different perspectives, whilst rarely intending to make synthetic efforts to integrate their views across research fields. In other words, multidisciplinary research has tended to be conducted in a disciplinary fashion.

In contrast, scientists doing interdisciplinary research tend to actively interact across fields. Such a form of interaction may occur over the entire research process, from framing research problems and conducting research, to formulating and analysing results. Several studies suggest that an explicit intention of the goals of problem-solving is an essential criterion to distinguish interdisciplinarity from disciplinarity (Balsiger, 2004; Schmidt, 2008). With this intention, scientists collaborate actively in order to gain a comprehensive understanding of the problem, with the problem motivated by intellectual enquiry or socio-economic concerns.

Due to the lack of a clear definition, the notion of transdisciplinarity is more controversial, with the current debate largely related to the Mode-2 form of knowledge production put forward by Gibbons et al. (1994). The latter authors claim that one distinctive feature of Mode-2 knowledge is that it has its own theoretical framework that cannot easily be located in existing disciplinary structures. The interaction and communication among different disciplines is more dynamic. In practice, transdisciplinary research appears to be an idealised form of knowledge. The review of studies concerning the Mode-2 thesis by Hessels and van Lente (2008) indicates that the concept of transdisciplinarity is rather problematic in terms of both its theoretical foundation and empirical evidence.

As noted above, several studies have made an effort to clarify different notions, with no decisive conclusions yet reached. A common consensus rests on the degree of integration among disciplines. Nevertheless, the criteria for operationalising the cognitive notion of integration appear unclear because it is not easy to investigate the social process of integration (Wanger et al., 2011). There has even been a debate on whether interdisciplinarity actually exists. As noted by Weingart (1997) and Godin (1998), the specialisation and recombination of specialities has usually occurred within traditional disciplines and is almost never carried out in isolation.

Despite the ambiguous definition of interdisciplinarity and related terms, collaboration across disciplines has been regarded as an essential way to advance scientific knowledge, as well as solve major societal problems. The driving force of interdisciplinary collaborations seems to be a result of both the historical development of science and encouragement by science policies. On one hand, the increasing specialisation of scientific disciplines calls for a need to combine knowledge from different disciplines in order to gain a more comprehensive understanding of research subjects (Katz & Martin, 1997; Klein, 1996). On the other hand, it is widely believed

that essential socio-economic issues, such as climate change and economic sustainability, require synthesised inputs from various disciplines. The governments in many industrialised countries have launched several programmes to facilitate interdisciplinary research (e.g. Bordons et al., 1999; The National Academies, 2004). In general, interdisciplinary research has been rising on the policy agenda and is considered to generate positive effects on both scientific development and practical relevance.

Although a large number of studies have advanced our understanding of interdisciplinary and scientific collaboration from different perspectives, several issues remain open for debate and need further investigation (see Hessels & van Lente, 2008; Wanger et al., 2011). One important issue concerns the effect of institutional incentives on scientists' propensity to engage in interdisciplinary activities. Several studies argue that disciplines have long been served as the basis for organisational structures and for reward systems, thereby creating barriers to carry out interdisciplinary research (Brooks, 1978; Porter et al., 2006; Ziman, 1994). Scott (2004) shows that evaluation exercises usually reward research activities in disciplinary traditions, thereby making interdisciplinary research more difficult to maintain. The empirical studies by Carayol and Thi (2005) and van Rijnsoever and Hessels (2011) present that junior scientists tend to produce disciplinary research outputs. In addition, both studies point to the years of work experience as an important factor for scientists to be involved in interdisciplinary research. From the resource-based perspective, van Rijnsoever and Hessels suggest that networking activity and academic position provide a set of resources that benefit scientists' knowledge production.

At the level of individual scientists, seldom have studies investigated interdisciplinary collaboration by looking at scientists' interactions among different departmental institutions and universities. One reason may be related to certain

methodological issues, which will be discussed in Chapter 3. The lack of empirical studies is surprising because several large programmes have either explicitly or implicitly aimed at encouraging interaction among different departments or institutions. For example, the US *Future Initiative* was established to "stimulate new modes of inquiry and break down the conceptual and institutional barriers to interdisciplinary research that could yield benefits to science and society" (The National Academies, 2004, p. ix). This account suggests that promoting a collaborative culture across institutions is also important and can help produce interdisciplinary research results. Previous research shows that geographical proximity tends to benefit research collaboration because tacit knowledge requires informal and face-to-face communication (Acota et al., 2011; Arundel & Geuna, 2004; Katz, 1994). According to this line of thought, one can argue that interdisciplinary collaboration within the same university could occur more frequently and be easier than collaboration outside of the university.

2.2.4 Summary and conclusion

Section 2.2 identifies three major approaches - in terms of research orientation, user involvement and interdisciplinary collaboration - of incorporating socio-economic relevance into the research process. This section also addresses the main features and the debated issues related to the three criteria. While these approaches for organising relevant research have been widely used in policy practices, this study suggests that they might not be implemented effectively. Like the notion of relevance, the above three criteria leave a space for varying interpretations and actions by different groups of people.

Our analysis suggests that conceptualising the notion of relevance into three approaches for organising research is an effective point of departure for us to further

investigate the issues of how best to organise research to achieve the socio-economic relevance of science. As Ziman (1984) puts it, "the notion of 'relevance' cannot be strictly defined or measured, but is always invoked in discussions of the social function of science, and is often the deciding factor in science policy" (p.143). Since the notion of relevance can refer to any anticipated socio-economic outcome, it might be difficult and ineffective for one to argue whether and to what extent a piece of research is relevant to the expected results. Scientists may claim that their research is somewhat of socio-economic relevance in various ways. Even simply advancing knowledge without considering relevance is useful and could have certain social implications (Small et al., 2008).

Given the problematic conception of relevance, it is crucial for policy makers to obtain a better understanding of how this notion is constructed in the knowledge production process. In this way, discussions under the proposed framework would be more specific and productive, thereby informing effective policy suggestions.

Rather than looking at the macro level of a science system, this study focuses on the level of individuals because academic scientists are the major actors who are expected to produce socially and economically relevant knowledge. Emphasising relevance often exerts an influence on science funding. To make effective funding decisions, it is crucial to know how scientists' research behaviours correspond to the requirements for relevance. The ambiguity of the criteria for achieving relevance also raises questions about what the real effects on scientists' research performances might be and how we can observe the possible effects. These questions will be discussed in the next section.

2.3 Measuring the relevance and impact of scientific research

Following the definition of relevance set out in section 2.1, the evaluation practices tend to deal with research impacts that focus on the exploitation and diffusion of research results to society. The assessment of the anticipated relevance of research tends to be incorporated into the *ex ante* evaluation and serves as a reference for funding decisions (EC, 2001). This section shows that measuring anticipated relevance is not so straightforward at an aggregated level. While there are systematic methods for impact evaluation, these methods do not directly consider the 'relevance' aspect as we define in this study. Instead, they only assume or imply the notion of relevance with regard to the utilisation of research results.

Section 2.3.1 reviews the evaluation of research impacts at different levels. Section 2.3.2 identifies the main problems associated with measuring impact. These evaluative problems might be a possible reason for the shifting focus towards more upstream control of science in current policy practices. Section 2.3.3 investigates the effects of pursuing 'relevance' on scientists' behaviours and their publishing activities.

2.3.1 Measuring research impacts: different levels of analysis with various foci

Since the 1960s, a number of empirical studies have investigated the relationship between public research and its potential benefits at different levels of analysis. A series of studies by SPRU analysts provide a comprehensive review of the main methodological approaches and identify several economic benefits of publicly funded basic research (Martin et al., 1996; Martin & Tang, 2007; Salter et al., 2000; Salter & Martin, 2001; Scott, et al., 2001). Overall, there are three kinds of studies with different foci. A macro-level econometric analysis is concerned with the productivity and rates of return from academic research. Sectoral-level innovation studies usually centre on technology or firms, and treat academic research as one of the sources of innovation.

Individual-level studies tend to focus on the linkages between science and technology in terms of scientists' publication outputs and their involvement in industrially relevant activities. On the basis of our distinction between relevance and impact (see section 2.1), these studies appear to investigate different dimensions of the impact of science as they tend to focus on the results or diffusion of research outputs. However, they shed little light on how research is usually organised to achieve the impacts.

Existing studies tend to lead to a general consensus that the benefits of publicly funded research are substantial, at least in terms of economic impacts (Salter & Martin, 2001). The various impacts can be realised through a variety of channels. Martin and Tang (2007) provide a conceptual framework of the main exploitation channels, which include much broader socio-economic benefits of academic research. They classify the channels through which basic research may benefit industry into seven categories: adding to the stock of useful knowledge, supplying trained human skills, providing new instruments and analytical methodologies, giving access to professional networks and social interaction, enhancing problem-solving capacity, generating spin-off firms, and providing social knowledge. Some of these channels are hardly quantifiable. Therefore, the authors stress that the use of quantitative methods to capture the socio-economic benefits of academic research has the potential to miss those that are not easily quantifiable.

The above studies also suggest that the research impacts tend to focus on the economic perspective or on the contribution to innovation. Nevertheless, the notion of relevance involves a rather broader concern than just the direct use or application of research results. For example, Rip (1997) and Shove (2003) suggest that government R&D programmes often aim at "generalised relevance rather than a concrete mission" (Rip, 1997, p.629). The objectives of the programmes are usually stated as creating research capacity, stimulating a collaborative culture and the continuation of relevant

research after the programme finishes (*ibid*.), most of which are not easily quantifiable.

2.3.2 Problems of measuring the impact of science

Despite the distinction between relevance and impact, both share several similar evaluation problems. This section reviews the conceptual and methodological problems with measuring the relevance and impact of science.

The first problem is related to the vague definition of basic and applied research, as well as the misconceived assumption about the relationship between the two. Several large-scale studies in the late 1960s and 1970s investigated the contribution of science to innovation by tracing back the sources of innovation. Project Hindsight (Sherwin & Isenson, 1967) and TRACES (Illinois Institute of Technology, 1968) are the main examples. Both projects firstly identified the crucial scientific and technological research events underpinning major innovations. Then the researchers classified those events into three categories. While Project Hindsight used the terms 'undirected science,' 'applied or directed science' and 'technology events' according to the intention associated with the events, TRACES used those of 'non-mission research,' 'mission-oriented research' and 'development and application work.' The three categories in each of the two studies do not seem identical.

These early studies also raise two important conceptual limitations. One assumes that the categories of basic and applied research are separate and opposing, while the other assumes that innovation is a linear process, in which innovation is either driven by science push or called forth by demand pull. As shown in section 2.2.1, both concepts have been criticised as unrealistic.

The second problem is concerned with the timescale used for evaluation. The retrospective approach tracing the innovation sources gives rise to the question of how far the innovations should be traced back. As Irvine and Martin (1984) note, the twenty-

year timescale of Project Hindsight excludes any significant basic research arising before that time. The TRACES study shows that non-mission research events tended to occur twenty to thirty years before innovation. It also suggests that the gap between scientific research and application could be considerable.

The third problem is concerned with attribution and the problem with the difficulty of identifying whether and to what extent a particular piece of scientific research contributes to a specific consequence. Other factors apart from science may also affect the realisation of socio-economic benefits. Moreover, Martin and Tang (2007) address the cross-country effects, where the sources of knowledge may come from other countries and the benefits may diffuse abroad.

This brief review of the problems in evaluation practices suggests that measuring the anticipated social and economic relevance of research is not so straightforward. While the policy objectives of funding science place increasing emphasis on enhancing socio-economic benefits, there remain several challenges concerning how to effectively measure the socio-economic relevance of science at an aggregated level.

2.3.3 Examining the effects of promoting the relevance of research

As governments in major industrial countries have emphasised the relevance of science in meeting socio-economic needs and witnessed changes in funding mechanisms for university research, a number of studies raise concerns about the unintended effects on academic scientists' behaviours and on their research practices (e.g. Geuna, 2001). The following discusses these two issues respectively.

The effects of promoting relevance in scientists' research behaviour

One of the main concerns is about whether there is a change in scientists' research behaviour towards conducting relevant research under the changing rationale for

research funding. Etzkowitz (1989) argues that changes in the research conditions are producing new norms about how science should be conducted, norms that are compatible with the traditional ethos within academia (Merton, 1973). For instance, the value of science can be reinterpreted, allowing scientists to simultaneously pursue truth of knowledge and profit-making.

However, the empirical studies show a rather diverse result in terms of scientists' behavioural changes. Calvert (2001) interviewed physical and biological scientists, and policy-makers in the US and UK, asking about their perceptions of the changing research system and the effects on conducting research. Her study shows that scientists do perceive the need to make research more applied. Surprisingly, both policy-makers and scientists are not particularly concerned about this change. Furthermore, the interviewed scientists tend to think that there is little effect on conducting basic research. Other studies also find that scientists tend to adapt, rather than transform, their research behaviour in certain ways under a changing research context (Laudel, 2006; Morris, 2003; Morris & Rip, 2006). While scientists tend to 'tailor' their work to fit in with the policy requirements, their behaviour concerning the realisation of research results is subject to a number of factors. For example, Landry et al. (2001) show that social-science research projects using external funding are more likely to be used by practitioners and other related professional than those using internal university funding. In addition, projects focused on users' needs are not significantly associated to the utilisation of knowledge. The above studies imply that there is certain inconsistency between scientists' perceptions and their actual behaviour in response to meeting the socio-economic needs of their research.

In recent years, a few studies have investigated how the changing research context affects scientists' research practices by conducting a more thorough analysis. Hessels (2010) carried out three case studies in chemistry, biology and agricultural science to

investigate scientists' struggle for relevance at Dutch universities. He proposed a model combining a science-society contract and a credibility cycle (Latour & Woolgar, 1979) in order to provide a better understanding of the role of relevance in the practice of academic research. The study shows how the scientists' identities, funding rationales and research conditions have changed over the past fifty years. The author argues that the quest for relevance in scientific practices has become increasingly intensive. Paradoxically, the bibliometric evaluation of scientific performance has strengthened scientists' publishing activity endeavours. The study also indicates that policy actions tend to be inconsistent in terms of pursuing academic excellence and societal needs, thereby having limited effects on research practices.

Scott (2004) arrives at a similar conclusion by investigating the factors that influence the conduct of a social-science research programme. Using documentary evidence, and interviews with policy makers and participant researchers in the programme, he finds that the designs for social relevance of the programme are not thoroughly interdisciplinary and interactive. Furthermore, Scott's study identifies several sources of difficulty in conducting relevant research: funding sources, academic disciplines, academic organisations and personal motivations. Taking these factors into account, he argues that relevance "is not generally seen to be a central quality criterion in academic research" (*ibid*., p. 8).

Leisyte (2007) examines the effects of the governance model in higher education on the research practices used in medieval studies and biotechnology at English and Dutch universities, finding that scientists' responses depend on the level of uncertainty found in their research environment. Based on neo-institutional theory and resource dependency theory, Leisyte identifies three types of responses and strategies ranging from passive compliance, symbolic compliance, to proactive manipulation and negotiation. She finds that scientists tend to protect their academic core activities to the

greatest extent by adopting different strategies, with some even perceiving a highly uncertain environment.

Despite the diverse results in terms of scientists' behaviour in the changing research environment, the previous studies suggest that scientists tend to adapt to certain rules to fit in with the research environment, while they also try to protect some of their research practices. These studies suggest that scientific performance remains a major concern for scientists to establish credibility. Performance-based funding and evaluation practices further reinforce scientists pursuing scientific credibility more than social accountability.

The effects of promoting relevance on scientific research

Related to the first concern, literature suggests that a tighter connection between university research and industrial needs may lead to application-oriented and short-term research at the expense of long-term and risky research (Geuna, 2001). The increasing need for accountability further strengthens this unintended consequence by introducing a contractual-oriented incentive structure. This concern contradicts the view that the goals for both use and understanding can exist at the same time (Rip, 1997; Stokes, 1997), as addressed in section 2.2.1.

Empirical evidence shows that this issue is far more sophisticated. While scientists are concerned that the demand for accountability might hinder long-term research, they think that this demand only increases their paper work (Morris, 2000). As addressed earlier, scientists use different strategies to adapt to external requirements without substantially affecting their research practices. The strategies used by scientists depend on whether the funding source they perceive is secured or not, and their level of credibility (Laudel, 2006; Leisyte, 2007). Our review implies that the effect of the quest for relevance seems to exhibit influence more on scientists' behaviour than on the nature

of their research. From the perspective of scientists, the real concern lies in the availability of funding sources.

In addition to the sociological perspective on the effect of scientific research, a number of studies examine this issue by investigating the relationship between publication outputs and entrepreneurial activities (see the review by Larsen, 2011). Entrepreneurial activities include industry funding, co-publication with industry and academic patenting. In general, evidence shows that these activities and publication outputs are positively related. Nonetheless, their effect on the nature of research is rather mixed, with one reason due to the different methodologies used to operationalise the notion of basic research in different studies.

Both quantitative and sociological research help shed light on the effect of promoting relevance on scientific research from different perspectives. Nevertheless, rarely have previous studies investigated the linkage between these two approaches. The bibliographic information of a scholarly publication reveals the result of social interaction between scientists and other actors, at least in a form of formal communication. This thesis will combine sociological and bibliometric approaches in order to triangulate the findings and enrich our understanding of the relationship between scientists' behaviour and their publishing activities.

Moreover, most of the empirical work took place in the field of biology or life science, and were carried out in the national contexts of the USA and some developed European countries. The conclusions might be questionable in other national contexts, particularly concerning the relationship between university research and industry because of the different industrial structure and developmental stage. In this respect, this study provides new evidence to the intellectual debate.

2.4 Towards a conceptual framework for this study

In accordance with the literature review, this section proposes a conceptual framework to guide our empirical investigation. Section 2.4.1 introduces the three components of the framework and section 2.4.2 addresses the theoretical foundations.

2.4.1 Components of the framework

Section 2.1 suggested that the notions of 'relevance' and 'impact' should be distinguished. Since this study is centrally concerned with relevance, the notion of impact will not be discussed in the rest of this thesis. Three components make up the conceptual framework of this study. The first component concerns scientists' research behaviour when dealing with the notion of relevance, which consists of two levels. At a more explicit level, we investigate the ways that scientists organise research aimed at being relevant. This study identifies three approaches in terms of research orientation, industry involvement and interdisciplinary collaboration (see section 2.2). It is worth noting that the three approaches might be inter-related. We deal with the three approaches separately but also look at possible associations with each other.

Previous literature shows that the above three approaches of ensuring the relevance of research are not particularly straightforward. In addition, the perceptions and research behaviours of scientists tend to be shaped by a number of personal and institutional factors, and may not entirely be oriented towards achieving socio-economic relevance. One of the objectives in this study is to identify the various ways in which scientists perceive and organise their research in the above three dimensions.

At a more implicit level, we look at the behavioural patterns of scientists' responses. As addressed in the literature review, scientists tend to use different strategies when responding to policy requirements. This study categorises scientists' behaviour using two concepts: adaptation and persistence. What we mean by adaptation is that

scientists tend to show their agreement with, or compromise, to the external requirements to a certain extent without substantially affecting their actual research behaviour. The concept of adaptation is somewhat equivalent to 'tailoring' behaviour put forward by Calvert (2001) and to the 'scaffolding' metaphor suggested by Morris and Rip (2006). Both studies also point to scientists' adaptive behaviours, finding that scientists tend to strategically show their compliance to policy requirements but without significantly affecting their research practices. Such adaptive behaviour is usually used by scientists to retain or project their self-image while securing resources.

This study extends existing knowledge on scientists' research behaviour by introducing the notion of persistence, showing that scientists are not always adaptive to external forces but might retain their research interests in some of their research behaviour. By persistence, we mean that scientists' behaviour tends to be motivated mainly by their own intentions and is rarely adjusted in light of external pressures. We need to point out the differences between the term used in this study and that in the literature. Ziman (1987) uses the same term 'persistence' in his study of changing research specialty in scientific careers. Similarly, Debackere and Rappa investigate the factors that influence scientists' choices and persistence in emerging fields of science (Debackere & Rappa, 1994; Rappa & Debackere, 1995). Their studies find that scientists who enter a new field early tend to remain in the field. In addition, they argue that early entrants are mainly motivated by their own perceptions of intellectual problems rather than by external factors, such as available funding and reward systems.

While existing literature related to the notion of persistence tends to focus on the changes of scientists' *research subjects* throughout their academic career, our study focuses on changes in scientists' *research behaviour*, specifically in the three dimensions identified in the conceptual framework. Nevertheless, these two aspects are related. Our review shows that career path is an important factor that influences

scientists' decisions on the involvement of activities aimed at achieving relevant research.

The second component concerns the relationship between scientists' research behaviours and their publishing activities. As addressed in the first component, the inconsistency between scientists' perceptions and research behaviours raises questions about, first, what kinds of research behaviour have really changed or been changing and, second, how the behaviour of scientists is associated with their publishing activities. The second objective of this study is to investigate the relationship between scientists' research behaviours and their publishing activities.

The third component takes into account the personal and institutional factors that may exert an influence on scientists' perceptions and behaviours. The existing literature indicates that institutional contexts give scientists mixed incentives to organise relevant research. On one hand, for instance, the organisational structure and reward system are very much disciplinary based, thereby providing barriers for interdisciplinary collaboration. On the other hand, institutions generally give scientists freedom of choice to engage in interdisciplinary activities. Overall, relevant research seems to be produced by a minority of highly motivated researchers (Morris & Rip, 2006; Scott, 2004). Although literature suggests that personal motivation tends to be a strong factor, cumulative knowledge and experience appears to be the main motivation behind scientists' behaviour. This study will investigate how scientists' behaviour is shaped and evolved by the interaction between personal and institutional factors.

2.4.2 Theoretical foundations: a resource-based perspective on the notion of relevance

This section introduces three theoretical perspectives to establish and interpret the relationships between the three components put forward in section 2.4.1 and to serve as a framework for interpreting the results. We combine the theories of boundary work

(Gieryn, 1983), principal-agent relationship (Braun & Guston, 2003; Guston & Keniston, 1994) and credibility cycle (Latour & Woolgar, 1979) as the analytical foundations of this study.

The fundamental premise is that the notion of relevance is a resource-based concept. As shown in section 2.1, 'relevance' is usually served to justify funding decisions. On one hand, policy makers allocate budgets in accordance through the prioritisation of socio-economic importance. On the other hand, scientists need to secure funding in order to carry out their research projects. In a changing research environment context, industry or other stakeholders emerge to serve as an alternative source of funding. Organising relevant research thus suggests that scientists will interact with other non-academic actors and scientists from different disciplinary backgrounds more frequently during their research process. The interaction among scientists, government bodies and other stakeholders can be interpreted as an activity of exchanging resources. The following introduces the main concept of each theory, the relevant perspectives applicable to this study and the limitations of the theory.

Boundary work

Boundary work is often used to understand how scientists flexibly draw a rhetorical boundary between science and non-science by attributing selected qualities of science in different circumstances. It is a particularly effective tool for interpreting a scientist's behaviour for securing the intellectual authority of science when one's credibility is highly contested. Gieryn (1983) argues that the ambiguous notion of science enables scientists to construct a space in the pursuit of authority, resources and the protection of their autonomy. He further puts forward that boundary work is also useful for "ideological demarcations of disciplines, specialties, or theoretical orientations *within* science" (*ibid*., p.792). He uses the concept of 'strains' and

'interests' to explain the inconsistent attributes selected by scientists. As Gieryn (1983) notes,

> "Alternative sets of characteristics available for ideological attribution to science reflect ambivalence or strains within the institution: science can be made to look empirical or theoretical, pure or applied. However, selection of one or another description depends on which characteristics best achieve the demarcation in a way that justifies scientists' claims to authority or resources" (p.781).

Gieryn (1983) identifies three forms of boundary work: expulsion, expansion and protection of autonomy. When the epistemological authority of science is challenged by rival authorities, scientists tend to monopolise the authority and resources by excluding rival professions as pseudoscience or by heightening the contrast between science and non-science. In the pursuit of scientific autonomy and public support, scientists tend to differentiate the features between science and its applications on one hand, while claiming the practical contribution to technological progress on the other. As shown previously, the issue of autonomy and accountability remains a central issue both for policy makers and scientists in terms of organising relevant research.

Accordingly, boundary work provides a suitable framework for us to investigate what is at stake for scientists involved in organising relevant research. As addressed in sections 2.1 and 2.2, the notion of relevance and the three criteria for organising relevant research are usually not clearly defined in policy practices. Furthermore, they provide certain incentives and create tensions for scientists during their research practices. Therefore, we expect that ambiguous notions related to 'relevance' enable scientists to do boundary work, thereby exhibiting inconsistency between scientists' perceptions and behaviours.

Given that changes to the research context are conceived as the blurring of boundaries between science and society, one may question whether the conception of

boundary work is still a useful tool in the current context. Jacob (2005) argues that this analytical device remains relevant in contemporary science policy. She examines boundary work and related notions in parallel with the policy instruments for closing the gap between science and society, concluding that new policy practices aimed at bridging the boundaries have paradoxically created new layers within science. Jacob's analysis also implies that the traditional form of research practices seems to be persistent to a certain extent (Calvert, 2001; Hessels et al., 2011; Leisyte, 2007; Waterton, 2005). On the other hand, several studies find that some scientists tend to adapt to the changing research context by taking different strategies ranging from more proactive to passive ones (Leisyte, 2007; Morris, 2000, 2003; Morris & Rip, 2006). Therefore, this study expects that scientists do not fully conform to the external rules of achieving relevant research. We investigate in what ways scientists are more adaptive in some practices while more persistent in others in terms of organising relevant research.

While the concept of boundary work is useful for analysing how scientists may respond to a disputed activity, it does not deal with why and in what circumstances some, not all, scientists feel under threat in the same activity, and what the consequences might be. The following presents the perspectives of principal-agent theory and credibility cycle to complement the view of boundary work.

Principal-agent theory

Principal-agent theory, which has been developed in the context of rational choice and transaction cost theory, was increasingly applied as a rigorous analytical tool for science policy-making in the 1990s (Braun & Guston, 2003; Guston, 1996; Guston & Keniston, 1994). This theory focuses on the social relationship of two actors in the exchange of resources. The main idea is that the principals, because they are incapable of performing certain tasks, provide resources to the agents, who in turn agree to realise

the interests of the principals. In science policy, the principal is mainly the state. The ultimate agent is the research community. Funding agencies responsible for implementing policy can be viewed as the agent of the state and as the principal in the relationship with scientists. Moreover, as shown in section 2.2, industry has emerged to act as the principal to provide alternative funding and may direct scientists' research agendas. In practice, the principal-agent relationship is far more complicated (e.g. Braun & Guston, 2003; Shove, 2003; van der Meulen, 1998). This study focuses on the relationship between funding administration, research community and industry.

In science policy, the principal-agent relationship mainly deals with the problems of delegation: the potential conflict of goals and information asymmetry between the two actors (Guston, 1996). These problems give rise to two major concerns; one concerned with whether scientists will really do their best to fulfil the tasks delegated by policy makers (moral hazard problem) and the other with whether funding agencies can find the best candidates to do the tasks (adverse selection problem). In order to stablise the relationship between funding bodies and scientists, policy makers have introduced certain mechanisms to enhance shared goals or minimise the shirking behaviour of scientists.

While boundary work focuses on scientists' behaviour, the principal-agent perspective reduces the foci of scientists' behaviour. Guston (1999) suggests that the two perspectives can be nicely complementary. He proposes looking at boundary-work under the structure of the principal-agent relationship in order to obtain the logic of the policy and the institutional arrangements for implementing the policy. This enables us to focus on the important activities of boundary-workers and interpret the implications of scientists' behaviour in response to policy requirements. Morris (2003) examines the interests and strategies of academic researchers in a UK context using the principal-agent model. She identifies four contextual features that create a space for scientists to

manipulate and reduce conflicts of interests between principals and agents.[6] Previous

studies prove that the two perspectives complement each other.

Credibility cycle

While the previous two theoretical perspectives focus on the interaction between

scientists and other actors in a specific institutional context, the concept of the

credibility cycle helps us understand scientists' behaviours and the underlying

motivations during the entire scientific production process. Latour and Woolgar (1979)

introduced the notion of the credibility cycle, arguing that scientists' behaviour can be

described as a cycle of converting one form of credibility into another. They distinguish

between credit as reward and credit as credibility, stating:

"Credit as reward refers to the sharing of rewards and awards which
symbolise peers' recognition of a past scientific achievement. Credibility, on
the other hand, concerns scientists' ability actually to do science" (Latour &
Woolgar, 1986, p. 198).

The above definition implies that the key driver for scientists to dedicate

themselves to conducting research is to gain peer recognition, thereby in turn receiving

more resources to invest in their credibility. Therefore, scientists' behaviour can be

conceptualised as a continual cycle of investing credibility in the process of conversion

between "money, data, prestige, credentials, problem areas, argument, papers, and so

on" (*ibid*., p.199). The credibility cycle concept enables us to identify the different

interests and motivations of scientists at different stages of the cycle, as well as explain

scientists' behaviour in their social relations.

Based on the credibility cycle concept, this study identifies three major types of

resources that enable scientists to establish their credibility: financial, symbolic and

---

[6] The four contextual features are common goals and shared perceptions, multiple principals, alternative
accountabilities and underground of trust.

intellectual capital.[7] Financial capital is a prerequisite for scientists to acquire symbolic and intellectual capital (Braun, 1998; Morris, 2003). Scientists convert financial capital into tools, research facilities and the recruitment of researchers to help carry out a research project. Symbolic capital refers to scientists' credit and recognition,[8] a kind of resource reflecting scientists' cumulative competence and social authority (Knorr-Cetina, 1982). Symbolic capital is considered a driving force for scientists to seek a powerful position to fulfil their research purposes (Braun, 1998; Knorr-Cetina, 1982; Latour & Woolgar, 1979). Intellectual capital refers to the quality and capacity of collaborators working with a scientist and can be regarded as a set of knowledge, skills and experience embodied in the collaborators.

While the credibility cycle has been criticised for its quasi-economic logic about the capitalist market of science (Knorr-Cetina, 1982), we consider the model, in a broader sense, to be a useful framework for capturing the main drivers and behaviour of scientists. We assume that scientists are involved in negotiating their resource relationships, as suggested by Knorr-Cetina (1982). Instead of looking from an internalistic perspective, we are thus concerned with both scientists' resources and their dependence on the institutional support by complementing the view of principal-agent theory. Previous studies have investigated scientists' actions or the role of funding agencies in a changing research context by using the credibility cycle concept (Hessels, 2010; Leisyte, 2007; Rip, 1994). The model has been proven to be a useful analytical framework.

---

[7] c.f. Braun (1998) classifies the motivations of scientists into three aspects in a broader sense: social, economic and cultural capital.

[8] Knorr-Cetina (1982) distinguishes the notions of credit and recognition. Recognition is a form of reward that serves as a mechanism to reinforce the essential behaviour of scientific production. Credit is denoted as symbolic capital gained as a result of the scientific production.

2.5 Summary

This chapter began by reviewing the notion of relevance addressed in existing literature. We found that the notions of relevance and impact are often used interchangeably and tend to refer to different levels of analysis with various foci in evaluation practice. Our study suggests that we should distinguish the two notions to ascertain a better understanding of their relationship. We further identified three major approaches of organising research that help ensure the relevance of research in terms of research orientation, industry involvement and interdisciplinary collaboration. Although the three practices have been widely promoted by policy makers and analysts, their definitions and how they achieve relevance are rather ambiguous. In addition, they challenge the conventional ways of conducting research by the scientific community, thereby raising the question about how scientists perceive the relevance of research and the possible effects it has on their publishing activities.

The demand for relevant research is also concerned with how we can measure the anticipated results. We briefly reviewed studies measuring research impacts using different perspectives, showing that there remain conceptual and methodological problems as to how one can effectively measure the impact of research at an aggregated level. We turned to examine the effects of promoting relevant research on scientists' behaviours and research practices. The picture of research activities at the level of individual scientists is more sophisticated. Moreover, scientists' perceptions and behaviours concerning the relevance of their research are less well covered. On the basis of the review, we proposed a conceptual framework to guide our empirical investigation. The next chapter presents the research design and methodology used in this study.

Chapter 3

Research Design and Methodology

The previous chapter proposed a conceptual framework to investigate the relationship between scientists' perceptions of relevance, their research behaviour and their publishing activities. This chapter addresses the research design in the empirical work. The literature review suggests that sociological approaches help us understand the differences between how scientists perceive their environment and how they actually behave. In addition, quantitative methods have usually been used to examine the relationship between scientists' behaviours and their academic performance. This study uses a sociological approach as the guiding framework and adopts bibliometric methods to enrich and expand our understanding of the empirical results.

Section 3.1 addresses the research questions and the rationale for the integration of sociological and bibliometric approaches in this study. It also explains why semi-structured interviews are a more appropriate qualitative method to collect data. Section 3.2 describes the interview method. This section presents why and how we selected the university scientists who have conducted nano-related research in Taiwan. The interview procedure will then be introduced. Section 3.3 presents the bibliometric and statistical methods applied in this thesis. It initially elaborates how research behaviour and scientific performance are operationalised in bibliometric terms before introducing the data collection, data processing and classifications, and the data analysis of the bibliometric records. Section 3.4 discusses the limitations of the methodology.

3.1 Research questions and methodology

The primary aim of this study is to gain a better understanding of scientists' behaviour organising university research that is aimed at achieving socio-economic relevance. The main research question is:

How should we understand the socio-economic relevance of research in terms of scientists' perceptions, research behaviour and publishing activities?

Empirically, this study investigates the above research question in the context of nanomaterials research in Taiwan, asking:

1 How do university scientists perceive and organise research that aims to be relevant?

2 What is the relationship between scientists' research behaviour and publishing activities?

In order to obtain valid and reliable findings, we need to clarify the unit of analysis and the nature of this study. The research questions suggest an investigation at the level of individual scientists working in universities. Therefore, academic scientists are the main unit of analysis and source of information. The two research questions show that we are not only interested in scientists' behaviour during the research process but also interested in how research behaviour relates to scholarly publications.

A second issue concerns the nature of this study. In general, the research questions are exploratory. As shown in Chapter 2, the term relevance and various related notions can refer to a variety of dimensions at different levels, thereby allowing different groups to interpret these notions for their own purposes. Although we have clarified the notion of relevance and conceptualised the term in three dimensions, the purpose of the empirical work is to identify the variety of ways that scientists may refer to relevance according to the conceptual framework. Moreover, we are not only interested in how

university scientists perceive relevance and actually behave but also in their underlying assumptions and rationales. Quantitative methods, such as surveys, are not as successful in obtaining this information as qualitative methods. Therefore, a qualitative approach seems more appropriate for this study.

Among the various qualitative techniques, this study uses semi-structured interviews to collect the data. As noted by Richardson et al. (1965),

"In a study of motives, attitudes, skills, opinions, health - or of anything else that is 'inside' an individual and is not directly reflected in observable behaviour or appearance - the interview is often used in conjunction with observation and documents" (pp. 19-20).

The advantage of using interviews is that it helps get close to scientists' meanings and the contexts of their responses. Through immediate interaction with informants during interviews, we will be able to ensure that our interpretation of interviewees' accounts reflect what the respondents mean. Semi-structured interviews allow scientists to freely express their experience and ask new questions while being interviewed under a developed framework. Moreover, face-to-face interviews with one individual scientist at a time is regarded as a better technique than phone interviews and group interviews because scientists will be able to elaborate on their own perspective more easily when being interviewed in person.

A participant observation seems to be less effective for this study. As shown in Chapter 2, the notion of relevance can be implemented in different forms across the entire research process. Given the time constraint of this project, data collected by observing only one or a few cases would not provide sufficient evidence under the conceptual framework. Compared with interview techniques, however, a participant observation has the advantage of learning how scientists actually behave in detail. It is worth noting that scientists may not present what they really think and do if they feel

that seeking relevant research is a sensitive issue. Section 3.2.2 will address the interview strategy used to check the claims made by the scientists. In addition to the interview data, this study incorporates bibliometric data to enrich our understanding of scientists' actual behaviours and its relationship with publishing activities.

The strengths of bibliometric sources are that they are stable, unobtrusive, informative and offer broad-coverage (Yin, 2009). Since the development of large databases of scholarly records, the full bibliographic information contained in a rather standardised form provides an alternative perspective of scholarly communication and allows for comparison if a research study is designed appropriately. This thesis deals with the ways that scientists incorporate socio-economic concerns into their research process, a process involving the communication of scholarly information through formal and informal channels. Bibliographical information can be served as written records of formal communication channels (Borgman, 1990).

Using bibliometric methods tends to raise a question about what exactly the indicators measure (Leydesdorff, 1989). This question concerns the degree of reliability and validity of bibliometrics. One advantage of bibliometrics is its high reliability since the data derived from standardised databases can be replicated (Borgman, 1990). Although individual records may contain some errors, such as misspelling and variations of the same names, they can be corrected and cleaned.

Most of the criticisms of bibliometrics are related to the validity - the degree to which bibliometric tools measure what they claim to measure. A vast volume of studies have attempted to clarify the extent to which bibliometric data, such as co-authorship and citations, are applicable in policy studies (e.g. Bronmann & Daniel, 2008; Katz & Martin, 1997; Lundberg et al., 2006; Martin, 1996; van Raan, 2005a). One of the common conclusions is that using only bibliometric indicators provides an incomplete picture of policy-related issues and may lead to misinterpretation of the results. Studies

suggest that bibliometric indicators better serve as a support to other measures or evidence (Borgman, 1990; van Raan, 2005a). Section 3.3 will present the bibliometric techniques used in this study, with the reliability and validity also discussed.

In summary, the empirical enquiry of this study is guided by a sociological approach, within which we adopt semi-structured interview and the support of bibliometric methods to generate and analyse data. The next section describes the interview method.

3.2 Description of the interview method

This section presents how we selected the data sources of interviewees and the interview procedure.

3.2.1 Choices of data sources

The choice of nanomaterials research in Taiwan

The research questions and the methodology described in Section 3.1 have guided our sampling decision. We selected university scientists who have conducted nanomaterials research in Taiwan as the unit of analysis. As addressed in Section 1.4, the field of nanomaterials research has been chosen because materials science appears to be widely regarded as a bridge between science and application. The policy significance of the field is one of the main criteria for our choice. Over the past decade or so, nano-related research has attracted abundant resources and researchers. It has been one of the main prioritised subjects to be funded in most industrialised countries in the hope that the scientific breakthrough of nanotechnology will produce innovative applications and enhance industrial competitiveness. Given its multidisciplinary nature, nanomaterials research covers a wide range of disciplines, but narrow enough as a subject for investigation. Therefore, we took the field of nanomaterials as a point of departure to

select interviewees.

The university was decided as the site for choosing the sample scientists. Previous literature suggests that university scientists may encounter more tensions when pursuing scientific excellence and socio-economic relevance because their funding source is mainly from government budgets. The conceptual framework of this study may be applicable to other organisational settings in public research institutes (PRIs), although the institutional set-ups and culture of PRIs are different from that in universities. However, our second research question concerning the relationship between scientists' behaviours and publishing activities is less applicable to PRIs since publishing in scholarly journals appears not to be the major research output of PRIs.

We have chosen Taiwan as the empirical context. As Chapter 4 will show, Taiwan has followed a similar trend of changing the rationale for university funding over the past sixty years. Although universities in Taiwan have adopted the American model of higher education, the institutional arrangements and the relationship between university and society are rather different from those in the US. Few studies, however, have investigated this context.

The selection of interviewees

In order to cover different scientists' views within the nanomaterials field, the interviewees were selected according to criteria including discipline (natural, medical and engineering sciences), seniority (senior and junior), and funding level (individual projects and national programmes). Nanomaterials research is intrinsically multidisciplinary and is not confined within the clear-cut boundary of a particular scientific field. Therefore, it is not adequate to choose scientists from only a few university departments. The list of the potential interviewees was mainly ascertained

from a keyword search[9] of the Government Research Bulletin (GRB), a database containing information on publicly funded research projects in Taiwan. Since there is no consensus on the scope of nanotechnology, the information on funded scientists was cross-checked with other sources of information, such as their research specialties and publication outputs listed on their personal websites.

We decided to focus on scientists in the main publicly funded universities because they are the main actors who receive a large share of research projects and who tend to publish their results in scholarly journals.[10] Although the university culture might be different, scientists at national universities usually share a similar research mission and are regulated by similar funding rules and reward systems. Considering the time constraints of this study and the diversity of scientists involved in nanomaterials research, the interview sample of scientists from national universities appears to be representative of the purpose of this study.

In total, 34 interviews were conducted. Table 3.1 presents the descriptive information of the 34 interviewees. Seven scientists are ranked as assistant or associate professors and 27 full professors at the time of interview.[11] Three interviewees are female scientists. Research experience represents the number of years from the award of the interviewees' doctoral degrees to 2010. The years of research experience ranged from 6 to 35, with an average of 18.5 years. Five of the interviewees (with 10-15 years of research experience) had just been promoted to the rank of full professor from 2007-2009.

---

[9] The search strings include nano and (1D or 2D or 3D or catalysts or thin film or composite or self-assembly) nanoparticles, carbon nanotubes and nanomaterials (in Chinese) in project titles or keywords.

[10] National universities in Taiwan tend to be regarded as more prestigious and research-oriented than private ones due to the historical development of the higher education system (see Chapter 4). Therefore, national universities tend to attract talented academics and receive more public resources.

[11] The interviews were conducted across periods: November 2008 - January 2009 and April-July 2009.

Table 3.1 Distribution of scientists interviewed

Academic position & research experience / Affiliated department	Assist. or Assoc. Professor			Full Professor			
	<10 years	10-15 years	**Total**	10-15 years	16-20 years	>20 years	**Total**
Physics	1	2	**3**	2	2	3	**7**
Chemistry		2	**2**	1	4		**5**
Chemical and Material Sciences		1	**1**	1	1	6	**8**
Electrical Engineering					3	1	**4**
Mechanical Engineering	1		**1**			1	**1**
Medical Engineering				1		1	**2**

Source: calculated by the author.

We decided to distinguish between junior and senior interviewees by their research experience, rather than by academic position. Our interviews suggest that even several scientists just promoted to the rank of full professor regard themselves as relatively junior compared to their well-established peers. Scientists' behaviours when organising research seems to be influenced more by their research experience than academic position, although these two factors tend to be related. Based on the interview observation, this study considers that junior scientists are those with fewer than 15 years of research experience.

In addition, we categorised scientists' disciplines by their affiliated university departments. One main reason is that we are more interested in scientists' social interactions across departments in terms of interdisciplinary collaboration. As shown in the literature review (section 2.2.3 and section 2.3.3) and discussed later in respect to the policy context in Taiwan (section 4.1.4), policy practices tend to place emphasis on creating a collaborative culture across institutional boundaries to produce interdisciplinary research. It is assumed that university departments tend to be disciplinary oriented. We will investigate how the disciplinary structure affects

scientists' interdisciplinary collaborations.

The names of scientists' affiliated departments were unified and classified on the basis of the disciplinary code developed by the Ministry of Education (MOE) in Taiwan. The MOE classification code (see Appendix 3.1) is based on the International Standard Classification of Education (ISCED) designed by UNESCO in the 1970s. The purpose of the ISCED classification scheme is for education policy and decision-making.

The classification scheme raises a question concerning the extent that departmental structures reflect scientists' disciplinary backgrounds. For example, a scientist may work in a department that is different from his/her postgraduate training. A multidisciplinary-oriented department, such as that of materials sciences, may consist of faculty with various disciplinary backgrounds. We examined this issue by mapping scientists' affiliated departments to their educational backgrounds.

Our study shows that scientists' training tends to be very discipline oriented. Seldom have they shifted their academic training to different disciplines.[12] Moreover, most interviewees were trained and have held an academic position in the same disciplinary department since their undergraduate degrees. Table 3.2 shows that 25 scientists' (76.5%) affiliated departments are exactly the same as their doctoral disciplines. Two chemists' doctoral disciplines appear to be sub-disciplines of chemistry (in Analytical Chemistry and Biochemistry).

The table reveals that scientists in this study tend to pursue their academic work in the same or neighbouring disciplines as those in their doctoral training. Moreover, it shows that departmental structure tends to be discipline oriented, meaning that the academic faculty of a department is usually from the same or similar educational backgrounds but with different research specialties. Nevertheless, this preliminary

---

[12] Only three interviewees shifted their academic training from physics/chemistry in their Bachelor degrees to engineering in their PhD degrees or vice versa.

observation needs to be supported by further examining the departmental structure as a whole.

In short, the mobility of scientists seems to be lower than that in Western countries. In our sample, only two interviewees had once moved across universities in the same disciplines. Most of the interviewees stayed in the same universities since finishing their post-doctoral studies and had been there for a period of time. The low degree of mobility in academia may be related to the standardised compensation policy that is based on academic rank and seniority. In addition, the scientists interviewed are affiliated to national universities, which are considered more prestigious than private ones. Another cultural reason might be that a position in academia in Taiwan is often regarded as a stable job, especially in national universities.

Table 3.2 Mapping scientists' affiliated departments and their doctoral disciplines

Scientist	Current department	Doctoral discipline	Scientist	Current department	Doctoral discipline
08	Physics	Physics	02	Electrical Engineering	Electrical Engineering
14	Physics	Physics	07	Electrical Engineering	Electrical Engineering
19	Physics	Physics	10	Electrical Engineering	Electrical Engineering
23	Physics	Physics	17	Electrical Engineering	Electrical Engineering
25	Physics	Physics	04	Chemical Engieering	Chemical Engineering
27	Physics	Physics	29	Chemical Engieering	Chemical Engineering
32	Physics	Physics	09	Chemical Engieering	Chemistry
33	Physics	Physics	21	Chemical Engieering	Polymer Engineering
26	Physics	Physics	18	Materials Sciences	Chemistry
35	Physics	Materials science	16	Materials Sciences	Materials science
05	Chemistry	Chemistry	22	Materials Sciences	Materials science
20	Chemistry	Chemistry	11	Materials Sciences	Metallurgy and Materials Engineering
30	Chemistry	Chemistry	03	Nuclear Engineering	Nuclear Materials
31	Chemistry	Chemistry	28	Mechanical Engineering	Aeronautics and Astronautics Engineering
12	Chemistry	Analytical Chemistry	15	Mechanical Engineering	Mechanical Engineering
24	Chemistry	Chemistry and Biochemisty	06	Medical Engineering	Materials science
34	Chemistry	Nuclear Science	13	Medical Science	Medical Science

Source: Interview data developed by the author.

Note: Grey columns refer to the scientists whose affiliated departments in 2010 are not exactly equivalent to their doctoral disciplines. The classification of current departments is based on the disciplinary scheme developed by the Ministry of Education.

3.2.2 Interview procedure

<u>Preparation for the interview</u>

In order to better understand the policy context in Taiwan, a secondary analysis of public documents was initially carried out to build up background knowledge on related policy practices. The sources of documents include:

- National Science Council Review (1963-2007, every year)

- The documents of the National S&T Conferences (1978-2008, every four years)

- S&T White Papers (1997, 2003, 2007)

- Basic Guidelines of the S&T Development: 2008-2011 (2008)

- The Manual of National S&T Programmes (2003)

- Master Plans of the Nano Programme (2002, 2008)

The purpose of the analysis was to identify the changes in funding rationales over time, the policy instruments used and the context of promoting nanotechnology research. The preliminary analysis confirms that the funding of nanotechnology research in Taiwan provides an appropriate context for our empirical work. As we will show in Chapter 4, the policy practices associated with organising nanotechnology research tend to emphasise interdisciplinary collaboration or industry involvement to legitimise funding, notions that are closely related to the conceptual framework of this study.

Moreover, four key officials were interviewed in order to gain a more realistic understanding of the science-policy context and the settings of nanotechnology programmes in Taiwan. The interviews will further serve as a cross-check of the analysis of the policy context in Taiwan in Chapter 4. During my fieldwork, I attended the Preparation Conference for the Eighth National S&T Conference (1~2 December, 2008) to learn about discussions related to this research topic. In addition, I attended a workshop promoting university-industry collaboration in nanotechnology. The materials

ascertained from these activities are not directly used in the empirical analysis. Nevertheless, attending these activities served to illuminate the current situation and key issues.

On the basis of the research questions, a list of interview questions was developed. Prior to the main interviews with scientists, two senior scientists were interviewed as a pilot test of these questions. Each of the interviews lasted for two hours and provided a rather comprehensive discussion about the related institutional arrangements and funding policies of the current research environment in Taiwan. These accounts served as potential 'stimuli' to trigger more in-depth discussions with the interviewees during the main fieldwork.

Most of the candidate interviewees were contacted via emails, followed by phone calls and emails again if contact became difficult. Some interviewees were approached directly through recommendations from their peers. Once an interview was confirmed, their summaries of research projects and personal profiles on the websites were browsed in order to have a broad idea about their backgrounds and research experience, as well as to get some technical keywords for their research subjects.

Interview strategy

The face-to-face interviews lasted approximately one and half to two hours and were semi-structured. The conversation was mainly in Mandarin Chinese, which is the main native language in Taiwan. The interviewees sometimes used certain terms in English during the conversation. The quotations of the interviewees presented in this thesis were literally translated into English in the context of the conversation by the author. All the interviews were recorded with the interviewees' agreement.

The interviews were held in scientists' workplaces and the process generally went smoothly. When interviewing, I first introduced myself and my educational background,

and then briefly introduced the research purposes and the broad questions I wanted to ask. I also confirmed that the interviews would be treated confidentially and the results quoted in the thesis would be anonymous. This introduction helped gain their trust about my research motivation and to demonstrate that, science wise, I have basic knowledge about nanotechnology. The list of the interview questions is presented in Appendix 3.1. At the end of the interviews, some key points of the discussion were summarised and confirmed with the interviewees. After concluding the interviews, the conversations were transcribed and the collected data coded using NVivo software.

During the interviews, I attempted to be vague and neutral towards the research questions, allowing scientists to express their own ideas. I put forward the questions in an open-ended manner. If necessary, I provided some examples and asked about their own experience. The conversation started by talking about when the interviewees began to get involved in nano-related research. Most interviewees referred to the time of their doctoral training and positioned their research in a field (e.g. surface science, semiconductor or materials science) or a research area (e.g. catalyst, lithography or alloys). By asking this question, we have a historical perspective of whether and how scientists' research practices have changed over time.

Although I identified three main criteria for organising research aimed at being relevant in the conceptual framework, during the interview, I did not propose them as pre-determined criteria for organising 'relevant research' but did ask the related questions and wait for the scientists' responses. The interviews generally proceeded in a fluid way, depending on scientists' feedback, rather than on the list of prepared questions. I aimed to open up scientists' views on the notion of relevance. Nonetheless, as shown in Chapter 5, most scientists perceived the 'relevance' of nanotechnology research as an application for industry, even though they interpreted 'application' in various ways.

Any data gathering method will encounter accuracy problems. An interviewee may have a faulty memory and may intend to hide what they really think and do for their own purposes. I was aware that the topic of relevant research might pressure scientists. To avoid getting spurious answers that conform with the government's view, I sometimes took the opposite stance and asked their opinions. In this way, they often provided some of their own experiences as examples to support their claims or further explained their ideas. In addition, document sources were used as a concrete example for getting further information. In my preparation for the interviews, I took notes on the key profiles of the interviewees, such as whether they have been involved in large-scale projects, university-industry collaboration and technology transfers. During the interviews, I encouraged them to talk more about their experience in these activities. These strategies help uncover what scientists actually think and do.

Problems encountered and lessons learned

The main problem during the fieldwork occurred when contacting potential interviewees. In the early stage of the fieldwork, there were very few positive responses to the interview invitation. The main reason was the timing, with the scientists mainly declining an interview because they were busy writing grant proposals for the end of the year. Moreover, some scientists were suspicious of my role and intention. For example, one interviewed scientist was very cautious at the beginning when I introduced myself. He kept asking about my educational background, work experience, what is meant by nanotechnology and whether I know the government staff responsible for nanotechnology funding, etc. Later on, he explained that he has to be cautious in case the underlying purpose of my interview was to "steal" his ideas on behalf of a certain company. Over a phone conversation, another scientist questioned why she was chosen and whether my intention was to "check" whether she actually fulfilled what she

proposed conducting in her original research proposal. Although I explained the purpose of my research in a neutral manner, she declined my interview invitation by saying that her research was not related to nanotechnology very much. In hindsight, her concern appears to reveal the moral hazard problem, a key issue of principal-agent interaction addressed in Chapter 2. All these responses imply that the issue of relevance raises certain tensions for scientists and it should be treated carefully.

It is worth noting that some scientists who rejected my request for an interview responded that they did not do nano-related research, even though they have been funded and published research in international journals. Their responses may be only an excuse to get out of being interviewed. On the other hand, several interviewed scientists frankly stated that the notion of nanotechnology is as a political term and money matter. Some interviewees said that they would not highlight the term nano as their research subject. For example, one scientist said that "I don't care whether it [the research subject] is in nano-scale or not, I attribute it to the biotechnology industry" (Scientist 19). Another scientist criticised the abuse of the term nanotechnology as an advertising trick, thereby creating many nano-products of different quality in the market. As a materials scientist, he would consider the materials as inorganic materials rather than nanomaterials (Scientist 30). The interviewed and non-interviewed scientists' responses show that, like the notion of relevance and other policy languages, the term nanotechnology exerts an influence on scientists' perceptions and behaviours. As suggested by previous studies (Calvert, 2001; Morris & Rip, 2006), scientists tend to adapt their behaviour for different purposes.

In summary, despite the problems with confirming interviews, the non-interviewed scientists' responses seem aligned with the theoretical explanation of scientists' behaviours put forward in this study. In addition, the scientists' responses indicate that the notion of relevance seems to raise certain pressure for them.

Interview analysis

After finishing the fieldwork, a list of the interviewees' profiles was developed in accordance with the curriculum vitaes on their websites and the database of researchers maintained by the government.[13] The content of each scientist's profile included educational background, work experience, academic career, research specialty and research interest, as well as involvement in university-industry collaboration, patenting, licensing and technology-transfer activities. The information was used as a reference to cross-check and categorise the interview data.

After transcribing the interview data, the texts coded and categorised according to on the conceptual framework developed for this study. The method was inspired by Creswell's suggestion (2007) and Calvert's analysis (2001) in her study. Similar keywords of the texts were coded under the same label. For example, the label 'basic-oriented research' contains keywords such as basic research, understanding of properties, pure, theorising and fundamental. The related quotations were grouped as evidence of the coded label.

In addition to attaching the keywords to a label, the texts were also coded based on my interpretation of the underlying meanings of the data. The interpretation went beyond what scientists directly said and was based on the arguments suggested by the literature. For example, the label 'linear view' emerged from several scientists' statements in which respondents appeared to imply that basic research is a priori to applications. The classifications by different dimensions were further thematised. The themes were then interrogated in a broader context, providing insights for the research questions. Conflicting views about the same issue were compared and analysed to distinguish which factors influence scientists' perspectives. In the end, the relationship

---

[13] https://nscnt07.nsc.gov.tw/WRS/

between various themes and the supporting evidence was developed, thereby informing the main argument of this thesis.

3.3 Bibliometric and statistical methods

In addition to understanding scientists' perceptions towards the relevance of their research (Research question 1), we are interested in how their research is actually organised and the relationship between their research behaviours and publishing activities (Research question 2). The bibliometric methods extend our understanding of the second research question. This section describes how we operationalise the conceptual framework in bibliometric terms (Section 3.3.1). It then addresses the collecting (Section 3.3.2), processing (Section 3.3.3) and bibliometric data analysis (Section 3.3.4) methods.

3.3.1 The operationalisation of scientists' research behaviours and performance measures

On the basis of the conceptual framework of this study (see section 2.4, Chapter 2), we operationalise scientists' research behaviours in three dimensions, which are reflected in the bibliometric records. The first concerns research orientation. We adopted the journal classification system (2010 version) developed by the Patent Board, formerly the CHI Research Inc., to categorise the research orientation of a publication into four research levels. They are:

Level 1   Applied technology

Level 2   Engineering-Technological science

Level 3   Applied and targeted basic research

Level 4   Basic scientific research

The classification scheme is based on each journal's citation behaviour, which assumes that more applied journals tend to cite more basic ones (Narin et al., 1976). On the other hand, basic-oriented journals tend to cite journals in their own area of fundamental knowledge. In our study, we assume that scientists who considered their research basic in nature would publish papers in more basic-oriented journals.

It is worth noting that this journal scheme is better interpreted as the degree of basicness rather than as a linear scale of innovation. Although it is somewhat arbitrary to a certain degree, it provides an alternative perspective to investigate the changes of research orientation at a more disaggregated level rather than by the dichotomy of basic/applied research. We also note some limitations with the journal scheme. Firstly, the degree of basicness at the journal level does not entirely correspond to the research orientation of the papers published in that journal. While another study proposes the words in the title of a paper to categorise the research orientation at the publication level (Lewison & Paraje, 2004), this can only be applied in biomedical fields. Secondly, the research level of a journal may shift along with the citation behaviour over time. The scheme thus cannot reflect this change.

In terms of industry involvement and interdisciplinary collaboration, we use the bibliographic information presented in the address of a publication record. It is assumed that co-authorship partially reflects the result of collaborations with different actors and can serve as a formal mechanism of scholarly communication (Borgman, 1990). As addressed in section 3.1, bibliometric data can only capture part of the picture of policy-related issues and is better treated as a support or complement to other evidence. For instance, Katz and Martin (1997) suggest that the boundary of research collaboration is usually ill-defined and perceived variously. An inter-organisational co-authorship may not necessarily involve all individuals in a research group. In addition, scientists involved in a collaboration with industry may not publish research results due to a non-

disclosure agreement. In other words, co-authorship can only serve as a partial indicator of collaboration.

In order to capture different forms of collaboration, we categorise each publication into one of the five types of collaboration. They are:

- Single-University collaboration: co-authorship within the same university

- Inter-University collaboration: co-authorship between two or more universities in Taiwan

- University-Industry collaboration: co-authorship involves at least one industrial sector

- International collaboration: co-authorship involves at least one foreign country

- University-other collaboration: co-authorship except for the above four types. This type of collaboration mainly includes co-authorship with other national research institutes

Moreover, we distinguish the scope of disciplines involved in a paper in order to analyse the degree of interdisciplinary collaboration. Previous studies have used the co-occurrences of keywords, subject categories of journal sets, citation data and authors' affiliations to analyse interdisciplinarity for different study purposes (e.g. Hicks & Katz, 1996; Meyer & Persson, 1998; Porter & Rafols, 2009; Qin et al., 1997; Rafols et al., 2012; Rafols & Meyer, 2007, 2010; Schummer, 2004; Van Raan & Van Leeuwen, 2002). Although there is no universally accepted approach to assess interdisciplinarity, prior studies maintain that co-author analysis tends to focus on the social aspect of research practice rather than the cognitive nature of information (Qin et al., 1997; Schummer, 2004). Since this study focuses on the interdisciplinary character of research collaborations, we use departmental affiliations involved in a paper to measure the social interaction between institutional boundaries. Like the interview method, we use

75

the 158 disciplinary codes for university departments developed by the Ministry of Education of Taiwan as the basis of the disciplinary classification.

Furthermore, we use the average citations received per year and the journal impact factors of 2010 as the measures of scientific performance. Both indicators are normalised by the average scores in the same field[14] and year among all nano-related records in Taiwan. Therefore, the indicators are relative to the total nanotechnology research within a country rather than to a global scale. Again, we should see these measures as partial indicators for capturing aggregated phenomenon.

3.3.2 Data collection

This section addresses the procedure for collecting the bibliometric data. We combined a bottom-up and a top-down approach to identify university scientists who have carried out nanomaterials research. Figure 3.1 shows the details of the procedure.
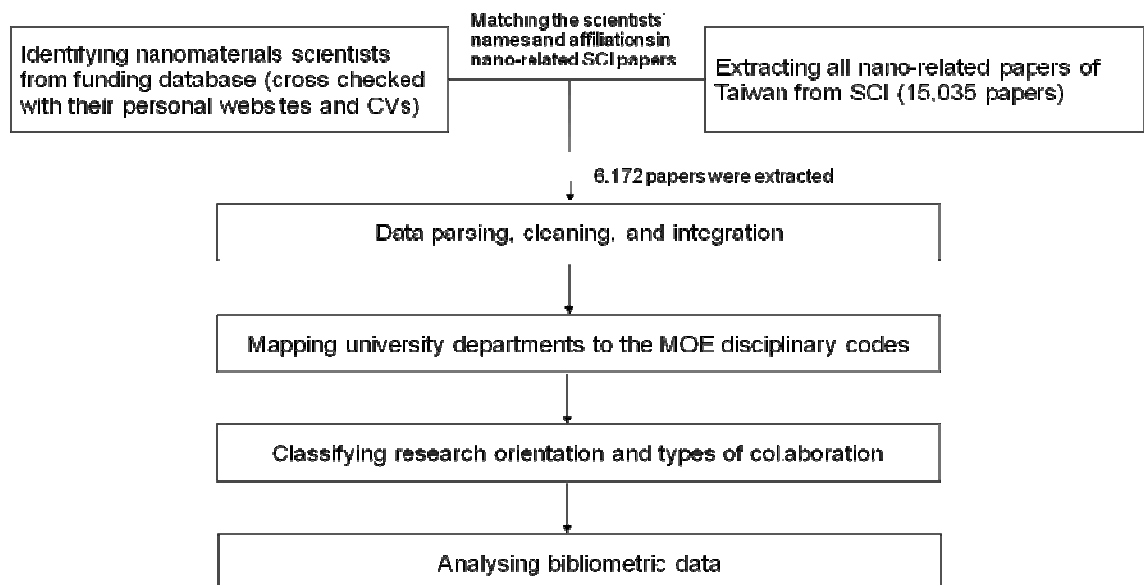
Figure 3.1 Procedure for collecting and analysing the bibliometric data
Source: developed by the author.

[14] We use the field classification scheme developed by the Patent Board, formally CHI Research Inc. Each journal is assigned in one field. The journals covered by SCI and SSCI are classified into 13 broad fields by the Patent Board.

First, we selected a pool of scientists funded to carry out nanomaterials research by the NSC from the research projects database. The database contains a number of key pieces of information, such as scientists' full names, affiliated universities and departments, funded years, funding amounts and funding institutes, covering the period from 1993 to present. Second, we extracted another pool of all nano-related papers published in Taiwan from the Science Citation Index. The time period covers from 1979, the earliest year in the database, to 2010. We used the keyword search delineated by Glanzel et al. (2003). Previous studies suggest that searching for nanotechnology papers in a bibliographic database presents certain challenges since the boundaries of nanotechnology are not clearly defined. Huang et al. (2011) carried out a comparative analysis of four major search strategies used in the literature. Their analysis shows that those search strategies produce very similar ranking profiles because they share a core set of keywords developed by Glanzel et al. (2003). Although this search strategy may not cover all nano-related records in Taiwan, we assume that the search results are satisfactory, if not the best, for reliable analysis.

We then matched the scientists' names and affiliations in these two datasets and selected scientists who have published at least five papers in the nano-related field as a more representative sample of nanomaterials scientists. In total, 6,172 papers were matched and 331 nanomaterials scientists identified[15]. Data on their professional rank, affiliation, educational background, year of PhD or highest degree, research expertise and career mobility were mainly collected from their personal websites at their universities. Other databases constructed by governmental authorities[16] were used to verify and complement the online information. The scientists' publication lists on their

---

[15] Some of the 331 scientists have co-authored papers among themselves, thereby producing 6,726 duplicate papers in total.

[16] https://nscnt07.nsc.gov.tw/WRS/ and http://hrst.stpi.narl.org.tw were mainly used.

websites or in governmental databases were collected as a reference to cross-check their publications in the Web of Science.

3.3.3 Data processing and classification

In order to carry out the bibliometric analysis, we parsed the extracted bibliographic texts into a relational database and unified the authors' addresses manually. After that, we matched the university departments to the MOE disciplinary codes and classified the types of collaboration based on the addresses. The research orientation of a paper was assigned according to the journal scheme developed by the Patent Board, formerly CHI Research Inc.

As discussed in section 3.2.1, we used scientists' current departments as an indication of their discipline. We initially investigated the degree to which the affiliated departments matched the scientists' educational backgrounds in their Ph.D. programmes. Table 3.3 on the next page presents a map for these two dimensions. In total, 212 out of 331 scientists (64%) have Ph.D. backgrounds in the same categories as their current affiliated departments. Furthermore, the table shows that scientists with Ph.D. training in materials engineering tend to be more distributed across different university departments. In terms of disciplinary mobility, 36 scientists (10.9%) have moved across universities or between departments in the same universities, 20 of whom moved to the same disciplines. Again, we can see that scientists' mobility across university and department is relatively low in Taiwan.

3.3.4 Data analysis

We use several statistical techniques to examine the data, most of which involve non-parametric methods. Parametric statistics are based on the assumptions of a random selection of the sample, normal distribution, large sample size and variables measured

on an interval or ratio scale (Israel 2009, p.xxix). Bibliometric data do not usually meet these assumptions (Van Raan, 2005b). First, several variables are nominal- or ordinal-level data, such as the type of collaboration and research orientation. Second, citation data tend to be very skewly distributed, making a statistical average potentially misleading.

Table 3.3 Mapping between departmental code and PhD discipline

PhD discipline / Dept_code	U	4401	4402	4403	5201	5202	5203	5204	5205	5207	5209	5211	5212	5213	5299	6208	7201	7208	Total
1402		1																	1
4203								1											1
4401	5	41		1				3	2					1					53
4402			1																1
4403	1			26	1			1											29
5201	1			5	20			5						2					33
5202						22		3	1				1	1					28
5203							1							1					2
5204	3	5		1		1		51	9		1			6					77
5205	1	5		6	5	2		10	43					1	2				75
5209						1	1				1								3
5211											1	1	1						3
5212					2	1		1					3						7
5213		1			1	1		1	1								1		6
5299						1													1
6202								1											1
6208																1			1
7201	1																		1
7202											1								1
7203								1	1										2
7207																	1		1
7208																		1	1
9999		1		2															3
Total	12	54	1	41	29	29	2	68	66	1	4	1	7	10	2	2	1	1	331

Source: developed by the author.

Note: 1402= Teacher Training for Non-vocational Subject; 4203=Biotechnology; 4401=Chemistry; 4402=Geology; 4403=Physics; 5201= Electrical and Electronics Engineering; 5202=Mechanics Engineering; 5203=Civil Engineering; 5204= Energy and Chemical Engineering; 5205=Materials Engineering; 5209=Environmental Engineering; 5211=Biomedical Engineering; 5212=Nuclear Engineering; 5213=Engineering, General; 5299= Other Engineering; Engineering Drawing, Metal Work, Vehicle Maintenance; 6202= Animal Husbandry; 6208=Agricultural Chemistry; 7201=Medicine; 7202= Public Health Services, Hygiene; 7203= Pharmacy, Pharmacology; 7208=Dental Service; 9999=Unspecified; U=Unclassified.

In general, we apply a Chi-squared test to measure the categorical data between two or more independent groups. In addition, we use the Kruskal-Wallis test, equivalent to the one-way ANOVA in parametric statistics, to examine the association between different patterns of research behaviour and scientists' citation impact.

3.4 Limitations of the methodology

One of the limitations in this study is concerned with the different sample sizes between the interviews and the bibliometric data. The sociological investigation of scientists' perceptions and their research behaviours is mainly based on the qualitative interviews with a smaller sample size when compared to the data drawn from the large amount of bibliometric records. While the bibliometric analysis helps expand our understanding of scientists' research behaviour, it involves scientists from more diverse disciplines and universities. The different sample sizes suggest that we should interpret the comparison between qualitative and quantitative results with some caution.

In addition, the structure of the sample suggests that the results may underestimate the perspective of junior scientists. Especially for junior scientists who have just entered nanomaterials research in recent years, the chosen method is less likely to access their information if they have not had any funded research project or publication.

We should also bear in mind that bibliometric indicators are usually used as partial indicators for analysing scholarly communications. This study assumes that international journal articles at the very least reveal a more visible and codified form of knowledge produced by scientists. The results of the analysis are based on the quality of bibliographic data. We have outlined the data processing and clean-up steps in order to enhance the reliability of the bibliometric data. We have also examined the validity of bibliometric indicators used in this study.

Chapter 4

The Institutional Context of University Research in Taiwan

This chapter introduces the institutional and organisational contexts that govern the behaviour of academic researchers in Taiwan, with a focus on the role of university research and its relationship with societal and economic needs. The text is organised into three sections. First, we trace the changing rationale for university funding over the last six decades. The analysis shows that funding for higher education has been closely linked to economic development since the Second World War and that the rationale has evolved under different socio-political contexts. The government actively took several policy actions along with the changing contexts. Section 4.2 examines nanomaterials research in Taiwan as the empirical focus of this study. Section 4.3 presents the summary of this chapter.

4.1 Economic rationale for university funding with a shifting focus

4.1.1 A brief introduction of the higher education system in Taiwan

Before addressing the changing rationale for university funding in Taiwan, we briefly introduce Taiwan's higher education system. The definition of higher education in Taiwan includes universities, colleges and junior colleges. While universities and colleges usually provide four-year academic programmes, junior colleges provide two or five-year programmes with a technological or vocational track. Since 1996, many junior colleges have been upgraded to colleges, with several colleges upgraded to universities. Overall, publicly funded universities are more prestigious than private ones due to the better quality of education and lower tuition fees. By 2011, there were 148 universities and colleges, 65.5% of which were private institutions, and 15 junior colleges in total.

Compared to that in the USA and Western European countries, the university system in Taiwan has a relatively short history due to the Japanese occupation from 1895 to 1945. Before 1945, Taihoku (Taipei) Imperial University was the only university, founded by the Japanese colonial government in 1928. The education system in colonial times was mainly at elementary level and only a few Taiwanese students were admitted to the university. [17] After the Chinese Nationalist government (Kuomintang or KMT) retreated from China to Taiwan in 1949, the higher education system adopted the US educational model of the 1920s (Law, 1995; Wu et al., 1989). For example, the study period, curriculum design and credential requirements are similar to those in American universities.

Unlike that in the USA, the administration of higher education in Taiwan has been highly centralised. During the martial-law period (1949-1987), Taiwan was ruled by a totalitarian system, with the planning of higher education also strictly controlled by the Ministry of Education. In 1959, the government established the Long-term National Science Development Council, renamed the National Science Council (NSC) in 1967, as the top agency responsible for overall S&T development in Taiwan. While the MOE is in charge of the annual budget allocation of universities, the NSC is the main funding source of research grants for university faculties.

The higher education system has gone through several stages of reform since the relocation of the KMT government in Taiwan in 1949. Several studies examine the reforms from historical, educational and political perspectives (e.g. Law, 1995, p. 85; Mok, 2000; Wu et al., 1989). This study focuses on the changing rationale for university funding and on how the role of research has evolved from the post-war period to the contemporary period, which can be further divided into three periods.

---

[17] Up to 1943, for example, 161 out of a total of 838 university graduates (19%) were of Taiwanese ethnic origin (Wu, et al., 1989).

The following will show that the rationale for university funding is closely related to concerns about economic growth and social demands. Meanwhile, the objectives, policy actions and mechanisms for resource allocation have shifted under different political and socio-economic contexts. Along with the changing environment, the purpose of university research has also evolved from training highly skilled graduates to advancing economic competitiveness.

4.1.2 From 1945 to 1985: manpower requirement for economic development

Over the years, the role of the university and the rationale for university funding have both evolved, with economic concerns the primary reason for the transformation of higher education. In the 1960s and the 1970s, the major function of higher education was to produce middle-level and advanced skilled manpower that was needed for economic development. One feature of cultivating well-trained personnel during this period was that the projection of manpower, based on economic plans and industrial structure, were used to guide education policies (Wang, 2003). Figure 4.1 shows that the first expansion of higher education occurred in the early 1960s, at a time of rapid growth of labour-intensive industries. A majority of junior colleges were established to provide middle-level technicians needed by industry.

Due to a lack of public expenditure, these junior colleges were mainly funded by private sources. Since then, universities have been primarily financed by the government. From 1960 to 1969, the number of junior colleges increased from 12 to 69. 49 out of 69 were financed from private sources of funding. At the same time, the number of universities and colleges increased from 15 to 22 in total. 12 out of 22 universities and colleges in 1969 were private. In order to cope with the economic slowdown in the early 1970s, the expansion of higher education was limited by the government from 1970 to 1985.

No. of schools
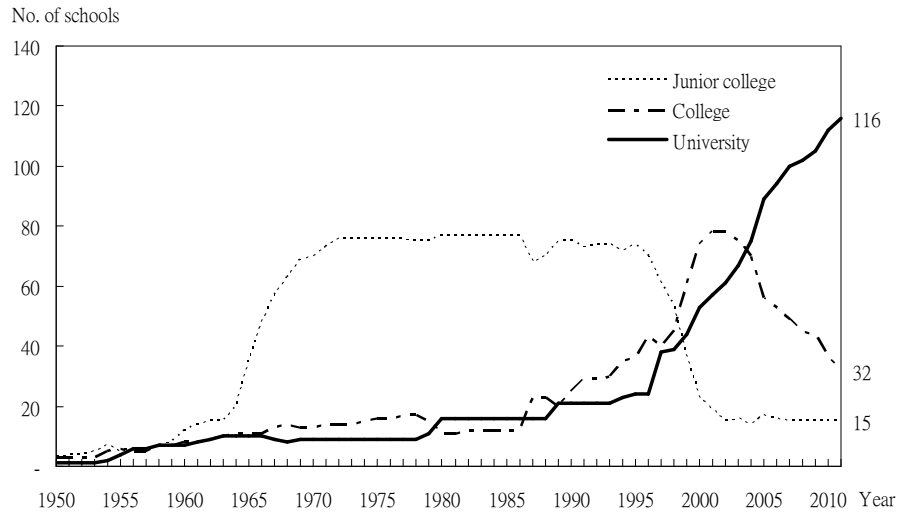
Figure 4.1 Number of higher education institutions, 1950-2011

Source: Ministry of Education Taiwan (2012). Figure developed by the author.

Another feature of cultivating advanced manpower was the government encouraging students to pursue post-graduate studies abroad because the higher education system in Taiwan was rather weak at that time. In 1955, the government restored funding to support overseas study. Since then, the budget has been increasing. As shown in Table 4.1, the number of overseas students has increased since the 1960s. A majority of the graduates who left to study were from science and engineering fields. University graduates tended to go to the U.S. for post-graduate studies, with most of them usually continuing their careers there. Thus, the outflow of university graduates raised concern about the brain drain. In the 1960s, the return rate of overseas students was only 5.5% (see Table 4.1). It is only since the late 1980s and early 1990s that we have witnessed a growing number of returnees to Taiwan (Lin, 1998; Luo & Wang, 2001).

Table 4.1 Number of students studying abroad and returning, 1950-1989

Year	Number of students studying abroad	Number of students returning	Return rate (%)
1950-59	4,515	400	8.9
1960-69	21,248	1,172	5.5
1970-79	31,365	5,166	16.5
1980-84	28,321	5,269	18.6
1985-89	35,859	9,611	26.8

Source: Adopted from Tsay & Tai (2001), p.20.

In addition to manpower planning, the government also placed emphasis on building national research capacities in higher education after World War II. Due to the invention of the atomic bomb and China's nuclear weapon test in 1964, the government recognised the significance of science and technology in modernising the nation. The funding of S&T development was mainly to improve the research infrastructure and improve science education. In the 1960s, the government attempted to deal with the problem of the brain drain. It considered that one of the key reasons might be the lack of a well-functioning job market or an attractive research environment, and consequently science could not be effectively developed in the nation.[18] Therefore, in 1965, the former NSC created five research institutes to train graduate students in Taiwan. The five research institutes were in the fields of mathematics, chemistry, physics, engineering and biology, and affiliated with three major universities and in one case to the Academic Sinica.[19] From 1966 to 1971, 59% of the funding for the five research institutes was allocated to establishing research facilities, instruments and laboratories (Yang, 1999). We can see that the rationale for funding research institutes in the universities at this time was mainly to produce well-trained graduates and improve the

---

[18] See the Annual Report of the National Long-term Science Development Council (1965).

[19] The research institutes in mathematics and chemistry were affiliated to National Taiwan University, the one in physics to National Tsing Hua University, and the one in engineering to National Cheng Kung University. The research institute of biology was affiliated to the Academic Sinica, which is the highest national academy in Taiwan.

local research infrastructure.

It is worth noting the shift in balance between basic and applied research in the post-war period. Although S&T funding has been closely linked to larger national development, there was a short period when basic research was considered the foundation for further application-oriented research and S&T development in the 1960s, a view espoused by the Chairman of the former NSC, Ta-You Wu (1907-2000). In the *Long-term National Science Development Programme* promulgated by the former NSC in 1959, it stated that funding for natural science, basic medical science and engineering should not be less than 80% of the total S&T budget. The funding of these three fields was mainly allocated to universities.

Nevertheless, this view was later criticised by the Minister of Economic Affairs, K.T. Li (1910-2001), and by several members in the legislative body arguing against "doing basic research for its own sake" (Yang, 2003, p. 85). Chairman Wu responded by arguing that most of the budget for basic science was allocated to building a research infrastructure and supporting research institutes affiliated with universities, among which included engineering and application-oriented fields. His view, however, did not receive further discussion. As indicated in the 1997 *White Paper on Science and Technology*, the launch of the *National Science Development Plan* in 1968 "broke with the previous emphasis on pure science and basic research by placing more attention on technological research aimed at meeting the needs of national development" (p.6). Since then, the NSC gradually increased the proportion of funding for engineering and applied research, which was mostly done by non-university research institutes. In 1972, for example, the budget for industrial and applied science was double that for basic research.

Since 1978 when the government held the first national S&T conference as the basis for planning S&T policy, focusing on technological and application-oriented research to meet national development has been the major direction of S&T policy-

making (National Science Council, 1997). In the conference, energy, materials, information and automation were designated as the four key technological areas for meeting the needs of national development. The second national S&T conference in 1982 added biotechnology, electro-optics, food technology and hepatitis prevention to the above four areas. This policy direction implies that basic research did not gain much significance because the government placed most effort on economic development in the post-war period.

4.1.3 From 1986 to 2000: the growing importance of university research

Since 1985, Taiwan has experienced a second rapid expansion of higher education, which was virtually a worldwide phenomenon in the late 1970s and 1980s. The expansion mainly occurred in universities and colleges at a time when student demand for higher schooling increased due to the growing number of students at secondary level. Generally, Chinese society puts more emphasis on pursuing education to earn higher social status, with many students and their families having a strong desire for a diploma. Over the past fifty years, Taiwanese students have had to take the Joint University Entrance Exam to gain admission to universities. In 1986, the admission rate was 30% (Wang, 2003), which indicates great competitive pressure for students.

In addition, political democratisation exerted an influence on the reform of the higher education system. Since the lifting of Martial Law in 1987, higher education has been questioned for its elitism and its function of education for economic development. As society became more democratised, university faculties also sought more academic freedom and autonomy. Following this trend of political democratisation, the MOE attempted to liberalise the higher education system and make it more flexible in response to the social demand for education. As Figure 4.1 shows, the number of universities and colleges increased from 28 in 1986 to 127 in 2000. 61.4% (78/127 in

2000) of the universities and colleges were funded by the private sector. In the same time period, junior colleges decreased from 77 to 23 because most were upgraded to college status.

The rapid expansion of universities and colleges increased the government's financial burden because higher education institutions in the public sector were fully funded by the government before 1996. Under the changing socio-political context in the late 1980s, universities went through a series of reforms. Three main features related to university funding can be identified in this period. Firstly, universities were empowered with financial independence from the government. Since the revised University Act was enacted in 1994, universities have been entitled to have more institutional autonomy with respect to personnel recruitment, curriculum design and funding sources. The university fund implemented in 1996 was the first attempt to enable public universities to generate income from various sources and reduce reliance on government support. Since 1999, all public universities and colleges have established a university fund at their institutions.

Second, basic research as a main source of national competitiveness gained increasing prominence in the mid-1990s. As in the post-war period, university research was considered to serve as a channel to produce highly-skilled human resources. In addition, the government appears to have had a rather linear view concerning the role of basic research in enhancing industrial competitiveness. As indicated in the first *White Paper on Science and Technology*, "basic research frequently leads to patents" and "it provides many opportunities to leap ahead of competitors" (National Science Council, 1997, p. 4). The government's view seems to be influenced by the global trend it perceived in major industrialised countries, such as the USA, Japan and Germany in the 1990s, in that these governments maintained a growing budget for basic research to increase industrial competitiveness *(ibid.)*. Furthermore, the government recognised that,

while Taiwan had produced a certain quantity of research outputs, in terms of academic papers in the database of Science Citation Index (SCI) and Engineering Index (EI), their quality in terms of citation impact factor still needed to be improved (*ibid*.). In the *White Paper* (1997), the government stated that funding for basic research should not be lower than 15% of total R&D expenditure. In addition, the government attempted to provide long-term funding for selected cutting-edge research topics, as well as establishing more effective funding mechanisms to pursue academic excellence. Nevertheless, basic research expenditure has remained at around 10% to 11% of total R&D expenditure since 1999 (NSC, 2012). This figure is considerably less than that in most OECD countries. In South Korea and Singapore, the share of basic research has gradually moved upward from 13.7% and 15.4% in 2002, to 18.2% and 20.6% in 2010, respectively.

Along with the financial autonomy granted to universities and the prominent role of basic research to achieve national competitiveness, the third feature of university funding is that the government started to place emphasis on direct cooperation between university and industry, and on facilitating the practical application of publicly funded research. In 1999, the government enacted the *Fundamental Science and Technology Act*, an Act that emulated the Bayh-Dole Act in the USA. One mandate of the Act was to grant intellectual property rights to universities, thereby promoting the commercialisation of public research. A survey of 58 universities and colleges in 2001 showed that more than half of them had established Technology Transfer Offices or equivalents, with approximately 40% having Intellectual Property Offices or incubator centres (Chang, et al., 2005). The latter authors argued that Taiwanese universities had shifted their knowledge production activities from 'scientific-government' towards a more 'scientific-economic' orientation since the passage of the Act. Overall, we can see that the government has decentralised its role of governing universities and placed more

emphasis on the role of basic research to enhance industrial competitiveness since the mid-1980s.

4.1.4 2000 onwards: emphasis on both scientific excellence and economic relevance

Over the last decade or so, Taiwanese universities have continued to experience dramatic changes. The expansion of universities has continued over the past decade due to the extensive upgrading or renaming of four-year colleges to university status. The number of colleges declined from 78 in 2001 to 32 in 2011, while that of universities increased from 57 to 116. Since 2006, the admission rate to university has been over 90%. This drastic expansion not only exacerbated the government's financial difficulties but also raised concern about educational quality. In this period, the government adopted market-style funding mechanisms to make the operation of universities more efficient. The rationale for funding university research has remained that of strengthening national competitiveness.

One of the features since 2000 is that the government has shifted its funding strategies towards more competitive schemes to support university research, a contractual-oriented approach that was generally applied in Europe (Geuna, 2001). An evident example for this approach is the launch of a series of National Science Technology Programmes (NSTP) since 1999. As indicated in the *White Paper on Science and Technology* (NSC, 1997, p. 37), the purpose of the NSTP is to support research projects that have a clear objective of contributing to industrial development or public welfare, that are interdisciplinary oriented and that have the potential to achieve a far-reaching impact. Up to 2010, ten NSTPs have been initiated, all of which were under the supervision of the NSC.

Another significant example is the series of programmes initiated by the MOE in order to pursue world-class universities in Taiwan. The Programme for Promoting

Academic Excellence of Universities launched in 1998 is one of the high-profile programmes that introduced large-scale competitive grants to pursue academic excellence in areas mostly related to Taiwan's economic competitiveness (Song & Tai, 2009). This programme also encourages universities to form intra- and inter-university cooperative research collaborations by soliciting joint proposals. Figure 4.2 reveals the shift in government R&D funding in the higher education sector over the decade. As we can see, the General University Funds, which tend to be the block grant received from the MOE, have gradually declined, while contractual-based Direct Government Funds have increased.
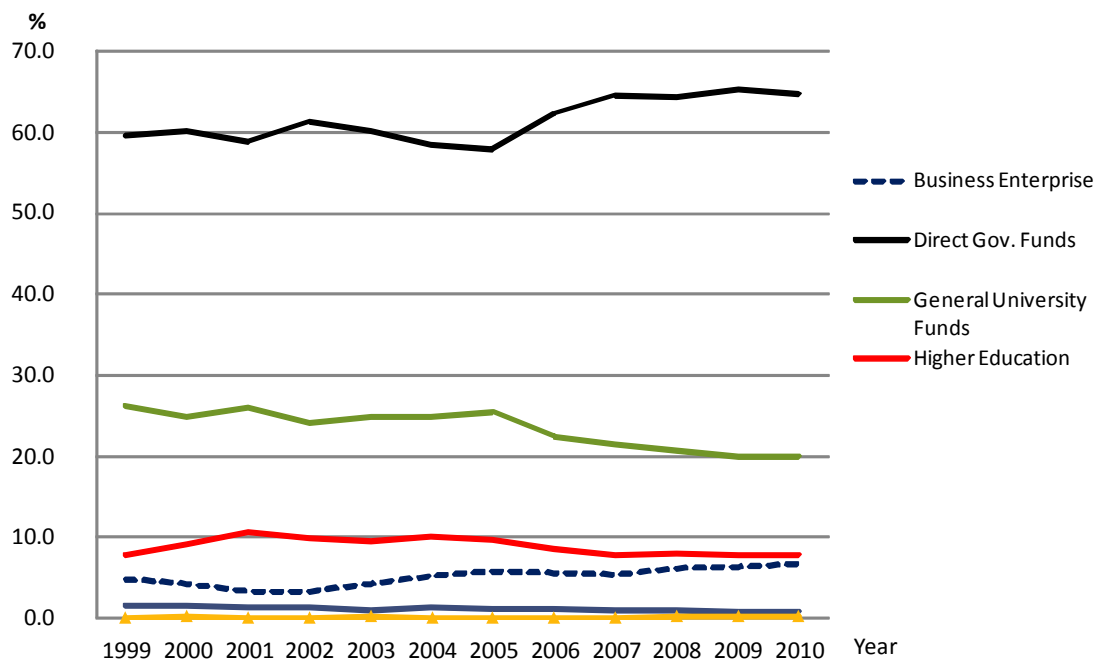
Figure 4.2 HERD by source of funds, 1999-2010

Source: NSC (2010, 2011). Indicators of Science and Technology Taiwan. Taipei: National Science Council. Developed by the author.

91

A second feature related to the launch of large-scale contractual-based funding is that the government has placed more priority on supporting cross-institutional and cross-disciplinary research projects (NSC, 2003). There are two main reasons for this change. First, it has been widely recognised that new discoveries and new technologies tend to be the result of collective efforts involving cross-boundary collaboration over recent years. By providing large-scale financial incentives, the government has attempted to encourage universities to collaborate beyond departmental and institutional boundaries in pursuit of world-class research. Second, universities were encouraged to merge or form alliances due to the lack of sufficient resources caused by the rapid expansion of universities. For example, the Research University Integration Programme was initiated in 2002 to support intra- or inter-university integration, a mechanism by which the government hoped to integrate resources and develop cross-sectional interaction among universities.

The third feature is concerned with evaluation practices. Under the expansion of universities and the growing importance of contractual-oriented funding schemes, the government has placed significant emphasis on more effective evaluation mechanisms to ensure the quality of higher education, as well as used the evaluation results as a reference for government subsidies. Before 1991, the MOE was fully in charge of the evaluation work. Since the University Act was revised in 1994, the MOE has transferred its power to universities to carry out self-accreditation. In 2005, the Higher Education Evaluation and Accreditation Council of Taiwan was established to carry out the evaluation of universities and colleges. The unit of evaluation is at the level of university departments. Although the evaluation items cover five dimensions,[20] it has

---

[20] The five dimensions are: (1) objectives, main features and self-improvement, (2) curriculum design and teaching, (3) student affairs and learning, (4) research and professional performance, and (5) careers of graduates (Higher Education Evaluation & Accreditation Council of Taiwan, 2010).

been highly criticised for its over-reliance on quantitative indicators and its over-emphasis on research performance, specifically on the number of journal publications covered by the SCI and SSCI database, to achieve the goal of becoming world-class universities. We can see that the government's funding mechanisms have shifted towards mission-oriented and performance-based approach over the past decade.

4.1.5 Summary

We have analysed the changing rationale for university funding and the related policy changes in the context of wider educational reform over the past sixty years, which is summarised in Table 4.2. Overall, the government has taken an active role in directing the functions of universities towards socio-economic needs over the past sixty years. Although the government has shifted toward a more decentralised model of governance and given universities more autonomy in terms of their administration and operation over the years, it continues to lead the direction of universities through various funding mechanisms.

We can see that, although the reform of higher education appears to broadly follow global trends, the changes in policy actions were mainly to cope with national needs under different socio-political contexts. While the higher education system has long served to provide abundant human resources to support economic growth in previous decades, the emphasis on the role of university research in supporting industrial needs and enhancing national competitiveness appears to be a relatively recent phenomenon.

Along with emphasis on the economic relevance of university research is the pursuit of scientific excellence at the international level to enhance the competitiveness of universities in such a highly competitive world. Since the late 1990s, the funding mechanisms for research grants in universities have been re-structured to meet the objectives of maintaining scientific excellence and national competitiveness. In the next

section, we address a specific case, namely public funding of nano-related research, which has emerged under this context.

Table 4.2 Changing rationale for university funding in Taiwan

	1945 - 1985	1986 - 2000	2000 onwards
Socio-political context	• Totalitarian regime • Education mainly at elementary level • Economic development as the priority national goal	• Political democratisation • Student demand for higher schooling due to the growing number of students in secondary level	• Constraint of government budget • Criticism for educational quality in universities
Role of government	• Centralised control of higher education in almost every aspect	• Decentralised the fiscal and managerial power towards universities	• Supervision
Reform in higher education	• First expansion of higher education (1960s-1970s), mainly in establishing two- and five-year junior colleges	• Second expansion of higher education (1986 up to now) occurred in universities and colleges	• Expansion occurred in upgrading colleges to university status
Rationale for university funding	• To produce middle-level manpower needed for economic development • To lay the foundation of the research environment • Balance shifted from basic research in the 1960s towards applied and industrial research in the 1970s	• To enhance national competitiveness through basic research	• To enhance national competitiveness • To pursue world-class universities through research excellence
Policy actions	• Encouraged post-graduate studies abroad • Established five research centres for the graduate training	• Initiated large-scale funding in selected fields • Granted intellectual property rights to universities • Encouraged collaboration between universities and industry	• More competitive funding schemes • Encouraged intra- and inter-university collaboration and integration • Launched university accreditation

Source: developed by the author.

4.2 The policy context of nano-related research in Taiwan

4.2.1 Introduction

Nanotechnology research has received extensive attention from governments around the world to invest in since the 1980s. Taiwan is no exception. In general, the funding policy of nanotechnology research in Taiwan tends to imitate and make adjustments to that undertaken in the USA. Since the launch of the National Nanotechnology Initiative in 2000 by the US government, the NSC started to prepare to initiate the Nano Programme, which was established in 2003. As section 4.1.3 shows, the rationale for funding the National S&T Programmes was to enhance competitive advantages and solve major socio-economic problems. Section 4.2.2 addresses how this policy mandate has been implemented in nanotechnology research. Section 4.2.3 presents an overview of the funding of nanomaterials activities in universities.

4.2.2 The initiation of the Nano Programme

Since the launch of the six-year plan for the Nano Programme in 2003, the Programme has received the largest amount of government funding among all national programmes up to 2011. According to the statement shown in the Master Plan of the Programme (Nano Programme Office, 2002), the objective of the Programme is "through the establishment of common core facilities and education programmes to achieve academic excellence in basic research and industrialisation of nanotechnology." While the objective of the Academic Excellence Research Programme is to enhance originality and excellence in nanotechnology-related basic research, there appears to be an expectation that the research outputs will contribute to industrial development in Taiwan. This intention is revealed in the priority settings of the research themes and in the evaluation criteria. These policy discourses appear to suggest that the relevance of nanotechnology tends to be interpreted as industrialisation.

There are four sub-programmes, namely the Academic Excellence Research Programme, the Nanotechnology Industrialisation Programme, the Core Facilities Programme and the Education Programme. 65% of the total funding is dedicated to the industrialisation of nanotechnology. Although a number of governmental agencies are involved in the Programme, they tend to have a rather clear division of labour. For example, the Academic Excellence Research Programme has been mainly charged by the NSC and the Department of Health under the cabinet. The main funding agency of the Industrialisation Programme is the Ministry of Economic Affairs.

Interdisciplinary integration is an important aspect of the Programme. The policy discourse for promoting interdisciplinary research suggests that the integration of research teams is expected to trigger emerging industries related to nanotechnology. In practice, the announcement of the call for proposals states that the Programme aims to "encourage professionals to organise cross-disciplinary and integrated teams." One of the major funding criteria for the Academic Excellence Research Programme is that there should be at least three academics from different disciplines serving as Principal Investigator (PI) and Co-PIs.

In terms of industry involvement in university research, the first phase (2003-2008) of the Academic Excellence Programme did not require industry to be involved, while the Programme in the second phase (2009-2014) distinguished between the University-Industry Programme and the Academic Excellence Programme. Although the overall goal of the Programme has placed significant emphasis on industrialisation, the review of the proposal grants remains to be judged by scientific peers.

4.2.3 Overview of the funding of nanomaterials research in universities

This section provides an overview of the funded projects in nanomaterial-related research in Taiwan. Figure 4.3 shows the funding level and number of nanomaterials

projects from 1997-2010. Since 1999, there has been an exponential growth both in funding level and the number of funded projects. A major growth in funding in 2003 appears related to the initiation of the Programme in that year. Nevertheless, this trend has stagnated somewhat since 2006.
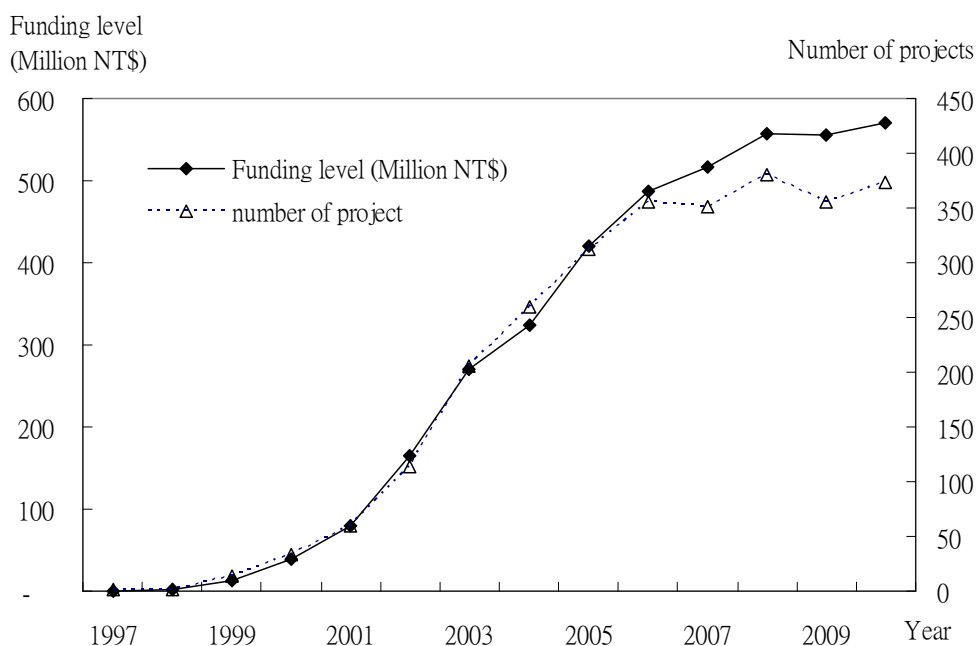
Figure 4.3 Funding level and the number of funded projects, 1997-2010

Source: Data extracted from the Government Research Bulletin

(http://grbsearch.stpi.narl.org.tw/GRB/quickSearch.jsp). *Statistics computed by the author.*

Figure 4. shows that the nanomaterials projects were funded for scientists through a variety of disciplinary affiliations. In terms of broader fields, a large proportion of the projects (70%) were granted to Engineering-related departments, followed by the projects granted to Natural Science (20%) and Health-related departments (4%). If we break down the fields into disciplines, the figure shows that Chemical Engineering (20%) has the largest share, followed by Materials Engineering (18%), Chemistry (12%), Mechanical Engineering (11%) and Electrical Engineering (10%).

Project distribution by broad fields

Project distribution by disciplines
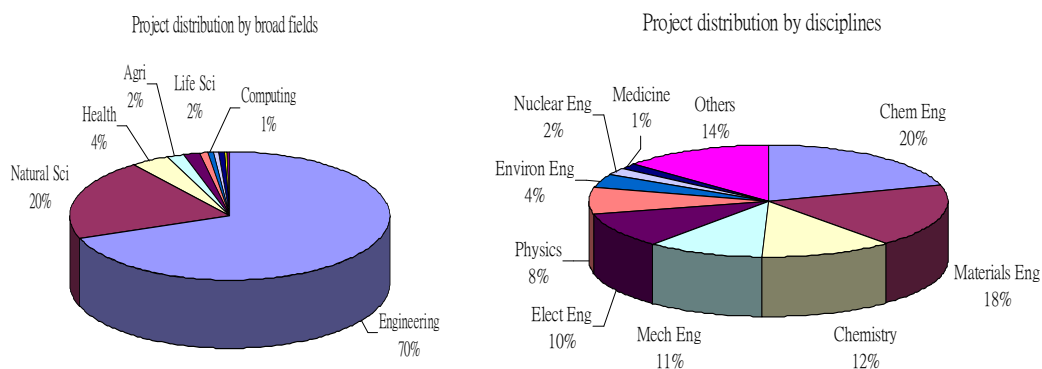
Figure 4.4 The distribution of participating departments in universities

Source: Data extracted from the Government Research Bulletin

(http://grbsearch.stpi.narl.org.tw/GRB/quickSearch.jsp). *Statistics computed by the author.*

Figure 4. compares the trend of nanomaterials publications with that of total nano-related papers in Taiwan. As is shown in the figure, the first nano-related paper appears in 1979 and the first nanomaterials paper in 1987. Since then, there was stable growth until around 2003. After that, the total number of nano-related papers grew rapidly. However, the number of nanomaterials papers seems to have levelled off in 2008. The slowdown in the publications appears to be related to stagnation in funding levels, as shown in Figure 4.. The reasons for the slowdown need to be further investigated.
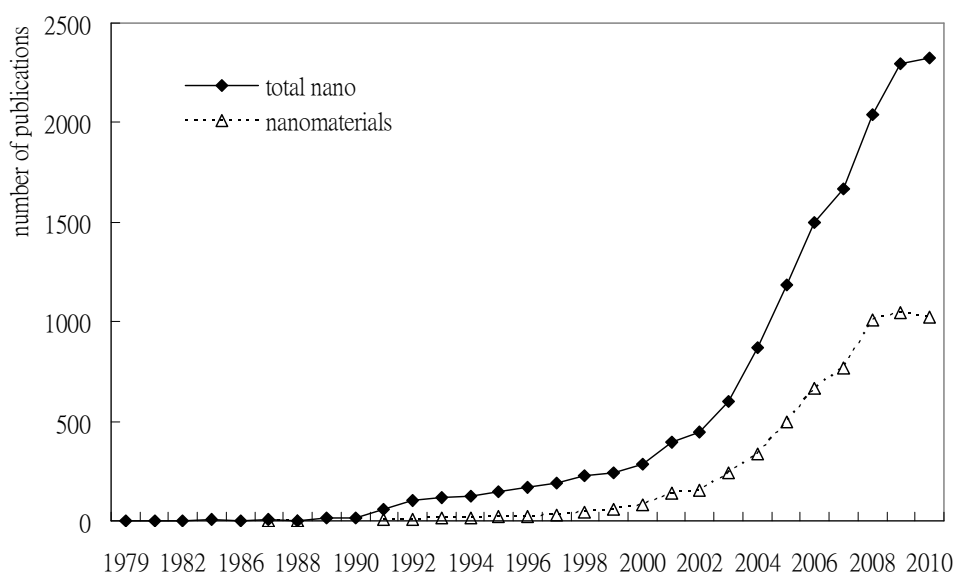
Figure 4.5 Publication trends in nano-related research

Source: Computed by the author.

The overview of funding for nanomaterials research in universities in Taiwan suggests that, since the launch of the Programme in 2003, the Programme has attracted a large number of actors to get involved, at least in nanomaterials research. The distribution of the involved disciplines reveals the multidisciplinary nature of nanotechnology, where a variety of scientists from different disciplinary departments have participated in nanomaterials research.

4.3 Summary

This chapter addressed the changes in funding rationale over the past sixty years and then focused on the policy context related to the funding of nanotechnology research. Our analysis shows that the economic rationale has been the central concern of publicly funded research since the early years. Nevertheless, the focus has shifted from producing manpower to producing socially and economically relevant knowledge. The policy context of nanotechnology research shows that it can serve as an empirical case for investigation in our study.

Chapter 5

Scientists' Perspectives on the Relevance of Nanomaterials Research

5.1 Introduction

This chapter addresses scientists' perspectives on the socio-economic relevance of their nano-related research. The objective is to identify their behavioural patterns when organising 'relevant research' and the underlying factors that shape their behaviour. According to the interview data, we present how scientists perceive and organise their research in terms of three aspects in the current research environment: research orientation, industry involvement and interdisciplinary collaboration. We will show that scientists' behaviours partly reflect the tension between relevance and excellence in the above three dimensions and is shaped by the personal factors and institutional environment they perceive themselves to be operating in.

Sections 5.2 to 5.4 present the above aspects respectively. In each aspect, we elaborate how scientists characterise their research, what they expect of or how they realise the relevance of their research, and what institutional incentives and barriers affect their research. Section 5.5 synthesises the three aspects. We then present the main conclusions in section 5.6.

5.2 Research orientation

This section presents the ways that scientists perceive and characterise their research orientation. The existing literature suggests that research aimed at being relevant tends to be guided by extra-scientific goals, under which the boundary between basic and applied research is blurred. We will show that the linear relationship between basic and applied research is still prevalent in practice. Nevertheless, scientists presented their research as being of a basic or applied nature in different ways.

Table 5.1 summarises scientists' responses to their research orientation across different disciplines and seniorities.[21] The interview question about research orientation was generally put forward in an open-ended manner when the scientists talked about how they began to be involved in nano-related research. Scientists often indicated their research orientation by talking about their research subjects or by referring to the disciplines or university departments they are affiliated to.

Table 5.1 Scientists' research orientation by discipline and seniority

Discipline \ Research orientation	Basic	Application	Mixed	No need
Physics	3	4	1	2
Chemistry	2	2	3	
Chemical and Materials Sciences	1	1	7	
Electrical Engineering		2	2	
Mechanical Engineering	1	1		
Medical Science and Engineering		1	1	
Total (% within 34 respondents)	7 (20.6%)	11 (32.4%)	14 (41.2%)	2 (5.9%)
Senior scientists	3	8	11	0

Source: developed by the author. N=34.

Basic-oriented scientists (20.6%) are those who explicitly position themselves to conduct basic research, those who mainly aimed to investigate the theoretical understanding of their research subjects and those who did not focus their research work on applications. Application-oriented scientists (32.4%) are those who explicitly position their research as application-oriented and those who do not consider their research as basic research. In addition, 41.2% of scientists regard their research as being

---

[21] In this study, the interviewed junior scientists (12 respondents in total) refer to those with fewer than 15 years of research experience. Most of them are ranked as assistant or associate professors or just promoted to the rank of full professor. 22 interviewees are senior scientists with more than 16 years of research experience, all of whom have the rank of full professor (see section 3.2.1).

both basic and applied in nature. Two scientists were fairly reluctant to characterise their research, seeing no point in distinguishing the type of research scientists undertake.

It is worth remarking that the notions of basic, applied and application are the main terms used by the interviewees, mainly sharing the widely accepted definitions of basic and applied research. The scientists had almost no problem with the conception in terms of the goal of research - that is, basic research is work without thought of practical application and applied (or application-oriented) research is work for practical (or potential) application. They tended to express their intentions and research interests driving the goals of their research. Nevertheless, we find that there is a nuanced response concerning scientists' research orientation. As Table 5.1 indicates, most scientists described their research as being oriented towards certain directions. At the same time, several interviewees categorise their research orientation in a relative way by comparing the position of their discipline with other disciplines. Our study suggests that how scientists classify their research is dependent on the context of their interaction with external groups. We will discuss this aspect in the concluding chapter.

5.2.1 Basic-oriented research

In the context of increasing demand for the socio-economic relevance of research, we expect that basic-oriented scientists might feel more pressure. On the contrary though, senior scientists seemed not to worry about the pressure for relevance very much. Junior scientists were more concerned about their scientific performance in order to secure their academic career and considered that research involved in application is detrimental to their career. Although the scientists characterised their research as basic-oriented, they also presented their research as somewhat relevant to application in different ways.

Our study finds that scientists tend to emphasise that their *intention* and *focus* drive their goal of their research. Meanwhile, they often associated their research with application to a certain extent by referring to their disciplines, research fields or potential application areas. In other words, they were rather flexible when positioning their research orientation. For basic-oriented scientists, the goals of their research were mainly to gain a better understanding of the properties or fundamental problems about their research subjects, but the research area is related to industrial application. They presented their research orientation by referring to their scientific fields or disciplines. The scope of a research area is flexible enough for them to address their research in a relative position. For example, one physicist said he was undertaking surface science, which is pure research. Later he stated that his broader research field (solid state physics) is rather applied (Scientist 14). One interviewee explicitly expressed that the position of a research project depends on what aspect of the research subject you focus on and whom you talk to. He stated:

> "There have been some new platforms for nanowires. Some researchers would be interested in the industrial application of nanowires, and some can do basic research on nanowires as well… If the audience is the general public, you have to talk about application. Several studies have claimed that they could produce refined nanostructure, but it is still unclear about the mechanism of electrical conduction in nanowires. For me, I am interested in understanding the properties of nanowires that will eventually be applicable. However, I am not interested in how the application is worked out" (Scientist 23).

His remark shows that the boundary between basic and applied research is not always clear-cut. How a piece of research is classified depends on a scientist's perspective and on the context of the interaction between a scientist and his audience.

In addition, we find that scientists seem to have a linear view of research and use this view to reiterate their research focus and to exclude considerations of application to

a certain extent. Although the linear model put forward by Vannevar Bush (1945) has been challenged by many policy researchers around the world (see section 2.2.1), the linear relationship between basic and applied research remains prevalent according to our interviews. Scientists in physics and chemistry tended to characterise their research as 'upstream' and priori for application (Scientists 14, 20, 24, 27 & 32). They considered that engineering scientists' work is closer to application. However, one junior engineering scientist also noted that somebody who is interested in application can 'use' their research later on (Scientist 28). Whether scientists do believe in a linear relationship between basic and applied research is open to question. According to these interviews, a few scientists expressed this linear view by referring to the history of S&T development. One physicist noted that "application is built upon basic research. It is natural that application will be there when pure science becomes rather mature" (Scientist 14). He argued that research itself will be useful for further application, but it is unpredictable.

While basic-oriented scientists do perceive a funding environment demanding relevant research, their research orientation remains unchanged. Senior scientists considered that there are still many fundamental problems to explore. In addition, the security of a scientist's position and the availability of research grants, both of which reflect a scientists' level of credibility, exhibit a certain influence on scientists' research orientation. One senior scientist wondered whether he might be granted in the future or not because the Nano Programme is increasingly asking for application (Scientist 23). Nonetheless, the grants received from his individual research projects and research facilities allow him to continue the research. He stated that he is generally still granted with larger funds than other scientists, so did not worry much about the availability of funds.

Junior scientists were more concerned about their scientific performance, specifically their publication records, and would not take application into account in their research. Here we note that junior scientists denote basic research as scholarly work, which is more publishable. They assume a conflicting relationship between basic and applied research because the latter is less publishable or less creative. Since publication performance is a dominating factor for a promotion, their purpose behind the goal of undertaking basic research is to secure their academic careers. One junior engineering faculty noted:

> "After being awarded my PhD degree, I focused my research on application, aiming to be of help for industry. The grant proposal was written from the perspective of industry… I have an engineering background, which makes me think about how to translate the results of academic research into mass production and economies of scale to a certain level, but I found that the application of nanotechnology in industry remains rather limited. In addition, we need publications for academic promotion. The nature of publications tends to be more scholarly. Therefore, I shifted my research focus to be more academic" (Scientist 29).

While he considered his research academic, he said that the topics focus on industries in Taiwan, such as semiconductors, photonics and energy, so that students could find jobs more easily. One junior scientist shared a similar opinion, saying that he would not get heavily involved in applied fields before becoming an established member of faculty. "It would be a problem to get grant funds if the basic research performance is not good" (Scientist 25). In addition, the former scientist pointed to the potential application of nanotechnology in industry as a constraint for him to consider the applied dimension in his research agenda. We will address the aspect of industry involvement in section 5.3.

The interviews suggest that the research orientation of junior scientists tends to be influenced by academics' shorter research experience and by the reward system, in

which publishing in scholarly journals is a determining factor for academic promotion. Considering their academic career, they tend to place more emphasis on pursuing scientific performance and regard getting involved in industry-related research as detrimental to their academic performance.

5.2.2 Application-oriented research

11 out of 34 interviewees (32.4%) explicitly stated that their research is mainly application-oriented because the goal of their research is for industrial application and the research topics were aimed at potential application. The research agendas were primarily initiated by the scientists themselves. One scientist said that academics normally generate their research ideas from scholarly articles (Scientist 22). A scientist would not know about industry related problems unless they were approached by an industrialist. In other cases, the scientists reported that interaction with industry helped inspire their research ideas.

It is worth mentioning that, although scientists had certain freedom to design their research agenda, the research topics might be influenced by the industrial circumstances they perceive. For instance, one senior scientist shifted the potential application areas of carbon nanotube research from field emission display (FED) to fuel cells. He perceived that the industrial application of FED was not as promising as expected and that several multinational companies had discontinued their R&D in FED. As we will see in this sub-section, several engineering scientists regard their disciplines as essentially application-oriented. They tend to address the social context of their research subjects by referring to certain practical problems they perceive in a specific application field or industry, such as semiconductors and light-emitting diodes (LEDs), and expect that their research will yield certain benefits to solve the problems. Scientists in this group tended to consider that the application of nanotechnology research is a global trend.

In addition, seniority exhibited a certain influence on scientists' research orientation. All scientists were ranked full professors or associate professors. A couple of interviewees stated that their research was relatively basic-oriented in their early career and over time they have taken application into consideration when designing their research approach. One reason for this research orientation shift is the accumulated knowledge in their research subject, which inspires them to focus on different research aspects. Two interviewees explained this in a similar way by saying that the shift in the application focus is mainly influenced by their personal interest because "naturally you will know the applicability when you understand the physical and chemical properties of the research subject" (Scientist 18).

Like the basic-oriented scientists, several application-oriented scientists positioned their research by pointing to the way they approach the subjects. They tended to characterise their research by their intention, regardless of the epistemological features of the research subject. In spite of emphasising their application goal, the nature of their research as described is somewhat similar to the remarks by the basic-oriented scientists, who mainly focus on understanding the properties or new phenomena at the nanoscale. A couple of scientists noted that the research theme is applied oriented, under which basic research is involved in the process. One senior scientist stressed that his research has been applied rather than basic since he began to be involved in his subject. He stated that the investigation of physical and chemical properties is applied research and is useful because the ultimate goal is to find useful materials for application (Scientist 35). Another scientist stated that electrical engineering is application-oriented by nature, a discipline that mainly focuses on the control of reproducible phenomena. She investigates the difference between theoretical and practical phenomena, hoping to offer new concepts to the semiconductor industry (Scientist 7).

As we have seen, application-oriented scientists often refer to their scientific disciplines when addressing their research orientation. Nevertheless, it is not easy to distinguish the research nature between basic and application-oriented scientists. A couple of engineering scientists mentioned that their disciplines are essentially applied. Some pointed to the relative position compared with other disciplines. For instance, two scientists said that engineering is by its nature more application-oriented than physics, chemistry and medical science (Scientists 2 & 15). The former scientist then indicated that physics and chemistry tend to have a 'higher status' than engineering, arguing that academic research is merely a profession and should not be distinguished as basic or applied. Again, this scientist's remark suggests that the type of research depends on the context of discussion.

The interviews with the application-oriented scientists reveal an ambivalent position to 'application' because they tended to use the notion in an ambiguous way. When asked what is meant by 'application', several referred to the 'likelihood of application' and stated that there are many problems with practical applications, such as cost, prototype and mass production (Scientists 2, 18, 21 & 22). In addition, some problems are routine work, which concern reproducible testing and are not the main interests of scientists. What the interviewees indicate is related to the role of university and its relationship with industry.[22] It is believed that engineering and applied disciplines in university are naturally driven by practical problems (Nelson, 2004; Rosenberg & Nelson, 1994). Moreover, a large number of innovation studies also show that technological development is evolutionary (e.g. Nelson & Winter, 1982) and that scientific knowledge tends to indirectly contribute to the process of innovation (e.g. Gibbons & Johnston, 1974; Salter & Martin, 2001). The issue then is where we should

---

[22] We will address the issues of industry involvement in section 5.3.

draw a line between university and industry in order to ensure a more mutually productive relationship between the two. As the interviewees reported, they were not particularly motivated to solve specific problems in industry. This issue is also concerned with the industrial features and the role of public research institutes, which will be addressed in section 5.3.

It is worth mentioning that one scientist characterised his work in a different way. He distinguished his academic research studies from those for application in terms of the type of work he is involved in and by the amount of time he allocates. What he meant by doing academic research is undertaking work that is publishable in academic journals but may not have practical application. Concerning application, he spends approximately half of his working time interacting with firms, providing them with material samples and discussing collaboration opportunities. He stated that these application-oriented activities are usually regarded as a form of public service in academia, which is not of much help for publishing papers and is not recognised very much by the university and funding agency.

This scientist argues that the lack of pluralistic incentives has confined scientists' freedom to be involved in activities other than publishing papers. He heavily criticises the current reward system dominated by the SCI publications. As he remarked, "The more publications, the higher funding available and the more the honours" (Scientist 30). In this system, scientists tend to investigate novel materials, even though the materials may be too expensive to be of practical application.[23] Moreover, scientists tend to gain smaller grants for collaborative research with industry than that for NSC research projects, as well as having more restrictions on autonomy. These factors discourage

---

[23] His remark is aligned with what several interviewees reported - they aimed to investigate new materials or new properties at the nanoscale. One scientist said that academic research is more fancy and you do what others don't have (Scientist 29).

scientists from interacting with industry.

His criticism concerning the culture of pursuing publications was shared by several interviewees and has been a crucial issue in recent years. Nevertheless, most scientists tend to comply with the rules of the game because publication records directly affect their performance and career, especially for junior scientists. A similar concern was observed in a previous study (Gulbrandsen & Langfeldt, 2004), showing that industrialists were worried that getting publication records increasingly preoccupied Norwegian professors. In a recent report published by the European Commission (European Commission, 2009), the expert group also raised a question that the emphasis on publication indicators in order to strengthen 'excellence' might hinder the pursuit of relevance.

In our interviews, several scientists often associate the orientation of research with its effect on scientific performance and perceive that research involved in practical application undermines the novelty of research work. This perception seems to contradict the views of science-policy analysts and sociologists (e.g. Rip, 1997; Stokes, 1997), as addressed in section 2.2.1. Nevertheless, as the following will show, other scientists consider that the novelty and application of research is complementary. On the other hand, they had another concern about the dominance of publication performance. Several scientists argue that the publish-or-perish rule has only produced more papers at the expense of research quality. In other words, the publication outputs may not really push back the knowledge frontiers and are not necessarily creative.

5.2.3 Mix of basic and applied consideration

The existing literature proposes alternative notions to depict research aimed at being relevant as the co-existence between basic and applied science, such as Pasteur's Quadrant, Mode-2 research and strategic research (see section 2.2.1). A couple of

scientists interviewed did share this view without explicitly referring to the alternative terms. One scientist indicated that nanotechnology is 'comprehensive basic research,' which does not have a clear boundary like physics and chemistry do (Scientist 4). Another scientist referred to nanotechnology using the prevalent term of 'enabling technology' (Scientist 13). During the interviews, they mainly used the notion of basic and applied to characterise their research, considering these two features as inter-related or that their research consists of specialties from basic and applied research. Several scientists emphasised collaboration with other scientists when carrying out their research. Significantly, all of them have the rank of full professor with at least 13 years of research experience.

A few scientists interviewed in this group also referred to how they approach a topic, an approach that was similar to that presented by the application-oriented scientists. One scientist reported that he aims to develop indigenous materials. In order to reach systemised results, it is necessary to make a breakthrough in basic research. He stated,

> "Chemical engineering as such is an applied-end approach… There are two approaches in nanotechnology research. One approach focuses on new materials but may not have any core application. Although such research is creative, it is difficult to converge towards application. The other approach is based on the application. This approach seems to limit our knowledge base in a field, but the constrained resources are not wasteful" (Scientist 4).

In this group, one scientist indicated that the type of research is relative to what the work compares with and by whom. He reported that it is natural in his field to investigate new phenomena at the nanoscale. Later, he addressed his type of research in a rather ambiguous way. As the interviewee put it, "materials science is application-oriented relative to physics and chemistry and is basic-oriented relative to mechanical and electrical engineering…. From the perspective of the NSC, we are in the applied

side" (Scientist 11). What the scientist means is that the type of the same research work is varied among different groups at different standpoints.

According to the interviewees' remarks, it is difficult to distinguish the nature of research among the three addressed groups of scientists. Similarly, most scientists have investigated the basic features or fundamental problems of their research subjects. At the same time, their research is somewhat associated with practical problems or applications in different ways. In addition, several scientists characterise their type of research in a flexible way, regardless of the nature of the research. Our interpretation of scientists' responses is that the type of research is not really so meaningful to scientists and is context-dependent. Our interviews support the previous study by Calvert (2001), which suggests that the terminologies of basic and applied research are mainly useful for scientists when they have to interact with external groups. We will return to discuss this aspect in the concluding chapter.

One distinction of this group is that a few scientists addressed their research as an interactive process between basic and applied research. They noted that the goal of their research is to develop applications or solve practical problems, yet, certain basic questions emerge in the research process. By saying 'basic questions,' they referred to the understanding of new phenomena or properties at the nanoscale. One scientist explained that "the research is led by practical problems, but the goal would not be fulfilled without making breakthroughs on the fundamental [questions]" (Scientist 17). Another scientist used the metaphor of "rolling a snowball" (Scientist 13) to describe his research, a process in which new phenomena are observed and scientific principles generated in the pursuit of application. In turn, he designed experiments to test theoretical principles back and forth in order to enhance the feasibility of application. Several scientists shared a similar view that the goal of their research is based on potential application, in which basic research is often an integral part before they can

move on to the goal of application.

Moreover, several scientists perceived that the goals of understanding and application are complementary and interactive rather than conflicting. They implied that nanotechnology is 'science-based technology.' A number of scientists indicated that nanotechnology research has a wide range of applications. Nevertheless, in many cases, its realisation lies in knowledge breakthroughs, where the university plays an important role in the process. One scientist noted:

> "There are multiple applications of nanotechnology research, but there are in fact a lot of basic sciences involved…at the nanoscale, such as quantum mechanics, catalysts and the conception of electronic devices. These are very much basic in nature. Nonetheless, understanding these new theoretical principles at the nanoscale enables scientists to design new materials" (Scientist 13).

Throughout the interviews, a recurring response concerning the changing research environment is that scientists perceive increasing weight on publication records to demonstrate scientific performance. However, the funding amounts did not increase accordingly. Most scientists did perceive the demand for the industrial relevance of research, but that mainly occurred when writing research proposals. One scientist frankly expressed that he goes where there is money. He argues that nanotechnology is a political term rather than a technological term. His research is nano-related because the Nano Programme provides a larger grant. For individual research projects, there is almost no regulation examining their research results. For research granted under the Nano Programme, both the ex-ante and ex-post peer panels mainly consist of overseas scientists.

Additionally, due to the over-emphasis on publication records, the funded scientists may strive to produce more papers at the expense of research quality in the short term. A number of scientists argue that the publish-or-perish culture has made scientists over-

produce publications that have little novelty. One scientist suggested that the current reward system tends to deteriorate long-term and high-risk research, stating:

> "Nowadays, what we lack in Taiwan is not the quantity of papers but the quality. High quality research needs long-term investment. Under the current rule of counting the RPI [research performance index], how can a professor work for a paper aiming to be published in *Nature* without producing any other publication in five years? That's why some people said that only when you become a full professor can you endeavour in research quality because you don't need to strive very much" (Scientist 13).

Throughout the interviews, we found that scientists feel more pressure for 'excellence' by demonstrating their publication performance than for the relevance of their research. In the course of our fieldwork, we asked scientists how they define 'research excellence' and how 'excellence' should be measured and rewarded. Most scientists pointed to novel ideas or scientific breakthroughs. Nevertheless, there is no consensus on how excellence should be judged [24]. Despite discontent with the use of publication-based metrics in evaluating research excellence, scientists tended to comply with the rule since publication record has been considered the most important criterion for academic performance and promotion.

5.2.4 No need to distinguish the research orientation

During the interviews, two physicists were fairly reluctant to characterise their

---

[24] In our interviews, scientists indicated three challenges for judging research excellence. The first challenge concerns delayed recognition. A few scientists referred to the Nobel prizes as an exemplar of rewarding scientific advances, but they also indicated that excellent research may go unnoticed for several years. The second challenge concerns the transparency of peer review. While scientists agreed that academic peers are capable of judging research quality, they acknowledged that the decision-making processes are rather subjective and the criteria for research excellence are not always so clear. The third challenge concerns the validity of quantitative metrics, such as impact factors and citation counts. While some scientists criticised the use of quantitative indicators to measure research excellence, other scientists indicated that these metrics have become the conventional practice in scientific communities.

research in terms of any specific orientation. Both are rather junior, with an average of 10 years of research experience. They saw no point in making a distinction between research orientation. Nonetheless, they occasionally indicated that their research is basic in nature and is of potential application. The scientists appear to feel a certain tension to characterise their research as basic-oriented.

Both scientists expressed a linear view of research and used this view to justify their focus on the upstream part of science. In their opinion, reliable research is useful research. They shared the view that research will be eventually useful if one rigorously investigates a research question. One scientist stated that "what I define to be a feasible application is to investigate the properties of materials from the perspective of physics - effectively and delicately… However, the practical application of research is beyond a physicist's work" (Scientist 32). Again, we see a similar response to the basic-oriented scientists being concerned about the division of labour in science.

We also see that scientists position their research flexibly by referring to their discipline and research focus. One scientist stated that "to understand the research subject is academic work, but the research has an ultimate goal for application" (Scientist 27). The other scientist noted that research in the department of physics is generally oriented towards academic goals, even though his research concerns semiconductor surfaces, which has had certain applications in industry. He points to the development of the Internet, which was derived from physics, stating that "it is hard to say that physics is basic research. There is no clear cut distinction [between basic and applied research]" (Scientist 32).

What we have shown throughout this entire section that there is no consistency in how scientists understand the notions of basic and applied research. The categorisation of research might not always be meaningful and is often used symbolically. Particularly in the context of an interview, the scientists seemed to feel some tension in associating

their research with basic research. One scientist in this group considered that research for pure discovery has little possibility of being funded. Nevertheless, he seemed not to worry much, stressing that "there is no job without pressure. Science is academic research. Either doing basic or applied research depends on a researcher's interest" (Scientist 27). The other scientist shared a similar idea, noting that "physicists are often interested in the realisation of ideas. We can write a grant proposal oriented towards application, but it is not necessarily meaningful" (Scientist 32). Again, we see that scientists tend to cope with the external demand of demonstrating potential application without affecting their own research interests.

5.2.5 Summary of the main findings

We have analysed how scientists characterised their research, whether and how their research orientation is associated with 'relevance' and what personal and institutional factors affect their research orientation. The following summarises the main findings.

First, although most scientists characterise their research in different ways, the nature of research is somewhat similar. They tend to address their research orientation by how they approach the subject, emphasising their intention and focus more than the nature of the research. Scientists also flexibly position their research orientation by referring to their disciplines, the scope of their research fields or their departments. The flexible ways of addressing research orientation enable scientists to associate their research with application to a certain extent. Our study finds that research categories are sometimes used in a relative way and dependent on the discussion context.

Second, most scientists interviewed, except for some with mixed basic and applied research goals, conceive a linear relationship between basic and applied research, although they indicate that their research is basic in nature and related to applications.

This linear assumption enables basic-oriented scientists to exclude their involvement in application, but also created tension for most scientists to identify their work as basic research. In addition, several scientists consider that research involved in practical applications is less publishable.

Third, scientists perceive the demand to demonstrate relevance in the current funding environment, but this demand mainly occurs when writing grant proposals and scientists can cope with this demand without much difficulty. Generally, they have a certain freedom when designing their research agendas. On the other hand, they perceive that the weight is more on publication records for a positive grant decision and for scientific performance. There are different views concerning the effects of over-emphasising publications on industrial relevance and the novelty of research. While there is a concern about pushing scientists away from being involved in relevant research, another concern is about producing voluminous papers at the expense of research quality.

5.3 Industry involvement

This section addresses the ways that scientists interact with industry and their perceptions of their relations with industry. We will show that the interaction between university and industry mainly occurs when disseminating knowledge. Scientists generally remain in control of their research agenda, even when they do interact with industry. In addition, industry often does not serve as an alternative source of funding for scientists. Our study suggests that the divisions of labour between university, industry and public research institutes remain clear.

5.3.1 Patterns of interaction with industry

According to the interviews, 14 out of 34 scientists (41.1%) have interacted with industry at some stage through formal research projects or informal consultancy, and meetings in terms of their nano-related research, including three who are junior scientists. In addition, one university faculty recently established a start-up enterprise in 2008 (see Table 5.2). The following addresses the three patterns of interaction with industry in terms of the purpose of industry involvement.

Table 5.2 Types of industry involvement

Industry involvement	Forms of interaction	Characteristics of the interviewees
University as a knowledge provider (11 scientists)	• Informal consultancy and meetings • Collaborative projects	• 4 scientists in Physics & Chemistry; seven scientists in Engineering; 3 are junior scientists • 9 academic inventors • 4 scientists were involved in technology-transfer activities
Industry as a joint research partner (3 scientists)	• Joint R&D projects	• Engineering, Chemistry, Medical science • One academic inventor
Academic entrepreneur (1 scientist)	• Start-up company	• Physics
No industry involvement (19 scientists)	--	• 11 scientists in Physics and Chemistry; 8 scientists in Engineering • Twelve academic inventors

Source: developed by the author.

<u>University as a knowledge provider of academic services to industry</u>

The first and most common reason why scientists interact with industry is to provide their knowledge and technical assistance to specific companies. Several senior scientists have heavily interacted with industry for a long time, with such interaction seeming to bring about further knowledge-transfer activities. As nanotechnology emerges as a new technological opportunity, several companies in Taiwan are exploring

its potential application actively and sought help from universities to solve technical problems and use their facilities. One junior scientist was contacted by some industrialists because of his patent. Scientists often interact with industry through personal contact, informal consultancy and meetings, and formal collaborative research.

The companies involved in this type of interaction appear to have limited or low level R&D capabilities. The interviewees indicated that the main difficulty for industry to become involved is not money but its lack of capabilities. For example, four scientists who have been involved in collaborative projects were mainly funded to explore the applicability of nano-related techniques on the basis of their research expertise. Rarely were the companies involved in the projects. As one scientist put it, his involvement in the collaborative project was based on his experience and profession because the collaborative company was neither familiar with the new material, nor with the required facility. He provided an experimental facility in the laboratory for the company's reference, with the company able to further search for appropriate facilities for real production. Another scientist, who has had informal interaction with one company for about ten years, states that the R&D activities of his collaborative company were conducted in the laboratory of his university because the company is sales-oriented and places little emphasis on R&D.

The interviews highlight that personal motivation is a major factor for scientists to interact with industry. A few scientists actively participated in exhibitions or workshops to 'promote' their research and seek opportunities to interact with industry. Scientists regard this type of interaction as a service to industry and that it has little direct benefit to their research. Nevertheless, such interaction provides them with different perspectives and ideas concerning their research subjects. Three junior scientists have interacted with private companies through consultancy, informal meetings or collaborative projects. One noted that, in addition to gaining certain extra income, the

interaction helps him make sense of the industry.

Our study suggests that the traditional functions of research and teaching remain the norm in universities and that the research function is even reinforced by the current reward system. Some scientists indicated that research, teaching and service are the three missions in a university. However, the weight is more on publication records and research performance than the other two functions. While scientists considered the interaction as being positive, some scientists indicated that such work is less recognised in the reward system.

Industry as a joint research partner

The second type of industry involvement is carrying out joint R&D, which tends to have a specific goal of developing products for the market. Three scientists had just initiated joint R&D projects when interviewed, all working on biomedical research. Compared with the collaborative projects addressed in the previous sub-section, the joint R&D projects were initiated by the scientists rather than the industrial actors. It is worth mentioning that the three scientists were in the interviewee group embracing both basic and applied considerations in their research. Their research goal was to solve a practical problem, while basic and applied research were interactive in the process in order to achieve the goal. One scientist noted that he has investigated the basic research of the research subject for six years and has now begun to move to the application of research (Scientist 13). The collaborative model was new to him, but what motivated him was the expectation of realising research that could be of actual benefit to patients. His remark reveals that prior fundamental knowledge is essential for forming such collaborations.

Scientists in this group regarded the collaborative companies as their partners rather than users. One scientist pointed out that the notion of a 'user' is similar to

consumer behaviour - "I buy what you made and I do not need to get involved" (Scientist 13). He continued to explain that "I think that the firm is a partner, a co-inventor, and an investor. It invests not only money, but also techniques." The three scientists place emphasis on the dedication of industry to achieve the joint R&D goal. As one scientist put it,

> "Companies have to think about whether they can afford to invest in a new field for three to five years before making profits. It might be difficult for them to survive if the economies of scale are not large enough… The incentive for [my] collaborative company to be involved is the potential market share it anticipates. In addition to investing money and manpower, the company has to adjust its manufacturing procedure in order to do the pilot run. All of the work is time-consuming" (Scientist 17).

The interviews show that the common shared expectation, commitment and trust from both parties are crucial factors to achieve the joint R&D goal. It is the huge potential market that mainly attracts the firms to become involved. Meanwhile, the collaborative firms also need to commit their financial and research resources. On the other hand, the above scientist stated that the company was more willing to collaborate because he filed a patent application to protect the intellectual property.

Academic entrepreneurship

In our study, one scientist has just established a start-up company directly from university. The reasons for the academic entrepreneur setting up his own startup rather than collaborating with industry reveal several challenges that other interviewees perceived in getting industry involved in their research work. The relations with industry that the scientists perceived will be discussed in the next section. In general, the entrepreneurial scientist pointed to the different norms and goals between university and industry, thereby weakening the mutual trust between the two. For university scientists, what interests them more is to confirm theoretical ideas and develop early-

stage technologies. Academics prefer to do something new in the world and are then happy to publish the results. On the other hand, industry is concerned with the market competitiveness of new tools or new technologies in terms of cost and function. As the entrepreneurial scientist put it, the SMEs in Taiwan tend to seek help with functional improvements from university; nevertheless, scientists prefer to do innovative things. The scientist further explained why he decided to set up his own R&D-oriented company, stating,

> "In general, a scientist has to put a lot of effort into the laboratory to produce good research work. I am not sure whether somebody could understand my work thoroughly if I handed it to him or her… In addition to the technical issues, the degree of mutual trust is a major factor for collaboration… As a professor, to take part in an university-industry collaboration takes extra time in dealing with the technical aspects, which is usually not publishable and has no incentive for a professor to get involved" (Scientist 19).

As shown in section 5.2, several application-oriented scientists were not very inspired to get involved in solving practical problems for industry. They considered such work as repetitive and that it does not yield much benefit for their research. This raises a question concerning the role of universities meeting industrial needs. As the next section will show, scientists' perceptions of the relationship between university, industry and public research institutes is inconclusive.

To summarise, the analysis addresses three types of industry involvement in terms of their different purposes. The interviews reveal that university-industry relations in nano-related research primarily occur in relation to seeking university knowledge and resources, with a few companies having started to get involved in joint R&D with university scientists. Moreover, this study suggests that university scientists remain focused on their traditional academic activities, with their involvement with industry exerting little influence on their research agendas. University-industry relations are not

only shaped by their different norms but also by the institutional arrangements in Taiwan's context, which will be discussed in the following section.

5.3.2 Scientists' perceptions of the relations with industry

When discussing whether there is any industrial partner formally or informally involved in the research process, many scientists pointed out several challenges in terms of the industrial features in Taiwan, the academic environment, the role of public research institutes and the features of nanotechnology research. These challenges indicate that the current institutional structure is not oriented towards a more interactive relationship. What the scientists said might be as expected. On the other hand, a couple of scientists expressed different opinions on the above challenges. Their views on the basis of their own experience and general perceptions only reflect part of the conditions in the institutional environment. Nonetheless, these perceptions shape scientists' motives and research behaviours when interacting with industry.

Challenges concerning industrial features

In line with expectations, several scientists referred often to the industrial structure in Taiwan as something that challenges university-industry relations. A couple of scientists state that their collaboration with industry did not continue because the SMEs lacked the resources to invest in R&D and they looked at short-term returns. The major concerns of industry are mass-production, profit and increased market share, rather than exploring the frontier of technological innovation. Some application-oriented scientists indicate that they would not get industry involved too early in the research process until the research was more well-rounded because industry often expects to see specific results as soon as possible. A couple of scientists pointed to the above differences by comparing them to industrial features in the USA and Japan, where firms tend to have

their own R&D centres and a long tradition of collaborating with universities.

Some scientists implicitly suggested the concept of the public good of university research and raised the question of how close the interaction between university and industry is 'relevant.' They stated that the technical problems raised by industry should not necessarily be addressed by publicly funded universities. A couple of scientists pointed to the short-term mentality of industry in Taiwan as the major obstacle for industrial upgrading and university-industry collaboration. As one scientist put it, sometimes the technical problems of SMEs are not difficult for university academics. Nevertheless, it is worth thinking about whether it is appropriate for academics in national universities to become involved, arguing that:

> "The university should help industry with the fundamental changes, thereby adding value to industry or transforming industry into the knowledge economy. If industry only needs a helping hand from universities, there is no harm to scientists. This type of work is relevant to industrial needs but it may not be excellent work… [because] the industry uses public resources and the kind of work is not the most appropriate application of university capabilities to industry" (Scientist 15).

Nevertheless, a couple of interviewees shared an opposing view concerning industry involvement in nanotechnology research. Some of the leading semiconductor firms in Taiwan have already developed more advanced nano-scale technologies than those in universities. In addition, several scientists stated that nanotechnology ought to provide an opportunity for Taiwan's SMEs to collaborate with academics because university scientists often specialise in specific areas and often involves a component rather than an entire product. Similarly, SMEs in Taiwan also tend to specialise in producing a single component. One scientist noted that his collaborative project with a small company revealed that nanotechnology appears to enable small firms to make breakthroughs in their products. In short, what constructs a proper relationship between university and industry in nanotechnology research remains open to debate.

Challenges concerning the academic system

A second challenge relates to the institutional arrangements of universities in Taiwan. One of the most often mentioned factors is the current reward system that mainly focuses on academic papers. As discussed earlier, a number of scientists mention that interacting with industry tends to yield little benefit in terms of their publication records. On the other hand, several scientists had concern that the publication-driven university culture has pushed scientists away from engaging in relevant research. Although many scientists acknowledge that the policy aims to encourage close linkages between university and industry, some believe that industry involvement is a plus for their academic performance but do not necessarily put much effort into interacting with industry.

Although the dominance of publication records has been criticised as a major problem for achieving the socio-economic relevance of research, we should keep a healthy scepticism about over-emphasising its effect on university-industry relations. As presented in section 5.3.1, personal motivation is a major factor for scientists to interact with industry, despite the lack of incentives.

Although various mechanisms to encourage university-industry linkages have been established by the government and universities, several scientists question their efficacy. For instance, incubating companies are mainly motivated by the lower rent and public subsidies provided by universities rather than by a university's basic research capabilities (Scientist 3). Moreover, the technology transfer offices in their universities tend to act passively as an administrative unit and suffer from a lack of ability in marketing technologies and patents developed by scientists. Another scientist pointed to the strict compensation structure that scientists' incomes mainly depend on government funding and is rarely from industry (Scientist 7). Therefore, there is not much incentive for university faculty to interact with industry.

Challenges concerning the relationship with public research institutes

We find that there remains a clear division of labour between university and public research institutes. Several scientists refer to the Industrial Technology Research Institute (ITRI), the main public research institute for facilitating the industrial application of technology, as the 'industrial actor' when asked about their experiences interacting with industry. A couple of scientists interacted with ITRI through licensing because ITRI is closer to industry and can provide a total solution to industry.

Nevertheless, some scientists consider that ITRI remains focused on short-term research, which is not university scientists' main interests, thereby hindering university scientists' motivation to collaborate with ITRI. In addition, some scientists raised the issue of sharing intellectual property rights as a challenge to collaborating with ITRI. Although ITRI has played a major role in the development of high-tech industries in Taiwan since 1973, a couple of scientists questioned its operational model in realising nanotechnology research. As one scientist put it:

> "Traditionally, ITRI introduces new technologies from abroad to local industries. The performance is easily accountable. However, nanotechnology research is different. The goal to initiate the Nano Programme is to build up indigenous technologies, with it hoping that ITRI can transfer technology to industry. If the source of technology is from a university, there is an issue of IPR contribution between the two parties… I think the underlying problem [in collaborating with ITRI in nanotechnology research] is the different funding sources of the Nano Programme. The funding source of the ITRI is mainly from the Ministry of Economic Affairs, while that of universities is from the NSC" (Scientist 11).

We find that the institutional arrangements seem to not have co-evolved to be more interactive. As shown in Chapter 4, large-scale policy initiatives in nanotechnology research have attempted to integrate resources from individual agencies. However, the funding structure remains based on the traditional functions of the actors in the innovation system and restricts interactive activities.

5.3.3 Summary

Our interviews find that industry involvement in the research process is not a conventional practice in Taiwanese universities. Interaction with industry tends to occur when industry seeks knowledge and technical assistance from a university, in a way most scientists consider to be a kind of service to industry that is of little direct benefit to their academic performance and little rewarded. This kind of relation between university and industry appears to be related to the industrial features in Taiwan and the related institutional arrangements in the research environment as perceived by scientists. Nevertheless, a few scientists have just started to initiate joint R&D projects with industrial partners in biomedical research. The major motivation for scientists is to realise research ideas rather than seeking external funds. This analysis suggests that industry generally does not play an active role in scientists' research processes. Scientists would adhere to scientific inquiry even when industry is involved in joint R&D projects.

5.4 Interdisciplinary collaboration

This section addresses scientists' perspectives on their interdisciplinary collaboration in nanomaterials research. While several studies attempt to offer definitions of 'interdisciplinarity' and distinguish the term from other related notions (section 2.2.3), we aim to explore how scientists distinguish the term based on their research collaboration, how they expect or realise relevance by interdisciplinary collaboration, and the factors affecting collaboration.

Before we proceed to present the empirical results, it is worth mentioning the term 'interdisciplinarity' used in Taiwan's context because its concept is related to how scientists organise their research. In the Chinese language, the equivalent term '*Kua-ling-yu*' appears to have no clear definition, although it has been widely used in recent

years.[25] This term is relatively new terminology and adopted from the notion of interdisciplinarity and related terms to depict the various kinds of interaction between different disciplines. To the author's best knowledge, in the domain of science policy, the term 'interdisciplinarity' first appeared in the *White Paper on S&T* in 1997. It referred to one of the criteria for the National S&T Programme in Taiwan, a criterion for initiating the "interdisciplinary projects that transcend the scope of individual agencies" (NSC, 1997, p.37). In fact since the 1980s, there were some similar initiatives under the name 'integrated projects.' However, there was virtually no discussion about the meaning of these terms. In academic communities, the term 'interdisciplinarity' and related notions began to be prevalent in the social sciences and humanities in the 1990s,[26] but these studies mainly focused on their research subjects. Only a few studies addressed or investigated the definition of interdisciplinarity.

The notion of interdisciplinarity is also widely used in the policy documents of nanotechnology initiatives. It often refers to the collaboration of different agencies, the integration of different disciplines and the cultivation of talents with multi-skills and knowledge. As addressed in section 4.2.2, one funding criterion of the Nano Programme is that there should be at least three academics from different disciplines serving as Principal Investigator (PI) or Co-PIs. The notion of interdisciplinarity used in policy practice often refers to the scope of collaboration. However, it remains unclear what the scope of a discipline covers and what attributes constitute interdisciplinary collaboration.

In the interviews, we observed that most scientists denoted the term 'interdisciplinarity' uncritically. They tended to express positive attitudes towards interdisciplinary collaboration. Some scientists stated that interdisciplinary

---

[25] The first word *'kua'* means cross and the last two words *'ling-yu'* means domain or field. In an academic context, *'ling-yu'* tends to mean discipline.

[26] This observation is based on the search of the titles in the local journal articles.

collaboration just 'happens naturally' (Scientists 2, 9 & 16). As one scientist put it, "if you have a good research topic, you would naturally attempt to find the relevant scientists you need" (Scientist 16). Such responses are expected but intriguing. On one hand, scientists' positive attitudes might be related to the promotion of the term in policy discourse and the large grants provided by the NSC. On the other hand, interdisciplinary collaboration involves more interaction with scientists from different backgrounds, a division of labour and mutual trust, to name a few. Scientists' remark that it 'happens naturally' suggests that such collaboration is a self-organising activity and not too difficult. Nevertheless, this section will show that scientists implicitly embrace different conceptions of interdisciplinary collaboration.

The following uses the notion of interdisciplinarity as a general concept covering different types of collaboration elaborated by scientists, unless specified. Section 5.4.1 presents the notion of interdisciplinary collaboration defined by scientists, the reasons for their collaboration, the institutional incentives and barriers. Section 5.4.2 addresses the two patterns of collaboration revealed from the interviews.

5.4.1 Scientists' perceptions of interdisciplinary collaboration

This section presents the criteria, reasons and institutional factors for interdisciplinary collaboration perceived by scientists, investigating what features distinguish interdisciplinary collaboration, the rationales for scientists to be involved in interdisciplinary collaboration and how such collaboration is associated with the relevance of research.

5.4.1.1 Criteria for interdisciplinary collaboration

Table 5.3 summarises how scientists addressed interdisciplinary collaboration. These criteria are not mutually exclusive and some scientists addressed more than one

criterion. Most responses were based on scientists' research practices. Four junior scientists noted that their research is mainly disciplinary oriented, so their remarks were based on their general perception.

Table 5.3 Criteria for interdisciplinary collaboration

Criteria for interdisciplinary collaboration	Number of responses	%
With scientists from different disciplines	15	44.1
With scientists from different research specialties	14	41.1
With students from different disciplines	4	11.8
With application goal	2	5.9
Integrating basic and applied research	1	2.9
Integrating upstream and downstream research[27]	1	2.9
Unclear notion of 'interdisciplinarity'	2	5.9

Note: The number of responses is not exclusive (i.e. some interviewees gave more than one response). N=34.

Source: developed by the author.

The scope of collaboration

Table 5.3 presents that most scientists pointed to the *scope* of collaboration when depicting interdisciplinarity. In addition, discipline and research specialty were usually inter-related. Most scientists referred to the collaboration with scientists from different disciplines, where the collaborators' research specialties were located. For example, one scientist stated that his research on magnetic materials needed expertise from organic chemistry to synthesise materials and from physics to examine the properties (Scientist 2). Another scientist said that the research team consisted of faculty from physics and electrical engineering, whose specialties are quantum communication and computation (Scientist 7). A couple of scientists noted that their 'interdisciplinary' collaborations

---

[27] This criterion put forward by an interviewee (Scientist 31) is very much similar to that of integrating basic and applied research. Upstream research involves understanding the fundamental properties of nanomaterials and downstream research involves investigating problems that are relatively closer to practical applications.

remained within their disciplines, such as within materials science and within the school of engineering. We see that the scope of a discipline that the scientists put forward was rather diverse. In our study, the department of materials science tends to be involved in scientists with various disciplinary backgrounds. Therefore, their collaborations were mainly within the institutional boundary.

Scientists' responses suggest that interdisciplinary collaboration tends to occur between university departments, which have long been institutionalised. This hypothesis is supported by evidence from other criteria and institutional factors that affect interdisciplinary collaboration.

Exchange of students

Four scientists highlighted the importance and benefits of having postgraduate students exchanged between laboratories in interdisciplinary research. Postgraduate students are not only assistants but also those who usually carry out the experiments in practice. One engineering scientist stated that the research team could *integrate* different techniques by exchanging students in the joint project (Scientist 15). Other scientists stressed the exchange of students among different disciplines as important training in interdisciplinary work in one's early career (Scientists 13 & 17). An entrepreneurial scientist echoed this point on the basis of his experience, stating:

> "I worked as a post-doctoral fellow when I was involved in an interdisciplinary project initiated by two distinguished professors. Nearly everyone [in our scientific community] knew that they were working on this research subject. They were the leaders of the project and I was the one who mainly carried out the research. To be recognised, you have to put in the effort to accumulate your credits over a long time" (Scientist 19).

His remark also indicates that seniority is a crucial factor for a scientist to carry out interdisciplinary collaboration. This aspect will be addressed later in this section.

Application goal

Two scientists referred to motivation as the main criterion and explicitly emphasised the application goal in interdisciplinary collaboration. One scientist said that "only research which is involved in practical application would I consider as being interdisciplinary" (Scientist 32). Another scientist shared the same opinion, saying that "what matters is not whether you collaborate across fields but whether there is any purpose for application" (Scientist 21). While other scientists did not identify the application goal as a criterion for interdisciplinary collaboration, twelve scientists stressed the necessity of interdisciplinary collaboration in order to increase the likelihood of realising the application of their research (see Table 5.3).

As shown in section 5.2, the application goal seems to be an arbitrary position because scientists may demonstrate their goal in various ways. Our study suggests that scientists' intentions behind the goal appear to play a significant role in determining scientists' research behaviours. What is more important is understanding the factors that shape scientists' intentions. This will be addressed in section 5.5.

Integration: degree of interaction

Several scientists highlighted *integration* between basic and applied research or between the 'upstream' and 'downstream' disciplines as an important criterion for conducting nanotechnology research. Such a response reflects a highly specialised division of labour among institutional disciplines. The interviewees indicated that the emergence of nanotechnology research has triggered interaction between basic and applied research, which were originally compartmentalised. They point out that what distinguishes the purpose of nanotechnology research is 'integration', rather than the criterion based on the technical definition at the nanoscale. For instance, one scientist involved in nanomaterials research for decades, stated:

"I know how to produce nanomaterials and I know their properties. That's it!… The application will be rather limited if the research is only from the perspective of chemistry. Without collaborating with scientists from downstream disciplines, the application would not be realised… To put it simply, it is about the integration of up-, mid- and down-stream research" (Scientist 31).

Another scientist pointed to the same aspect, stating:

"In the past, nano-related research was carried out separately in different disciplines. For example, research on nanoparticles might be done in the department of materials science. Now the outcome of the Nano Programme is to integrate expertise from different disciplines" (Scientist 6).

The notion of integration as a criterion for 'interdisciplinarity' is acknowledged by several studies (see section 2.2.3). However, we find that what scientists meant by integration often refers to the degree of *interaction* in the collaboration, which depends on the complexity of a research project. One scientist, whose research is on the application of a nanoelectronic device in the biomedical area, noted:

"If a doctor in the biomedical area has no idea about the mechanism of how the device works, the outcome of his/her involvement in the project would be rather small. To *integrate* means to get him/her involved and to understand how the device operates, instead of only thinking about what I should do or what I could do for you. In fact, the [interdisciplinary] work is rather tiresome. It would be good enough if every scientist had his/her own expertise in a field. Why do I have to take a step further and explain repeatedly what I consider to be common sense to others? Nevertheless, once we establish the collaborative approach, we all learn a lot from the collaboration" (Scientist 17).

The above scientist's account shows that interdisciplinary collaboration does not usually 'happen naturally.' Scientists have to be heavily involved in communication, coordination and negotiation during the process. Nevertheless, our interviews suggest that scientists seem unworried about the loss of their autonomy in organising interdisciplinary collaboration. A couple of scientists stated that it is personal choice and

that not every scientist has to do it. As the following will show, scientists perceive that the benefits outweigh the barriers of collaboration.

Our study finds that the degree of interaction is a distinctive feature for differentiating different forms of collaboration. We will elaborate the patterns of collaboration revealed from the interviews in section 5.4.2.

Unclear definition of interdisciplinarity

While most scientists seemed to not have any problem denoting interdisciplinary collaboration, two scientists considered the term questionable. They pointed to different aspects, but both implied a problem with lacking a clear definition. One said that such collaboration was already common forty years ago and happens naturally. He indicated that the definitions of nanotechnology and interdisciplinarity need to be clarified. When talking about his research, the collaboration he addressed was mainly disciplinary without much interaction. Another scientist raised the issue that some interdisciplinary collaborations only adopted the concept or model from other disciplines. He indicated that "what we regard as a crucial aspect of research might be seen as peripheral in other disciplines… If we want to have good results from the collaboration, we need to have a substantive mutual understanding of different disciplines" (Scientist 23).

Our study suggests that, while the lack of a clear definition of interdisciplinarity provides scientists certain freedom to fit in with policy requirements, a more explicit discussion about the definition might enrich common understanding in the scientific community and effectively encourage interdisciplinary collaboration.

5.4.1.2 Reasons for interdisciplinary collaboration

Table 5.4 presents the main reasons scientists addressed for their collaboration. The interview question was put in an open-ended manner, so the scientists responses tended

to point to the purposes, motives and benefits of collaboration, although some of them are inter-related. Overall, they considered interdisciplinary collaboration necessary for achieving application, with the benefits seeming to outweigh the costs.

Table 5.4 The reasons for interdisciplinary collaboration

Reasons for interdisciplinary collaboration	Number of responses	%
For the purpose of potential application	12	40.0
Research need (expertise, method, equipment)	9	30.0
Common research interest	5	16.7
Comprehensive understanding	5	16.7
To obtain large research grants	4	13.3
Outstanding academic performance	2	6.7

Note: The number of responses is not exclusive. N=30.

Source: developed by the author.

Twelve scientists indicated that interdisciplinary collaboration is a necessary criterion to facilitate the application of nano-related research because it covers a more comprehensive perspective of a research subject. Nonetheless, it is not a sufficient condition for realising practical application. As one scientist noted, how market demand and the level of current technology can be coordinated is also a crucial factor for the successful application of research (Scientist 33). Due to the industrial features in Taiwan (see section 5.3.2), a few scientists would carry out application-oriented research by collaborating with academics familiar with the industrial circumstances rather than with industry from the beginning of the project.

In addition, research need was a main reason for collaboration. In particular, scientific instruments play a major role in forming a collaboration. Some scientists stated that their research would be incomplete without expertise or equipment from other scientists. Several scientists noted that application usually involves conducting experiments, which needs more advanced precision instruments to examine and observe

nano-related phenomena. A laboratory cannot usually afford to buy one. In addition, to use such instrument requires different skills, making it necessary to collaborate with other scientists.

Some interviewees noted the common research interest of a topic as one of the main reasons for their collaborations. What they emphasised was the underlying motivation and attitude towards interdisciplinary collaboration as a prerequisite. Without a common interest, a collaboration would not be formed or achieve the goal successfully. Such common research interest implies that scientists need to dedicate themselves to interacting with other scientists. One scientist expressed that "patience, enthusiasm and common interest are the drive for a collaboration… There is no shortcut" (Scientist 31).

We find that large grant funding is the dominating institutional incentive for scientists to be involved in interdisciplinary collaboration. A number of scientists put forward the benefits as reasons for their collaborations, which will be addressed in section 5.4.1.3.

Moreover, the benefits of a comprehensive understanding of a subject and outstanding scientific performance are related to intellectual stimulation and the quality of research. An unexpected response is that publishing interdisciplinary research in high impact journals seemed not to be a major problem to the interviewees. We assumed that the disciplinary structure and incentive system might disadvantage the recognition of interdisciplinary research. However, several scientists pointed out that interdisciplinary research tends to be published in high impact journals because it provides a more comprehensive perspective of the subject and often has scientific breakthroughs. In addition, newly established journals with high impact factors related to nanotechnology

create an incentive for scientists to engage in interdisciplinary research. [28] Some

traditional journals also welcome interdisciplinary research, as several scientists noted.

5.4.1.3 Institutional incentives for and barriers to interdisciplinary collaboration

We find that large-scale funds are the dominating, and probably only, incentive in

the current institutional arrangements for interdisciplinary collaboration. The large

funds not only provide financial resources but are also considered a symbol of

recognition, thereby attracting researchers with common interests to be involved in

interdisciplinary research. A number of scientists referred to the initiative of the Nano

Programme in recent years and the fact that the available funding is larger than for

individual research grants. One scientist stated that "sometimes it is not easy to find a

collaborator in a scientist's own project. Integration would be difficult to realise without

the driving force of large funding amounts" (Scientist 12).

Moreover, the Programme helps break down the discipline-based funding system.

One interviewee in an engineering department stated that:

"there is a need for basic research in order to achieve system optimisation
in fuel cells. However, the grant proposal for chemical research is traditionally
judged by the division of natural sciences [in the NSC], and that of chemical
engineering research is judged by the division of engineering. Therefore, a
basic-research project related to chemical engineering generally cannot get
funded easily by the division of natural sciences [because it is considered
applied]. There is no such problem under the Programme" (Scientist 4).

Although the NSC and a number of universities have encouraged interdisciplinary

collaboration, there seems to be a lack of other institutional arrangements to support

such collaboration. Several scientists stated that, although universities organise regular

seminars or workshops to enhance interaction among different disciplines, these

---

[28] Several interviewees pointed to new nano-related journals, such as *Nanotechnology, Nano Letters, Nanoscale* and *Journal of Materials Chemistry*.

activities have little effect on real interaction if there is no mutual interest in the research topics. They often get in touch with potential collaborators through informal contact and most of their collaborators are those they have known for a long time. To them, it is not a major problem finding collaborators as long as they share a common research interest.

Some scientists indicated the constraints of disciplinary structures restricting collaboration among different disciplines. One obstacle is the problem of recruiting students with different disciplinary backgrounds. As one physicist put it:

> "Nowadays, the disciplines are highly specialised in universities in Taiwan. There is not much interaction among university departments even under the same school. Conventionally, we [in the department of physics] only recruit postgraduate students with an academic background in physics, which is now an obstacle to carrying out interdisciplinary research" (Scientist 33).

The above scientist's remark reveals that disciplinary structure remains to be organised along with departmental structure, with there being some tension between the traditional function of teaching in a university and the execution of interdisciplinary research. He further referred to the education system, in which students in senior high schools have to choose a specialised orientation between natural/engineering sciences and humanity/social sciences. As a result, educational training is often oriented towards a specialised profession. Another scientist indicated that several peers in his department objected to merging between two disciplines because some peers questioned what they should teach in the interdisciplinary field. Part of the reason might be that not all faculty members within a department are specialised in nano-related subjects. The merging of disciplines in a university department may not meet the needs and interests of all faculty members.

Specialised disciplines in university departments might be related to sectoral specialisation in industry. As presented in Chapter 4, the traditional function of higher

education in Taiwan has been to provide human resources in accordance with industrial needs. With the progress of computer science and the division of labour in semiconductor and ICT (information and communication technology) sectors, several subdisciplines in engineering have been established as independent units in universities.

Strong disciplinary culture also hinders the involvement of members from different disciplines within a department, whether students or scientists. As presented in Table 5.3, several scientists emphasised the exchange of students as a way of carrying out interdisciplinary collaboration. Our interviews suggest that interdisciplinary collaboration tends to occur at the interface between university departments.

The fact that scientists do not seem to be discouraged by the lack of institutional support is related to their seniority and status. Our study reveals that seniority affects scientists' involvement in interdisciplinary collaboration. On one hand, interdisciplinary work takes a certain time to develop the necessary mutual background knowledge and make a collaboration go smoothly. A couple of scientists indicated the challenges of handling interdisciplinary collaboration, including different disciplinary languages, different logics of thinking and different perceptions of the output results in a collaboration. Although it might take about one or two years to achieve mutual understanding among different disciplines, senior scientists regarded these challenges as a learning process. For junior scientists, it is an additional pressure if they do not produce research results in the short term. As described by one scientist, "generally in Taiwan's research environment, if you want to do interdisciplinary research, first you must have something to *survive* by yourself" (Scientist 13). He continued to explain:

> "When becoming involved in interdisciplinarity, you probably have no publications for the first one or two years because you are still learning. If the laboratory research can operate and you can produce publications without the funding of the Nano Programme, then you can spare part of your time to do interdisciplinary work."

The above scientist's remark shows that he has to manage the balance between disciplinary and interdisciplinary research, so that he can demonstrate the publication performance in the short term while keeping interdisciplinary research proceeding in the longer term under the current review system.

On the other hand, seniority also partly reflects scientists' scholarly reputation and coordination ability that may affect the initiation of interdisciplinary collaboration. During the interviews, four junior scientists mentioned that they mainly focus on disciplinary research without collaboration across disciplines due to a lack of cumulative experience and resources, such as necessary funding budget, facilities and manpower. One scientist stated that he started to do more interdisciplinary work after he was promoted to the rank of full professor. In addition, a couple of scientists stressed that successful interdisciplinary collaboration depends on whether the team leader is a good coordinator or not, which is also related to a scientist's experience in handling a joint project.

Nonetheless, a few scientists also pointed to the 'old boys club' phenomenon reinforced by the peer review system. They expressed that young scientists might be more enthusiastic to explore creative research areas, but it is almost impossible for them to gain large research grants because of no substantive publication records.

In summary, scientists did not perceive substantial support in the current institutional environment, except for the large-scale funding opportunities. Despite this, the benefits of interdisciplinary collaboration seem to outweigh its costs. As presented previously, scientists note the financial and intellectual benefits as the main reasons for collaboration. They were motivated to initiate interdisciplinary collaboration and organise such collaborations through personal networks. Since nanotechnology research has been a popular topic in recent decades, newly established journals have enabled scientists to gain recognition for their interdisciplinary research.

5.4.2 Patterns of interdisciplinary collaboration

Although most interviewees expressed the view that their research is interdisciplinary, our analysis shows that the ways they delineate interdisciplinarity are both ambiguous and diverse. A distinctive feature is the degree of interaction.

One type of collaboration seems to be the conventional way that collaborations occur within the scientific community. Scientists sought to involve others who possess the skills needed in a research project, while the participants appeared to be mainly responsible for their own expertise without much interaction with other scientists. The research projects were carried out within a discipline and involved scientists from other disciplines. There was a clear division of labour, with the collaborators not necessarily involved in the entire research process. Several scientists in this group often stressed the role of scientific instruments or facilities during research collaborations.

In the other type of collaboration, scientists tended to get involved in the entire research process and understand the work of other specialists to produce better research results. They often stressed that they had to "take a step further out of their disciplines" (Scientists 13, 17, 31 & 33) and cross over the interface into application, or integrate upstream and downstream research. When asked about the goals of their research, they often argued that the overall goal is solving a practical problem, while basic and applied research are inter-connected to achieve the goal. As the projects involved scientists with diverse disciplinary backgrounds, such collaborations need more interaction and mutual understanding to make the projects advance smoothly. Some scientists said that the collaborative process is not easy and that there is no pressure for scientists to do so. However, the benefits outweigh the drawbacks once they overcome the obstacle of interaction at the beginning of a collaboration.

Our study suggests that the second type of collaboration is closer to the 'interdisciplinary research' that the existing literature often denotes (e.g. Klein, 1990;

Rossini & Porter, 1979). Literature suggests that interdisciplinary research tends to focus on the goal of solving societal or practical problems, often attempts mutual interaction and is more integrated than additive by nature. Other studies note that an explicit expression of goals for problem-solving is a key criterion to distinguish interdisciplinarity from disciplinarity research (Balsiger, 2004; Schmidt, 2008). According to the interviews, there were a few cases in this type of collaboration, with all their research related to biomedical fields.

We consider that the first type of collaboration is more about a regular research collaboration and may not necessarily be multidisciplinary in nature. Literature suggests that multidisciplinary research tends to draw the perspectives of a research topic from different disciplines, with there being no attempt to synthesise different views on a topic. In the first type of collaboration, the main reason for scientists to collaborate is to seek the expertise or equipment from other disciplines in order to complete a research project. Moreover, some scientists indicated that their collaborators are from within their own disciplines. In other words, their collaborations are mainly disciplinary than multidisciplinary in nature.

Nonetheless, it is worth noting that the two types of collaboration may not be mutually exclusive. Scientists carry out both disciplinary and interdisciplinary research. As one physicist stated, he now carries out more interdisciplinary collaborations after being promoted to a full professor.

5.4.3 Summary

The interviews suggest that interdisciplinary collaboration is mainly driven by policy initiatives, which provide large-scale funds to encourage scientists to collaborate. Scientists tend to have a positive attitude towards interdisciplinary collaboration, despite lacking institutional support. Moreover, seniority plays a role in developing

interdisciplinary collaboration. A further examination of what scientists mean by interdisciplinary collaboration revealed two patterns of collaboration. One more concerns a regular research collaboration carried out in a discipline without much interaction, whilst the other tends to involve more interaction and commitment among scientists throughout the entire research process. While several scientists stated that interdisciplinary collaboration is a necessary condition for realising applications, they were also motivated by financial, intellectual and symbolic resources brought about by such collaborations. In addition, scientists perceive that interdisciplinary research tends to be published in high impact journals. Our interviews suggest that the benefits of interdisciplinary collaboration in nanomaterials research tend to outweigh its barriers.

5.5 Scientists' perceptions and research behaviours towards organising relevant research

This section summarises the previous three sections of how the interviewees perceived and organised research aimed at being relevant. Our study shows that scientists exhibit various ways when organising research, which partly reflects personal factors and the institutional environment they perceive themselves to be operating in. Section 5.5.1 summarises scientists' perceptions of the current research environment. Section 5.5.2 synthesises scientists' behaviours in response to their research orientation, industry involvement and interdisciplinary collaboration.

5.5.1 The institutional environment perceived by scientists

Overall, scientists did perceive a funding environment emphasising the potential application of research. A couple of scientists expressed the view that purely basic research stood little chance of being funded. On the other hand, they perceived that publication records remain or are increasingly serving as the dominant criterion for

funding decisions and performance evaluations, even though the funding amounts have not increased accordingly. In other words, scientists face the challenges of demonstrating both the relevance and excellence of their research. As addressed in the next section, scientists' behaviours show their concerns and the underlying tension between relevance and excellence.

Our study finds that the institutional environment is not very oriented towards the support for 'Mode 2' knowledge production. The disciplinary structure in universities is institutionalised and often resistant to change. As a result, it creates barriers to recruiting students or faculty from different disciplinary backgrounds in a university department. While several universities do organise workshops or meetings to encourage interaction among the faculty, scientists tend to develop their interdisciplinary team through personal networks. Moreover, the launch of the Nano Programme has played a major role in facilitating the collaborative culture among scientists and help break down the disciplinary-based funding structure. Nonetheless, the funding schemes for university research and industrial applications are charged by different governmental bodies. Therefore, the Programme provides little incentive for academics to interact with public research institutes (mainly the ITRI) to materialise the industrial application of research.

In addition, scientists generally do not consider industry to be a competent collaborator in carrying out joint research, except for a few cases in biomedical studies. The different norms between universities and industry, the lack of R&D capabilities in industry and relatively small-scale grants tend to discourage scientists from getting industry involved in the research process. In addition, the publication-based reward system does not provide much incentive for scientists to interact with industry.

5.5.2 Scientists' behaviour towards organising research aimed at being relevant

The interviews reveal scientists' different behavioural patterns in how they organise nanomaterials research. We find that, although they point to different research orientations, the nature of research is somewhat similar to one another. In addition, they are rather flexible in associating their research with applications. Our interpretation of the scientists' responses is that, firstly, nanomaterials research, as such, is generally conducted 'in the context of application' and there is no clear distinction between basic and applied research. A couple of scientists note that the ultimate goal of nanomaterials is for practical application. Whether the research is oriented towards being basic or applied depends on a scientist's intention and focus.

Another interpretation is that scientists may want to produce a self-image that is aligned with the external expectation of their research. The interviews show that a few were fairly reluctant to characterise their research as a certain *type* of research. Specifically, basic research was regarded as the absence of practical concern. As a result, the notion of basic research appears to create a certain tension for scientists to relate their research to it. In the interview context of this study, they are conscious about *presenting* their research to different 'outsiders.' The flexible features of science have enabled the interviewees to address their research in certain ways and justify their behaviour in other ways. To support this point, we summarise the 'relevance' scientists interpreted in terms of their research orientation and the major responses concerning the materialisation of their research in Table 5.5.

Table 5.5 Scientists' perceptions and research behaviours towards the socio-economic relevance of their research

Rationales for justifying their research behaviour	'Relevance' interpreted by the interviewees in terms of the research orientation	Responses to the ways of achieving the envisaged relevance of research
Linear view of research Basic research is prior to application	• I do pure science, but the research field is rather applied (Scientist 14) • Eventually it will be useful (Scientists 23 & 24) • Rigorous research is useful (Scientists 27 & 32)	• Application is built upon basic research (Scientist 14) • Application is not my own interest (Scientist 23) • If we only are concerned about application, who will do the prior work (Scientist 24) • Someone who is interested in application can use it later on (Scientists 28) • Physicists are often interested in the realisation of ideas (Scientists 27 & 32)
Distance from application Many problems other than scientific ones need to be solved or be considered, which are often beyond a scientist's work	• Engineering is application-oriented by nature (Scientists 2) • The research themes are around the industries in Taiwan - semiconductors, photonics and energies (Scientist 29) • Application also needs originality; my research consists of both basic and applied (Scientist 21)	• There are many problems concerning industrialisation, such as cost, prototype and mass production (Scientists 2 & 29) • 'Likelihood' of application, beyond which is the routine work (Scientist 21)
Division of labour Application-oriented public research institutes (specifically ITRI) are closer to industry	• I aim to provide new concepts to industry (Scientist 7) • FED is industrially applicable in TFT-LCD (Scientist 3) • Engineering is rather applied; the overall goal of my research is for application, under which basic research is triggered (Scientist 16)	• Industry in Taiwan tends to pursue specific and short-term returns, which are not the main interests of academics (Scientist 7) • It is weird to bypass ITRI and seek academics to be involved directly in application (Scientist 3) • I collaborate with ITRI because it is closer to industry (Scientist 16)

Interdisciplinary collaboration Interdisciplinary collaboration as a necessary way of realising application	• Biomedical research is product-oriented (Scientist 6) • A major function of nanomaterials is for application (Scientist 31) • The research direction is oriented towards application (Scientist 33)	• We need to get scientists from different disciplines involved (Scientist 6) • Only by doing interdisciplinary collaboration would I say that I do nano research (Scientist 31) • Interdisciplinarity is a necessary requirement for applications (Scientists 33 & 35)
Industry involvement Joint R&D	• The goal is to solve practical problems, yet, certain basic questions emerge during the research process (Scientists 13 & 17)	• We do not get industry involved too early until the research is well-rounded (Scientist 33) • Industry is a partner (Scientists 13 & 17)
Activities related to the diffusion of research results Knowledge provider (consultancy & formal projects), patents, technology transfers, spin-offs and informal interaction with industry through exhibitions and workshops	• I aim to investigate useful materials; this is applied rather than basic research (Scientist 35) • The research is basic-oriented but the overall goal is for application (Scientists 4, 12, 17 & 35) • Engineering is relatively more applied than physics and chemistry (Scientist 15) • The ultimate goal of materials is for application (Scientist 30)	• I focus on the patent portfolio and technology transfer by collaborating with ITRI because this field is rather competitive and timing for filing patents is crucial (Scientist 4) • We tend to file patents right after publishing the papers (Scientists 17 & 33) • I spend half of my time interacting with industry (Scientist 30) • I frequently interact with firms through workshops or informal communications (Scientists 15, 29 & 35)

Source: developed by the author.

Table 5.5 shows that scientists are rather flexible in associating their research with 'application' in regard to their research orientation (see the second column). They present the relevance of their research by referring to the positions of their scientific discipline (e.g. engineering), to a specific application field (e.g. FED) or to certain industries (e.g. semiconductors). On the other hand, a number of scientists implicitly refer to several features related to the traditional conception of basic research to justify their research behaviour (see the third column). For instance, basic-oriented scientists put forward a linear view and consider that they are doing upstream research, which will be of practical application in the future. Several application-oriented scientists point to the distance from application and division of labour as the challenges for realising the relevance of research. In addition, a couple of interviewees highlighted the importance of student training and scientific knowledge that often indirectly contributes to industry. These examples show that the research orientations addressed by scientists are partly real and partly ideological concerning research relevance; the ways that scientists present the relevance of their research may not necessarily reflect their actual research behaviour. This finding is in line with previous research, showing that the ambiguous notion of relevance creates incentive and tension for scientists to demonstrate their research (Scott, 2004). In addition, the conception of basic research and the traditional function of universities is still in existence to a large extent (Calvert, 2001), even though the scientists were rather reluctant to associate their research as basic oriented in the current research environment.

The flexible way of addressing research orientation implies that the goal of research is problematic because a piece of research work can be characterised as either basic or applied, depending on the circumstances that best fit scientists' needs. Nonetheless, our interviews reveal that scientists' intention behind the goal plays a crucial role in their decision to engage in the realisation of research. The evidence is

more obvious in the scientists' remarks concerning their interdisciplinary collaboration and industry involvement, where they express opposing attitudes towards the two research practices. Despite lacking institutional support and facing disciplinary barriers, they had a positive attitude and actively initiated interdisciplinary collaboration. On the contrary, only a few scientists have had industry involved as a partner in the research process. While there were different forms of collaboration and interaction with scientists and industry, we observed that an explicit goal for application distinguishes scientists' behaviours when organising relevant research. Their intentions are shaped by a number of factors, such as beliefs, interests, norms, experience and interaction with external groups. A fully fledged investigation of scientists' intentions is somewhat beyond the scope of this study. A theme emerged from the interviews is the concern of credibility, which reflects a scientist's career status, research experience and the resources needed for conducting research.

This study finds that senior scientists show that an explicit intention is involved in 'Mode 2' knowledge production. The interviews show that junior scientists tend to carry out basic research and disciplinary collaboration. Their research behaviour was strongly affected by the reward system, in which journal publications are the major criterion for assessing their academic performance.

Several factors shaped scientists' intention to engage in relevant research. The first concerns the path dependency of scientists' research agenda. A number of scientists expressed that their research orientation has shifted towards being more applied because of the accumulated knowledge in their fields. As one scientist noted, the fundamental knowledge in his prior work enabled him to further realise his research subject practically. The second factor concerns scientists' academic status. The large-scale funding available provides incentives for scientists to collaborate with top scientists in order to compete for the resources. The third factor concerns the underlying tension

between relevance and excellence. This study finds that most scientists conceive a dichotomous relationship between basic and applied research, and consider that the latter generally does not provide valuable inputs to scientific advancement. In addition, they reported that interaction with industry yields little benefit for their research. Only a few scientists have had industrial partners involved in the research process. The purpose for their collaborations with industry was more to realise their research ideas than seeking financial resources, so they remained in control of their research agenda. To conclude the factors that shape a scientist's intention, our study suggests that scientific credibility remains a major concern that influences scientists' intention to get other scientists or industrialists involved in the research process.

5.6 Conclusion

This chapter presented the perceptions and behaviours of scientists concerning the ways they organise research aimed at being relevant. This study shows that the socio-economic relevance of research is more to do with the institutional division of labour than with the nature of research. While the current institutional environment does not provide much support for scientists to engage in relevant research, several scientists did express a more explicit intention to realise the application of their research. From a resource-based perspective, scientists' behaviours are mainly shaped by their concern for scientific credibility and the resources provided by the institutional environments they perceived themselves to be in.

In addition, the interviews show that the publication-based reward system tends to directly influence their research behaviours. In general, they considered that interdisciplinary collaboration tends to produce high-impact publications, while collaboration with industry does not yield much benefit for their research performance. The next chapter sets out the perspective using bibliometric records.

Chapter 6

The Relationship between Nanomaterials Scientists' Research Behaviours and Their Publishing Activities

The objective of this chapter is to triangulate the main findings of the interview data and to establish the relationship between scientists' research behaviours and their publishing activities. We will show that the overall pattern is generally in line with the interview data. In addition, the research behaviour is different between junior and senior scientists.

We analyse a set of 331 nanomaterials scientists' publication outputs from their earliest records up to 2010. The chapter is organised in four sections. After describing the data source (Section 6.1), Section 6.2 presents the overall pattern in terms of research orientation, industry involvement and interdisciplinary collaboration.[29] The relationship between the above three forms of publication behaviour and scientific performance will be analysed. Section 6.3 breaks down the analysis to the level of individual scientists, investigating the publication behaviour among scientists with different years of research experience. Section 6.4 compares the interview and bibliometric analysis data. Section 6.5 presents an overall summary of this chapter.

6.1 The characteristics of the 331 nanomaterials scientists

Table 6.1 shows the distribution of scientists by professional rank. 81% are full professors, 14% associate professors and 5% assistant professors. The distribution may slightly underestimate young scientists' involvement in nanomaterials research since

---

[29] We use the term 'interdisciplinarity' in this chapter as a general concept covering different forms of collaboration across departmental disciplines.

they may produce fewer publications than senior scientists. [30] Nevertheless, the professional rank may not be a reliable indicator of scientists' seniority. As shown in Table 6.1, the distribution of PhD award year is rather dispersed and skewed in the full professor rank. In this study, we calculate years since PhD award to the year 2010 as an indicator of scientists' research experience. For example, in Table 6.1, the average PhD award year among the of assistant professor rank is 2003, meaning that their average research experience up to 2010 is seven years.

Table 6.1 Distribution of scientists by professional rank

Professional rank	Count	PhD award year				
		Minimum	Maximum	Mean	Median	Std. Dev.
Full Professor	267 (81%)	1964	2007	1989	1990	7.34
Associate Professor	46 (14%)	1988	2007	2000	2001	3.61
Assistant Professor	18 (5%)	1994	2006	2003	2005	3.76
Total Number	331 (100%)	1964	2007	1991	1992	8.34

Source: Computed by the author.

Table 6.2 shows the distribution of scientists by research experience and professional rank. We observe that scientists with more than 16 years of research experience unsurprisingly tend to predominate in the rank of full professor. 25.4% are scientists with 16 to 20 years of research experience and 21% with 21 to 25 years of research experience. This study did not collect information on scientists' ages since most of this information is unavailable online. The estimated age is calculated according to the year of their Bachelor Degree. The ages of scientists with 16 to 20 years of research experience ranges from 44 to 58 years old.

---

[30] A random search of 58 scientists who have produced fewer than five publications shows that 45% are full professors, 29% associate professors and 26% assistant professors.

Table 6.2 Distribution of scientists by research experience and professional rank

| | | Position | | | |
		Full Professor	Associate Professor	Assistant Professor	Total
< 11 years	Count	11	31	13	55
	% within Position	4%	67%	72%	17%
11-15 years	Count	42	13	4	59
	% within Position	16%	28%	22%	18%
16-20 years	Count	83	1	1	85
	% within Position	31%	2%	6%	26%
21-25 years	Count	67	1	0	68
	% within Position	25%	2%	0%	21%
> 25 years	Count	64	0	0	64
	% within Position	24%	0%	0%	19%
Total	Count	267	46	18	331
	% within Position	100%	100%	100%	100%

Source: Computed by the author.

Figure 6.1 presents the distribution of 331 scientists' departmental disciplines. 19% of the scientists are from Materials Engineering, followed by Chemical Engineering (18%), Chemistry (16%) and Physics (12%). The distribution of the disciplines is somewhat similar to that of the total funded projects in nanomaterials research (Figure 4.3, Chapter 4). This shows that our sample of 331 scientists is representative.
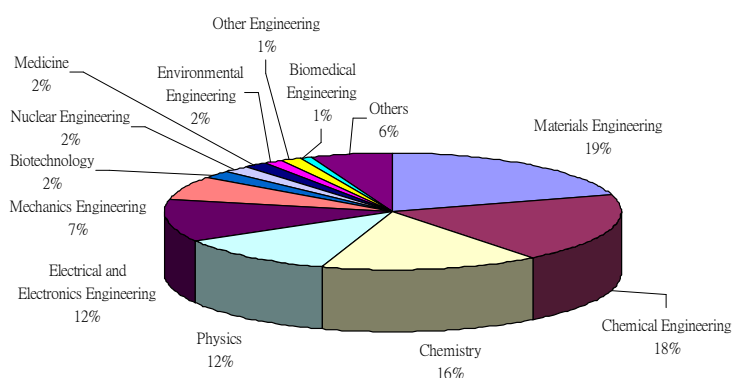
Figure 6.1 The distribution of scientists' departmental disciplines

Source: Computed by the author.

6.2 The overall pattern of research behaviour and scientific performance

This section investigates the overall pattern in the relationship between scientists' research behaviour presented in bibliometric terms and their scientific performance. The research behaviour in terms of research orientation, industry involvement and interdisciplinary collaboration is examined separately (Section 6.2.1 to section 6.2.3). Section 6.2.4 analyses the citation impacts of different types of collaboration.

6.2.1 Research Orientation

This study adopts the classification scheme of research levels (2010 version) obtained courtesy of the Patent Board, formerly CHI Research Inc., to analyse the trend of scientists' research orientation in terms of the published journals. In the research level scheme, Level 1 refers to journals more applied in nature and level 4 refers to those with the most basic-oriented nature.

Table 6.3 shows that 60% of the nanomaterials research published by academics are applied and targeted basic in nature. 17% of the papers were published in basic-research journals and 15% in engineering-science journals.

Table 6.3 Research orientation of nanomaterials papers, 1987-2010

	Number of papers	(%)
Level 1 – applied technology	68	1%
Level 2 – engineering science	908	15%
Level 3 – applied and targeted basic	3722	60%
Level 4 – basic research	1055	17%
Unclassified	419	7%
Total	6172	100%

Source: Computed by the author.

Figure 6.2 presents the major journal profile of nanomaterials research in Taiwan, showing that journal distribution is rather diverse. A total of 6,172 nanomaterials papers were published in 571 journals. *Applied Physics Letters* accounts for 7.1% of the total papers, followed by *Nanotechnology* (4.6%) and *Journal of Applied Physics* (2.9%). Among the top 15 largest shares of published journals, twelve are applied and targeted basic journals, two are basic-research journals (*Physical Review B* and *Journal of Materials Chemistry*) and one is an engineering journal (*Materials Chemistry and Physics*). Compared with a previous study on nanotechnology journal distribution on a global scale (Kostoff, 2007), our result reveals a general characteristic of nano-related research rather than a particular feature in Taiwan.
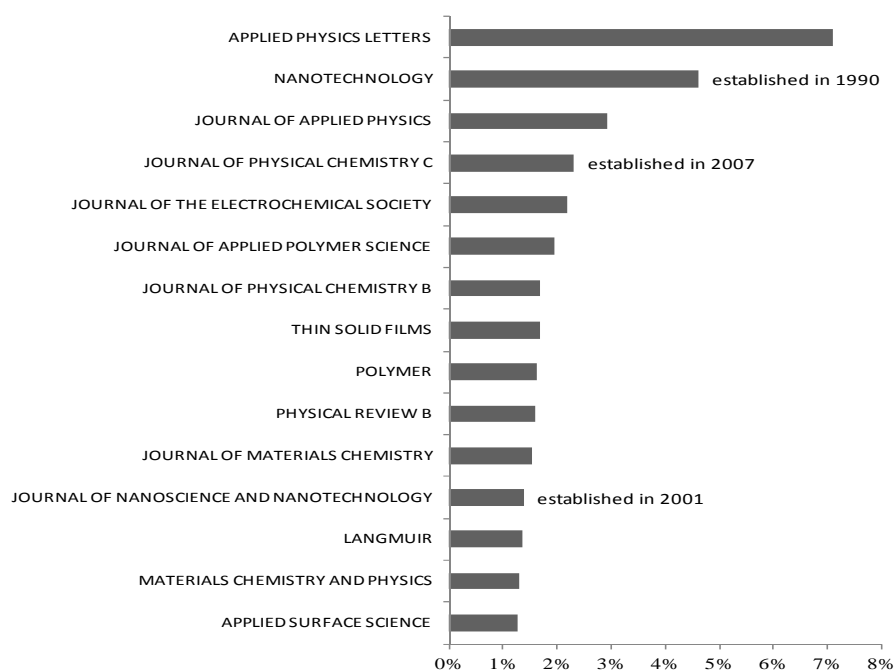
Figure 6.2 Top 15 journals for the publication of nanomaterials papers

Source: Computed by the author.

The large proportion in applied and targeted basic journals reveals scientists' publishing strategies in accord with the emerging studies of nano-related subjects in

recent decades. A list of nano-titled journals is provided in Appendix Table 6.1. Figure 6.2 shows that several newly established journals have been the major targeted journals in recent years, such as *Nanotechnology* (established in 1990), *Journal of Physical Chemistry C* (established in 2007) and *Journal of Nanoscience and Nanotechnology* (established in 2001). For example, *Journal of Physical Chemistry C* was established in 2007 and ranked fourth in terms of publication volume. The use of these emerging journals as a major target for publishing nano-related research implies that, as nano-related research has attracted significant attention from both governments and scientific communities in the past decade, scientists have shifted their publication strategy towards particular journals in order to establish their credibility and enhance visibility in the field. According to our interviews, several scientists indicated that these new journals tend to have high impact scores, thereby creating an incentive for them to publish articles in these journals (see section 5.4.1.2, Chapter 5).

Figure 6.3 further supports the above point. The share of applied and targeted basic journals (Level 3) has slightly increased since 2000. It is worth noting that the share of scholarly papers published in basic-research journals (Level 4) has declined since 2002, while that for engineering-science journals (Level 2) has increased and outperformed basic-research journals since 2008. This trend suggests that nanomaterials research has gradually shifted its focus from basic to the engineering field, although applied and targeted basic journals remain as the largest share. We investigated papers published in 2009 and 2010, finding two engineering-science journals (Level 2) listed in the top 15 journals. The papers published in the two journals, *Biomaterials* and *Sensors and Actuators B - Chemical*, might be related to the investigation of nanomaterials in biomedical research.
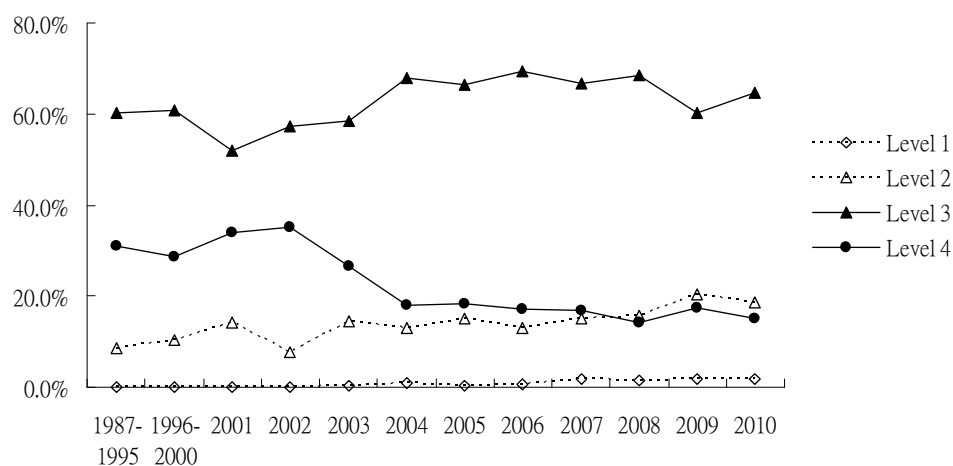
Figure 6.3 Overall research orientation trend, 1987-2010

Source: Computed by the author.

We further investigate the trend across fields and find a similar result. The journal distribution pattern is somewhat similar across fields (Table 6.4), showing that applied and targeted basic journals (Level-3) account for the largest proportion. In addition, biomedical research tends to have an equal share among different research orientations. The result shows that the boundary between basic and applied research in nanomaterials studies is not always clear cut in a field, especially in biomedical research.

Table 6.4 Research orientation by journal field

Journal Field	Level 1	Level 2	Level 3	Level 4	N/A	Total	No. of papers
Chemistry		4%	**71%**	22%	2%	100%	2276
Physics		6%	**73%**	21%		100%	1688
Engineering & Tech	2%	38%	**51%**	8%	1%	100%	1492
Biomedical Research		**38%**	29%	34%		100%	226
Earth & Space	30%	**67%**		3%		100%	69
Clinical Medicine	7%	11%	**82%**			100%	45
Biology		25%	**50%**	25%		100%	16
Mathematics		100%				100%	2
Social Sciences	100%					100%	2

Source: Computed by the author.

Note: The journal fields are based on the classification scheme developed by the Patent Board.

The declining share of basic-oriented journal papers can be observed in the fields of Chemistry, Physics and Engineering & Technology, which account for 92% of total nanomaterials papers in Taiwan. Table 6.5 shows that the proportion of papers published in basic-research journals (Level 4) in these three fields has decreased, especially during the previous decade.

Table 6.5 Journal distribution of research level by fields, 1987-2010

Field	Year	Level 1	#	Level 2	#	Level 3	#	Level 4	#	N/A	Total
Chemistry	1987-2000			1%	1	61%	49	38%	30		80
	2001-2005		0	5%	25	71%	386	24%	132	1	545
	2006-2010		0	4%	69	72%	1186	21%	346	47	1651
Physics	1987-2000			1%	2	69%	94	30%	41		137
	2001-2005			2%	11	69%	308	29%	129		448
	2006-2010		2	8%	91	75%	829	16%	180	1	1103
Engineering & Tech	1987-2000			46%	24	44%	23	10%	5		52
	2001-2005	1%	4	43%	125	44%	127	12%	35		291
	2006-2010	3%	32	36%	418	53%	610	7%	75	14	1149
Biomedical Research	1987-2000					17%	1	83%	5		6
	2001-2005			40%	14	31%	11	29%	10		35
	2006-2010			38%	71	29%	53	33%	61		185

Source: Computed by the author.

To summarise, this section shows that nanomaterials research tends to be published in applied and targeted basic journals, with the proportion slightly increasing since 2000. This trend might be influenced by newly established journals focusing particularly on nano-related topics. In addition, nanomaterials research has been slightly more oriented from basic towards engineering since 2008.

6.2.2 Industry Involvement

Figure 6.4 presents the different forms of organisational co-authored papers over time. It shows that the proportions of the papers co-authored with industry, with other organisations and with other countries have remained relatively stable since 2000. The

changes in collaborative patterns mainly occur between universities. In total, single-university papers have the largest share among all nanomaterials papers, although the share has decreased over time. Since 2003, inter-university papers have become the second largest type of collaboration, with the share increasing since then. Moreover, it shows that, for nanomaterials research in Taiwan, collaboration between universities has become more frequent in recent years. This trend might be strongly related to several large-scale policy initiatives encouraging collaborative research among universities, as addressed in Chapter 4. Specifically, the launch of the Nano Programme in 2003 appears to have played a crucial role in this phenomenon.

Our analysis does not support the Triple Helix hypothesis (Etzkowitz & Leydesdorff, 2000; Etzkowitz et al., 2000), which suggests that the relationship between university, industry and government is becoming more interactive. At least in the form of formal communication presented in the scholarly publications of nanomaterials research, there have been certain collaborations between university and other external actors since the late 1980s. Nevertheless, such collaborative relationships have not intensified. The bibliometric data confirms the interview results, showing that institutional actors do not seem to co-evolve towards a more interactive relationship.
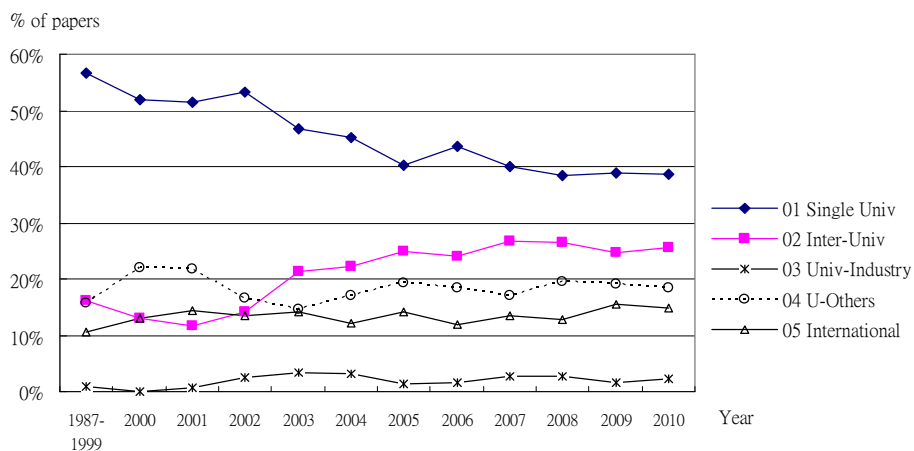
Figure 6.4 Share of papers in terms of organisational collaboration, 1987-2010

Source: Computed by the author.

In total, 62 firms have been involved in university-industry papers, producing 134 papers during 1987-2010. Table 6.6 lists the top 20 firms, which account for 72% of total U-I papers. It shows that the major industrial collaborators are from the electronic and semiconductor sectors, in which Taiwan is specialised. In addition, these firms have relative strength in R&D resources. Therefore, they might be more willing to explore the applications of new technologies and seek knowledge inputs from universities.

Table 6.6 Top 20 firms involved in university-industry papers

Firm	Industrial sector & product	No. of papers
Advanced Semiconductor Engineering	Semiconductor	25
Taiwan Semiconductor Manufacturing Co.	Semiconductor	11
ProMos Technologies Inc	DRAM	8
United Microelectronics Corporation	Semiconductor	5
Tatung Company	Computer hardware, electronics	4
Teco Nanotech Co. Ltd	Carbon Nano Tube Field Emission Display	4
Kinik Co	Semiconductor materials, opto-electronics	7
Walsin Technology Corporation	Electronic components	4
AGI Corp	Chemicals	4
Taiwan Power Co	Electronic power	3
Nanmat Technology Co., Ltd	Semiconductor deposition materials	3
Chunghwa Picture Tubes Ltd	Optoelectronic display components	3
Yeu Ming Tai Chemical Industrial Co.	Static sealing materials	3
Huga Optotech Inc	LED semiconductor devices	2
China National Petroleum Corporation	Oil and gas	2
Epistar Corp	LED	2
Genesis Photonic Inc	LED	2
China Steel Corp	Steel	2
Chang Chun Plastic Co Ltd	Chemicals	1
Nanya Technology Corporation	DRAM	1
	Total Number of papers	**96**

Source: Computed by the author.

We further compare the journal distribution of different research orientations across the types of collaboration, finding that nanomaterials papers with more diverse

organisations involved tend to be published in more basic-oriented journals. In addition, university-industry papers tend to be more applied than other types of collaboration. Table 6.7 indicates that, except for university-industry papers, the proportion of basic-research papers increases along with the type of collaboration. This pattern at the journal field level shows a similar result. Our analysis suggests that collaboration with heterogeneous actors helps intellectual stimulation and helps gain a comprehensive understanding of the research subject.

Table 6.7 Research orientation by type of collaboration

Type of collaboration * Research Orientation Crosstabulation

		Research Orientation			
		Engineering S&T	Applied and targeted basic	Basic research	Total
Single U	Count	413	1616	359	2388
	% within Type of collaboration	17.3%	67.7%	15.0%	100.0%
Inter U	Count	232	872	256	1360
	% within Type of collaboration	17.1%	64.1%	18.8%	100.0%
U-I	Count	28	91	5	124
	% within Type of collaboration	22.6%	73.4%	4.0%	100.0%
U-Others	Count	184	687	216	1087
	% within Type of collaboration	16.9%	63.2%	19.9%	100.0%
International	Count	119	456	219	794
	% within Type of collaboration	15.0%	57.4%	27.6%	100.0%
Total	Count	976	3722	1055	5753
	% within Type of collaboration	17.0%	64.7%	18.3%	100.0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	82.560[a]	8	.000
Likelihood Ratio	84.955	8	.000
Linear-by-Linear Association	28.601	1	.000
N of Valid Cases	5753		

a. 0 cells (.0%) have expected count less than 5. The minimum expected count is 21.04.

Source: Computed by the author.

Note: Due to fewer papers in Level-1 journals, we combine Level-1 and Level-2 papers into the Engineering S&T category.

As shown in Figure 6.3, while applied and targeted basic research accounts for the largest proportion of papers, nanomaterials research has been oriented from basic towards engineering since 2008. We examine the trend across different types of collaboration, finding that this shift in focus seems to occur during collaborations by a single university and other research institutes in Taiwan. Figure 6.5 shows that the number of engineering S&T papers in single-university and university-other collaborations outperformed that of basic-research papers in 2006 and 2008 respectively. According to our interviews, some scientists indicated that they interact with ITRI to facilitate the application of research as it is closer to industry. The figures suggest that university scientists have tended to carry out more applied research in recent years.
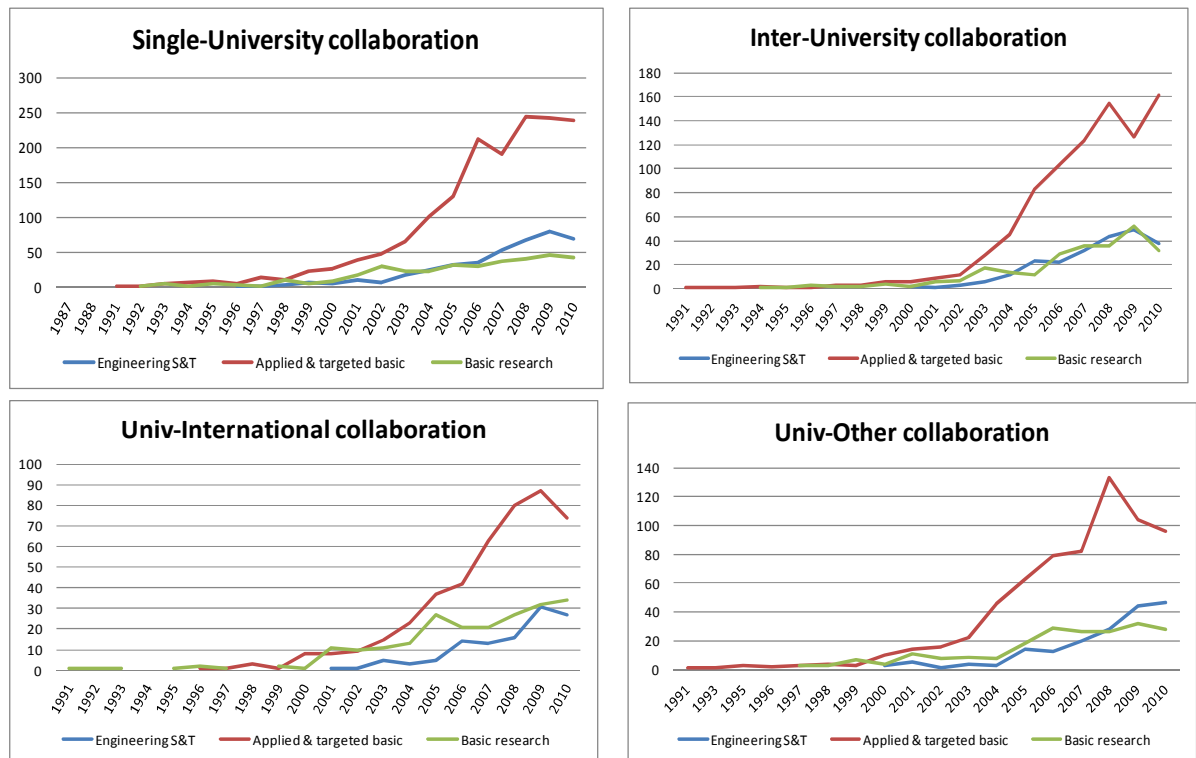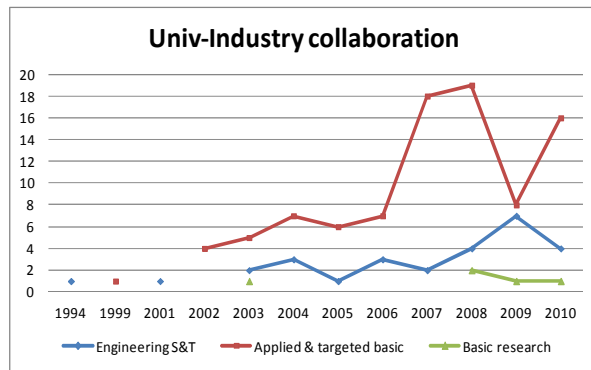
Figure 6.5 Research orientation trends across different collaborations, 1987-2010

Source: Computed by the author.

Note: The unit on the vertical axis is the absolute number of papers.

This section shows that industry involvement as a form presented in co-authored papers only accounts for a small proportion in the knowledge production of university research. The major change of the interaction tends to occur between universities. The next section will present the analysis of interdisciplinary collaboration.

6.2.3 Interdisciplinary collaboration

This study finds that collaboration across departmental disciplines has increased since 2002, even though single-discipline papers account for the largest share over time. Figure 6.6 presents the trend in the number of disciplines involved in each paper. Over the years, the percentage of single-discipline papers has decreased from 78% (up to the year of 1999) to 52% in 2010, while that of two-discipline based papers has increased from 20% to 32%. Although the share of papers involved in more than three disciplines has also increased since around 2004, the proportion remains rather low. In 2010, for example, only 15% of the papers have involved more than three disciplines. This result suggests that nanomaterials research has tended to extend beyond the boundary of a single departmental discipline over time, even though the number of disciplines involved in a collaboration remains rather low. This result accords with our interviews,

suggesting that what scientists perceive as an 'interdisciplinary collaboration' tends to be a regular research collaboration. In addition, not many papers are 'multidisciplinary' collaborative (in which at least three disciplines or more are involved) in nature.
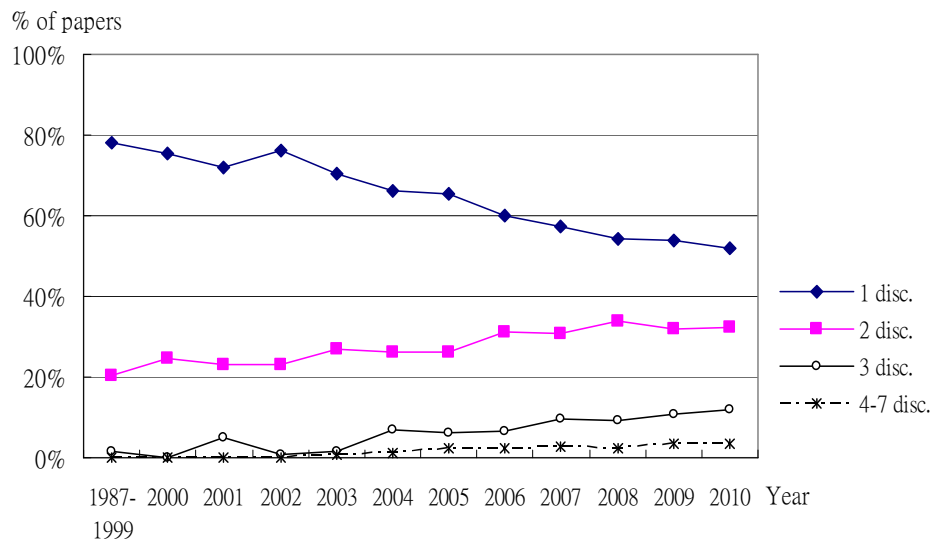
Figure 6.6 Share of disciplines involved in one paper, 1987-2010

Source: Computed by the author.

Table 6.8 presents the distribution of disciplines in different types of organisational collaboration, showing that interdisciplinary collaboration tends to occur between universities rather than within a single university. As we may expect, the more organisational actors involved in a paper, the more interdisciplinary the paper is. While 14.6% of the single-university papers involve two disciplines, the percentage for inter-university papers is 51.5%. In addition, a majority of the single-university papers (82.8%) only involve one discipline. This result suggests that scientists who organise their research teams within a department tend to have little collaboration or interaction with other departments within their university. If scientists seek collaboration with other disciplines, they tend to interact more commonly with researchers from other universities.

Table 6.8 Degrees of disciplines involved according to collaboration type

coll * No_Discipline Crosstabulation

% within coll

		No_Discipline				Total
		1	2	3	4~7	
coll	01 Single Univ	82.8%	14.6%	2.3%	.3%	100.0%
	02 Inter-Univ	31.1%	51.5%	13.5%	3.8%	100.0%
	03 Univ-Industry	63.6%	26.5%	8.3%	1.5%	100.0%
	04 U-Others	54.8%	31.3%	10.6%	3.3%	100.0%
	05 International	41.0%	39.3%	14.2%	5.5%	100.0%
Total		59.0%	30.2%	8.3%	2.4%	100.0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	1242.179[a]	12	.000
Likelihood Ratio	1318.835	12	.000
N of Valid Cases	6154		

a. 1 cells (5.0%) have expected count less than 5. The minimum expected count is 3.17.

Source: Computed by the author.

In our interviews, the scientists expressed that they tend to look for collaborators through their personal networks. Although some universities have organised workshops in order to encourage scientists to interact within a university, the effect appears limited. As addressed in section 5.4.1.3 in Chapter 5, one scientist indicated that there was not much interaction among university departments even in the same university (Scientist 33). This result challenges conventional wisdom concerning the role of co-location for a scientific collaboration (Acosta et al., 2011; Jaffe, 1989; Katz, 1994). This aspect will be discussed in more detail in section 6.4.

Figure 6.7 compares the level of interdisciplinary collaboration involved in single and inter-university collaborations over time. The figure shows that in both types of collaboration the number of disciplines involved has increased over the past decades. It is worth noting that inter-university papers involving two or more disciplines have become the norm for research practice. Furthermore, an increasing number of inter-university papers have involved three disciplines over the decade. Overall, the analysis

suggests that interdisciplinary collaboration tends to go across the boundary between universities more than within the same university.
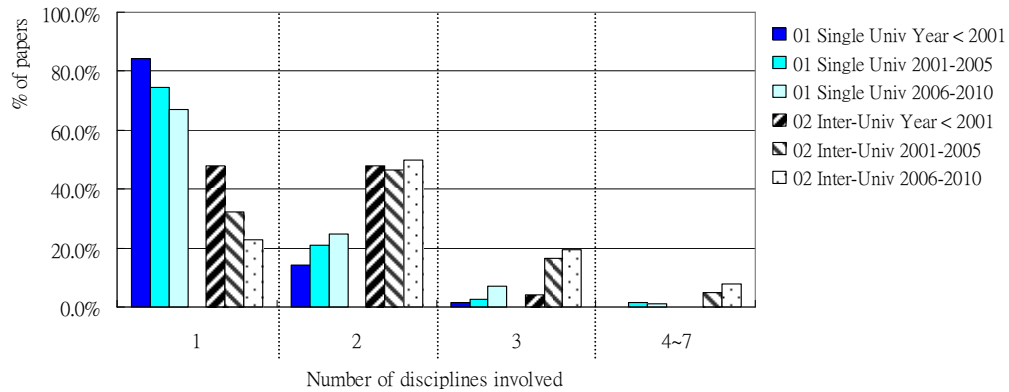
Figure 6.7 Comparison between single-university and inter-university collaboration in terms of the number of disciplines involved over time

Source: Computed by the author.

To summarise, the bibliometric analysis shows that interdisciplinary collaboration has increased since the last decade, even though single-university collaboration remains the major research practice. What is unexpected is that interdisciplinary collaboration tends to involve interaction across universities.

6.2.4 The relationship between research behaviour and scientific performance

According to the interviews, several scientists state that interdisciplinary collaboration tends to produce high impact scholarly publications. On the other hand, most of them considered that the involvement of industry does not yield much benefit for their research. This study uses both citations received by a paper and Journal Impact Factors from 2010 as partial performance indicators to measure citation impact. Table 6.9 presents the descriptive statistics of citation rates in each type of collaboration. A general observation is that university-industry papers have the lowest citation impact

and internationally co-authored papers have the highest. As the citation distribution tends to be highly skewed, we use a nonparametric method - the Kruskal-Wallis test, equivalent to a one-way ANOVA in parametric statistics - to examine the association between citation impact and the type of collaboration. If the difference is statistically significant at the 95% confidence interval, we further use the Mann-Whitney U Test to conduct a pair-wise comparison.

Table 6.9 Description of the citation rates by collaboration type

	Normalised citations					
	Count	Mean	Standard Deviation	Median	Minimum	Maximum
Single U	2568	1.14	1.63	.71	.00	35.39
Inter U	1484	.98	1.17	.65	.00	12.77
U-I	132	.74	.68	.62	.00	3.30
U-Others	1141	1.21	1.59	.77	.00	14.99
International	847	1.38	1.86	.83	.00	18.92
Total	6172	1.14	1.55	.72	.00	35.39

	2010 JIF					
	Count	Mean	Standard Deviation	Median	Minimum	Maximum
Single U	2568	3.11	1.90	2.77	.17	31.36
Inter U	1484	3.06	1.81	2.71	.19	12.73
U-I	132	2.38	1.20	2.07	.60	7.88
U-Others	1141	3.69	2.76	3.60	.19	30.31
International	847	3.69	2.78	3.49	.25	31.36
Total	6172	3.27	2.21	2.86	.17	31.36

Source: Computed by the author.

The statistical test in Table 6.10 shows that the citation impact for the various types of organisation are significantly different, while the result is mixed in the number of disciplines involved, where the association between normalised citations and number of disciplines involved is not significant (p=0.529). This suggests that citation impact is influenced more by the type of collaboration than the number of disciplines involved in a paper. We thus examine the citation differences among the different types of

collaboration by conducting a pair-wise comparison (see Table 6.11).

Table 6.10 Statistical tests of citation impacts by the type of collaboration and by number of disciplines involved

Ranks

	Type of collaboration	N	Mean Rank
Normalised citations	Single U	2412	2908.55
	Inter U	1383	2763.77
	U-I	124	2573.92
	U-Others	1094	2985.59
	International	803	3104.25
	Total	5816	
Normalised IF 2010	Single U	2399	2779.34
	Inter U	1375	2765.57
	U-I	122	2163.40
	U-Others	1090	3133.48
	International	794	3220.85
	Total	5780	

Test Statistics[a],[b]

	Normalised citations	Normalised IF 2010
Chi-square	28.501	95.756
df	4	4
Asymp. Sig.	.000	.000

a. Kruskal Wallis Test

b. Grouping Variable: Type of collaboration

Ranks

	No. of disciplines involved	N	Mean Rank
Normalised citations	1 disc.	3439	2913.97
	2 disc.	1750	2862.14
	more than 3 disc.	609	2925.12
	Total	5798	
Normalised IF 2010	1 disc.	3413	2845.14
	2 disc.	1741	2880.58
	more than 3 disc.	608	3088.23
	Total	5762	

Test Statistics[a],[b]

	Normalised citations	Normalised IF 2010
Chi-square	1.275	11.023
df	2	2
Asymp. Sig.	.529	.004

a. Kruskal Wallis Test

b. Grouping Variable: No. of disciplines involved

Source: Computed by the author.

The pair-wise comparison shows that, firstly, international co-authored papers generally receive more citations than other types of collaborative papers. This result is accords with previous studies (Bordons et al., 1996; Katz & Hicks, 1997; Sooryamoorthy, 2009). Secondly, the citation differences between single-university, inter-university and university with other institutions are not obvious, in that the statistical tests, in terms of citation rates and journal impact factors, present inconsistent results. While papers co-authored with other national institutes tend to have higher citation impact than single- and inter-university papers (see Table 6.9), the statistical test

is inconclusive. The analysis suggests that collaboration with other universities or institutes, at the very least, does not negatively affect the citation impact of the produced papers.

Table 6.11 Pair-wise comparison of citations in different types of collaboration

		Normalised citations	Normalised IF 2010
Single-U vs Inter-U	Z	-2.58	-0.23
	Sig.	0.01**	0.82
Single-U vs U-Other	Z	-1.26	-5.83
	Sig.	0.21	0.00***
Single-U vs International	Z	-2.89	-6.47
	Sig.	0.00***	0.00***
Inter-U vs U-I	Z	-1.17	-3.76
	Sig.	0.24	0.00***
Inter-U vs International	Z	-4.54	-6.11
	Sig.	0.00***	0.00***
Inter-U vs U-Other	Z	-3.25	-5.46
	Sig.	0.00***	0.00***
Single-U vs U-I	Z	-2.16	-4.13
	Sig.	0.03**	0.00**
U-I vs U-Others	Z	-2.63	-5.89
	Sig.	0.01**	0.00**
U-I vs International	Z	-3.30	-6.43
	Sig.	0.00***	0.00***
U-Others vs International	Z	-1.50	-1.14
	Sig.	0.13	0.25

Source: Computed by the author.
Note: ** $p < .05$; *** $p < .01$

Thirdly, the citation impact of university-industry papers supports our interview result, showing that university-industry papers tend to receive fewer citations than other types of papers. This finding contradicts the study by Hicks and Hamilton (1999). They presented that university-industry papers are more highly cited than single-university papers. In order to carry out a robustness check, we compare the citation rates of nanomaterials papers with those of all nano-related papers in Taiwan in terms of

different types of organisational collaboration. The result is similar, in that university-industry papers tend to receive the lowest citation rates (see Appendix Figure 6.1). In addition, the citation analysis across the three major journal fields presents the same conclusion (see Table 6.12). The reason might be related to the industrial features in different national contexts. As shown previously (see Table 6.6), the major industrial collaborators in nanomaterials research are from the electronic and semiconductor sectors. We will further discuss this finding in section 6.4.

Table 6.12 Citation impacts across fields

Type of collaboration	Chemistry		Engineering & Tech		Physics	
	C	IF	C	IF	C	IF
Single Univ	1.11	0.99	1.15	1.03	1.18	0.97
Inter-Univ	1.09	1.01	0.82	0.95	0.98	0.97
Univ-Industry	0.71	0.79	0.65	0.74	0.78	0.81
Univ-Others	1.08	1.11	1.22	1.28	1.24	1.16
International	1.32	1.17	1.59	1.47	1.32	1.08

Source: Computed by the author.
Note: C=Normalised citation; IF=Normalised journal impact factor

To conclude, the analysis of citation impacts broadly aligns with our interview result, showing that university-industry papers receive fewer citations. Moreover, while collaboration with other national organisational actors tends to receive higher citations, it is not statistically significant.

6.3 Research behaviour and scientific performance by seniority[31]

6.3.1 Research orientation by seniority

Table 6.13 presents the proportions of papers across different research orientations among senior and junior scientists. The statistical comparison of research orientation between each group shows that junior scientists tend to publish their papers in more applied journals than senior scientists do.[32] This pattern is consistent over the years analysed in this study (see Appendix Figure 6.2). This result contradicts an earlier observation that junior scientists tend to focus more on basic research (see Section 5.2). The different results between the interview and bibliometric data might be related to the notion of basic research put forward by junior scientists. This result will be discussed in section 6.4.

Table 6.13 Research orientation by seniority

Research experience * Research Level Crosstabulation

		Research Level				Total
		1	2	3	4	
<11 years	Count	13	123	452	91	679
	% within Research experience	1.9%	18.1%	66.6%	13.4%	100.0%
11-15 years	Count	7	150	686	167	1010
	% within Research experience	.7%	14.9%	67.9%	16.5%	100.0%
16-20 years	Count	15	244	938	333	1530
	% within Research experience	1.0%	15.9%	61.3%	21.8%	100.0%
21-25 years	Count	15	209	844	290	1358
	% within Research experience	1.1%	15.4%	62.2%	21.4%	100.0%
> 25 years	Count	4	210	1169	320	1703
	% within Research experience	.2%	12.3%	68.6%	18.8%	100.0%
Total	Count	54	936	4089	1201	6280
	% within Research experience	.9%	14.9%	65.1%	19.1%	100.0%

---

[31] We skipped the analysis of industry involvement by seniority due to the small number of university-industry papers.

[32] We use the Mann-Whitney U test to compare the groups with one another. The result shows that only the youngest scientists (with research experience of fewer than 11 years) are significantly different in terms of their research orientation.

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	65.963[a]	12	.000
Likelihood Ratio	68.110	12	.000
Linear-by-Linear Association	23.105	1	.000
N of Valid Cases	6280		

a. 0 cells (.0%) have expected count less than 5. The minimum expected count is 5.84.

Source: Computed by the author.

6.3.2 Interdisciplinary collaboration by seniority

The previous analysis of collaboration shows that a majority of single-university papers tend to only involve a single discipline, while inter-university papers tend to involve two disciplines (see section 6.2.3). This section further investigates this phenomenon in terms of scientists' seniority.

Table 6.14 presents scientists' profiles in terms of different types of collaboration in two time periods. The analysis reveals that scientists tend to carry out various forms of collaboration, showing that single-university papers involving one discipline account for the largest share (22% to 32% from 2006-2010), followed by inter-university papers involving two disciplines (13% to 15% from 2006-2010). These two collaboration categories also exhibit the greatest percentage change compared with the results for the 2001-2005 period.

The result suggests that 'Mode 1' and 'Mode 2' forms of knowledge are not clear cut. Disciplinary research remains the core activity for both junior and senior scientists. In addition, interaction of two disciplines between universities is the major form of interdisciplinary collaboration.

Table 6.14 Distribution of collaborative papers by research experience

Research experience	Year / # of discipline collaboration	2001-2005				2006-2010			
		one	two	more than three	Total # of papers	one	two	more than three	Total # of papers
<15 years	Single Univ	34%	6%	1%	318	32%	6%	2%	1541
	Inter-Univ	11%	13%	6%		9%	14%	5%	
	Univ-Industry	1%	1%	0%		1%	1%	0%	
	U-Others	9%	4%	1%		6%	7%	4%	
	International	7%	5%	1%		5%	4%	3%	
16-20 years	Single Univ	40%	7%	2%	376	32%	7%	2%	1197
	Inter-Univ	6%	9%	3%		5%	15%	8%	
	Univ-Industry	2%	0%	0%		1%	0%	0%	
	U-Others	10%	5%	3%		7%	5%	4%	
	International	8%	5%	1%		5%	5%	4%	
21-25 years	Single Univ	33%	7%	0%	387	22%	7%	2%	986
	Inter-Univ	8%	10%	4%		6%	14%	5%	
	Univ-Industry	1%	0%	0%		1%	0%	0%	
	U-Others	17%	7%	1%		11%	9%	5%	
	International	7%	5%	3%		6%	7%	4%	
>25 years	Single Univ	34%	5%	1%	461	25%	9%	1%	1148
	Inter-Univ	10%	11%	2%		10%	13%	5%	
	Univ-Industry	2%	1%	0%		2%	1%	0%	
	U-Others	14%	6%	1%		10%	7%	3%	
	International	6%	6%	1%		5%	5%	4%	

Source: Computed by the author.

We further compare the patterns of collaboration between single-university and inter-university collaborative papers among junior and senior scientists. Figure 6.8 shows that, in both types of collaboration, the proportion of papers for the junior scientist group (those with fewer than 16 years of research experience) has not changed much between the two time periods. On the other hand, the proportion of inter-university papers involving two or more disciplines among senior scientists have increased over the same time period. In the 2006-2010 time period, mid-career scientists (with 16-20 years of research experience) have become more active than other groups of scientists in carrying out interdisciplinary collaboration.
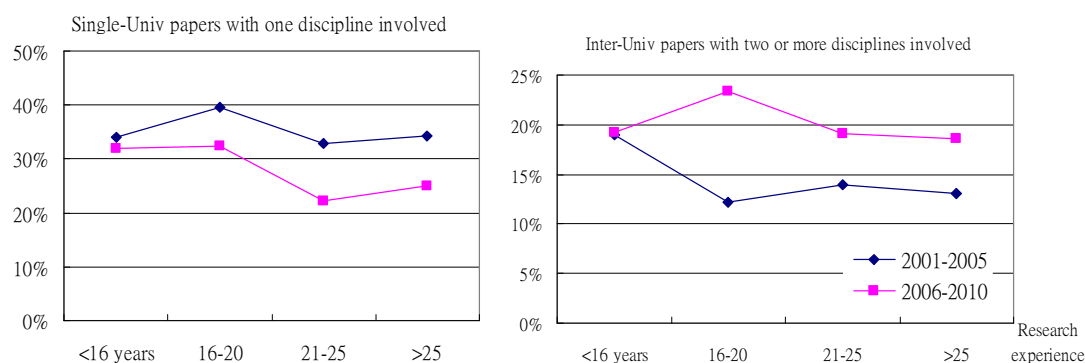
Figure 6.8 Shares of single-university and inter-university papers by seniority
Source: Computed by the author.

The result confirms our interview finding, suggesting that senior scientists tend to carry out interdisciplinary collaboration. As addressed in section 5.4.1.3 (Chapter 5), seniority partly reflects a scientist's status, reputation and capability to carry out interdisciplinary work, as well as being related to the intellectual and material resources that scientists have to accumulate in order to conduct interdisciplinary collaboration. Several young scientists stated that they mainly carry out disciplinary research because of their limited research experience and the lack of facilities. The interviews suggest that scientists tend to establish their research credibility and secure an academic position, thereby affording them the capacity to involve, or to be involved by, scientists from other different disciplines in their research.

6.3.3 The relationship between collaboration and scientific performance by seniority

Table 6.15 shows the citation rates and impact factors that scientists received across the range of research experience. The statistical test suggests that there is a significant difference in citation impact among scientists with different research experience ($p < 0.01$, by Kruskal-Wallis test). In general, junior scientists with less than 11 years of research experience tend to receive lower average citation rates than other

scientists (p < 0.05). Moreover, scientists with 16 to 20 years of research experience seem to have a slightly higher average citation record than others. This analysis suggests that senior scientists generally tend to perform better than junior ones in scientific publications.

Table 6.15 Descriptive statistics of citation impact by seniority

		Normalised citations					
		Count	Mean	Standard Deviation	Median	Minimum	Maximum
Research experience	<11 years	755	.98	1.33	.54	.00	14.51
	11-15 years	1111	1.08	1.58	.65	.00	20.19
	16-20 years	1640	1.23	1.81	.80	.00	35.39
	21-25 years	1451	1.08	1.39	.67	.00	14.99
	> 25 years	1769	1.16	1.50	.73	.00	14.91
		Normalised IF 2010					
		Count	Mean	Standard Deviation	Median	Minimum	Maximum
Research experience	<11 years	755	.92	.75	.80	.00	10.27
	11-15 years	1111	1.00	.76	.91	.00	6.14
	16-20 years	1640	1.07	.74	1.02	.00	9.71
	21-25 years	1451	1.05	.76	.97	.00	11.80
	> 25 years	1769	1.08	.73	1.00	.00	6.47

Source: Computed by the author.

Figure 6.9 shows that the citation patterns for interdisciplinary collaboration between single-university and inter-university papers across different seniorities are not particularly obvious. For single-university papers, scientists, except for the most senior ones, tend to perform better when one discipline is involved. On the contrary, scientists in inter-university collaborations tend to perform better when two disciplines are involved. This suggests that interdisciplinary collaboration tends to perform better when interaction is between universities than within just a single university.

In addition, mid-career scientists (with 16-20 years of experience) tend to outperform other groups of scientists. One possible reason for this result is that mid-career scientists might be willing to risk time out of their disciplinary work to explore

new research directions or to incorporate different concepts from other disciplines into their research work, thereby getting a more complete picture of the research topic. This phenomenon might be more feasible in emerging fields, such as nano-related research, where scientists are more actively competing for novel ideas in order to obtain large-scale government funding and gain recognition in the field.
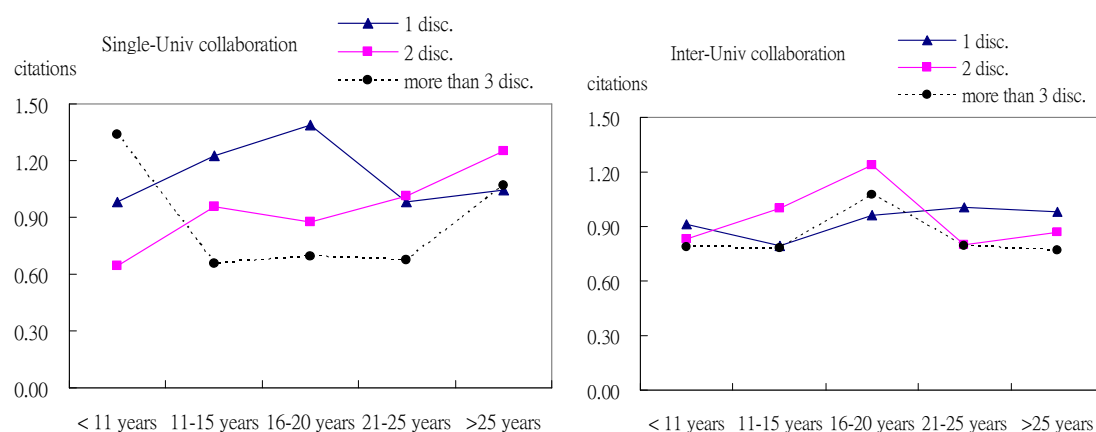
Figure 6.9 Average citation impact of single-university and inter-university papers with different disciplines involved by seniority
Source: Computed by the author.

6.4 Interview and bibliometric data comparison

This section compares the interview evidence and bibliometric results. While several results from the bibliometric analysis confirm the findings of the interview data (see Table 6.16) and extend our understanding of scientists' research behaviour, we should interpret the results with some caution. For example, although several statistical tests in the bibliometric results reveal a significant difference, the level of difference is rather small and may not be very meaningful. In addition, several possible interpretations of the bibliometric data addressed in this study need to be supported by evidence from further investigations.

Table 6.16 Comparison of qualitative and bibliometric results

Dimensions	Qualitative evidence	Bibliometric evidence
Overall trend	Nanomaterials research is oriented towards application or a mix of basic and applied considerations	*Confirmed*. Papers published in applied and targeted basic journals have increased since 2001 and towards engineering science in 2008
	• Industry involvement in the research process is not a major concern for nanomaterials scientists • Interaction with industry does not yield many valuable inputs to research and is less creative	*Confirmed* • The proportion of university-industry papers has been rather stable over time • U-I papers are more applied and receive a lower citation impact than other types of co-authored papers
	• Nanotechnology funding has encouraged interdisciplinary collaboration • Interdisciplinary collaboration tends to facilitate applications [Note: it is not possible to test this in the bibliometric analysis] • Interdisciplinary collaboration helps pursue scientific excellence and be published in high impact journals	*Partially confirmed* • More disciplines have been involved in each paper since 2003, but collaboration within a single discipline still accounts for the largest share; co-authorship between two disciplines seems to be the norm and it tends to occur more in inter-university papers • The more heterogeneous organisations involved in a paper, the more basic-oriented it is, and the more citations it receives. Nonetheless, the citation scores are not statistically significant
Differences in seniority	• Junior scientists tend to do basic-oriented research while senior scientists tend to take application into account in their research • Senior scientists tend to shift their research from basic to applied, although some senior scientists remain persistent in accordance with their research trajectories	*Contradicted* • Senior scientists tend to publish in more basic-oriented journals than junior ones, and receive higher citation rates
	• Junior scientists tend to do disciplinary research • Senior scientists tend to have the necessary cumulative advantage to engage in interdisciplinary collaboration	*Broadly confirmed* • Mid-career scientists are more actively involved in inter-university collaboration • Senior scientists (with research experience of over 16 years) tend to increase their level of inter-university collaboration over time

Source: developed by the author.

Research orientation comparison

The interview and bibliometric results both show the overall trend of nanomaterials research towards application or a mix of basic and applied considerations. This trend reflects scientists' publishing strategies being influenced by newly established nano-titled journals.

In terms of the comparison by seniority, the bibliometric analysis shows an opposing result to the interview data. In our interviews, junior scientists tended to carry out basic-oriented research, while their senior counterparts tended to take applications into consideration. The bibliometric analysis shows an opposing result, in the sense that publications produced by senior scientists tend to be more basic-oriented than those by their junior counterparts. One explanation is related to the definition of basic research suggested by scientists. As shown in section 5.2, what junior scientists mean by basic research tends to refer to scholarly publishable results. Nevertheless, scientists will not necessarily publish in highly influential journals in their early careers. The journals classified by the Patent Board as applied-oriented are based on the assumption that applied journals tend to cite more basic-research journals. Therefore, basic-research journals are often more highly cited.

Although junior scientists perceive their research as basic-oriented, they may publish their research in lower-rank journals in their early careers, due to their lack of cumulative knowledge in the subject area. Particularly under the current reward system emphasising publication records, junior scientists feel more pressure to produce papers in the short term. As a couple of scientists argued, the publication-based performance indicator exerts a certain influence on scientists' behaviour to produce more papers that often does not push back the frontiers of knowledge (section 5.2.3). Our analysis suggests that it more significantly affects junior scientists' research behaviour.

Industry involvement comparison

Both the interview and bibliometric data show that industry involvement in the research process is not a major concern for scientists. Our interviews indicate that scientists interact with industry by providing their existing knowledge. They usually regard interaction with industry as not being of much help to their publication performance. In addition, they are fairly reluctant to have industry involved in their research process. Scientists often perceive that industry lacks adequate capabilities and incentives to be involved in joint research if the research is remote from application. The bibliometric analysis reveals that university-industry papers tend to be published in more applied journals and receive lower citation rates. Furthermore, the proportion of university-industry papers has remained stable over time. It is worth noting that university-industry papers are better considered as the result of formal communication between university and industry. A number of interviewees have interacted with industry through informal communications, which cannot necessarily be detected in their publication records.

The bibliometric result challenges previous literature, which argues that industrially co-authored papers tend to have higher citation impact (Hicks & Hamilton, 1999), or at the very least, have equal citation impact with strictly university papers (Godin & Gingras, 2000). One main reason for the different results concern the industrial features in different national contexts. It is reasonable to suspect that university-industry collaboration in the US tends to occur in biological and medical sciences, where university research is relatively strong and is a major source of knowledge for developing 'new-science' based technologies (Pavitt, 2001).

In the case of Taiwan, the major industrial collaborators are from the electronic and semiconductor sectors (see Table 6.6), which have specialised in original equipment manufacturing (OEM) activities and tend to focus on process innovation and

technological improvements. Although universities have long focused on engineering and produced a large number of postgraduates to meet industrial needs, industries tend to acquire technology from more advanced countries, such as Japan and the US (Nelson, 1993). University research is rarely a direct source of knowledge for industrial development. According to our interviews, those scientists who have been involved in collaborative projects with industry often provided their existing knowledge to help solve technical problems rather than developing frontier technologies (see section 5.3.1, Chapter 5). As one scientist argued, industrial actors might just need 'a helping hand' (Scientist 15). This kind of research is relevant but not necessarily excellent. Our analysis suggests that university-industry papers are mainly based on the application of scientists' existing knowledge. Scientists are thus not very motivated to interact with industry.

We should note that a few university-industry papers have been published in basic-research journals since 2008 (see Figure 6.5). Since university-industry papers have only just started to emerge over the past decade, it is worth investigating whether this phenomenon can be generalised to the entire research system in Taiwan.

Interdisciplinary collaboration comparison

Results from the bibliometric analysis of interdisciplinary collaboration are generally aligned with our interview data and provide more detailed information about the publication behaviour of scientists. Firstly, although the proportion of single-discipline papers has declined over time, disciplinary papers still account for the largest proportion among all nanomaterials papers. The results show that there has been a shift in the balance between disciplinary and interdisciplinary collaborations since 2003. This may be related to the initiation of the Nano Programme, which encourages scientists to form interdisciplinary research teams. Secondly, while there are many scientists from

different disciplines involved in nanomaterials research, two-discipline co-authored papers appear to be the norm in collaborations. Thirdly, collaboration with different disciplines tends to occur *between* universities rather than *within* the same university.

The third finding challenges conventional wisdom regarding the benefits of co-location or geographical proximity to scientific collaboration (e.g. Acosta et al., 2011; Katz, 1994). Existing literature suggests that scientists tend to collaborate with actors who are more geographically co-located than distant from each other. It emphasises face-to-face communication in the exchange of tacit knowledge as an important factor for successful collaboration. Nonetheless, another study argues that there are different forms of proximity that contribute to interactive learning (Boschma, 2005). Boschma argues that geographical proximity may play a complementary role, rather than a prerequisite, to strengthen social, organisational, cognitive and institutional proximity.

Our study suggests that co-location plays a minor role in forming collaboration between different universities. One possible reason concerns the nature of research. A few scientists stated that their research was experiment-based, in which case a common research facility serves as the platform for interaction between scientists. The collaboration thus tends to occur within the same university. The bibliometric analysis shows that collaborations with other universities and other kinds of organisation tend to be more basic-oriented than those within the same university (see Table 6.7). The interview and bibliometric data imply that collaborations with actors outside the same university tend to focus more on theoretical or conceptual aspects of the research subject than on the applied end of nanomaterials research.

In addition, social proximity reduces the concern of geographical distance. Boschma (2005) defines social proximity as the socially embedded relations of a scientist, relations that involve trust on the basis of friendship or experience. Our interviews show that scientists tend to form their collaboration through personal

networks or with scientists they have long interacted with. Moreover, a few scientists expressed that travelling is rather convenient at bringing people together.

In terms of seniority, our study confirms what emerged from the interview data, showing that junior scientists generally produce papers with a lower citation impact and are less engaged in interdisciplinary collaboration than their senior counterparts. The comparison of different groups of scientists show that mid-career scientists with 16 to 20 years of research experience are more active in forming interdisciplinary collaboration and tend to have higher citation impact than other scientists.

6.5 Summary

This chapter expanded the sample size to 331 nanomaterials scientists and analysed their research behaviour in terms of research orientation, industry involvement and interdisciplinary collaboration reflected in bibliometric records. We examined the overall pattern and compared scientists with different levels of seniority. The results broadly accord with our interview data. In addition, the bibliometric analysis reveals several findings that extend our understanding of scientists' behaviours in terms of their publishing activities. Firstly, disciplinary research remains the core research practice among different groups of scientists. Secondly, two-discipline collaboration has emerged as the norm in interdisciplinary work and tends to occur when universities interact. Thirdly, the more heterogeneous the organisation involved in a paper, the more basic-oriented the paper is. Except for university-industry papers, collaborations with other types of organisations do not negatively affect their citation impact.

Chapter 7

Synthesis and Conclusions

7.1 Overview

This final chapter aims to answer the research questions put forward in Chapter 1 by synthesising the findings from the previous two empirical chapters. The discussion is structured by following the conceptual framework developed by this study (Chapter 2). Related evidence from the analysis of the policy context in Taiwan (Chapter 4) will be integrated into the discussion. We then draw the main conclusion of this thesis. After that, we address the contributions, policy implications and study limitations.

To recapitulate the topic, this thesis deals with the social organisation of science in the context of growing policy endeavours to ensure that scientific research is relevant to socio-economic needs. More specifically, this thesis looks at nanomaterials research contributed by university scientists in Taiwan, investigating the relationship between scientists' perceptions, research behaviours and publishing activities. Given the demanding requirements for relevance in policy practices and concerns with their negative effects on scientific development, this study aims to obtain a better understanding about scientists' research behaviours when dealing with the notion of relevance.

To achieve this aim, we initially reviewed the notion of relevance put forward by policy analysts and sociologists, and further examined the underlying assumptions (Chapter 2). The literature suggested that the term 'relevance' is very much related to resource allocation and acquisition. Policy practices that aim to achieve socio-economic relevance tend to focus on the research process. We then identified three major ways to analyse the knowledge production process - in terms of research orientation, industry involvement and interdisciplinary collaboration - with regard to the ways that

knowledge is usually organised to achieve the goals of socio-economic relevance. The analysis showed that the above three ways of ensuring relevance are not so straightforward at the level of individual scientists, although the claim of a changing science system has been rather influential in science-policy studies.

We then developed a conceptual framework and introduced a resource-based perspective to investigate how scientists deal with policy requirements for relevance. The empirical work took place among the university scientists conducting nanomaterials research in Taiwan. The main evidence was based on interviews and extensive bibliometric analysis. The details of the methodology are provided in Chapter 3. Chapter 4 set out the policy context and institutional backgrounds of nanotechnology research in Taiwan. The analysis of the changing rationales for university funding in Taiwan suggests that academic scientists have encountered pressure to achieve both scientific excellence and economic relevance with their research since the late 1990s. The emergence of nanomaterials research in Taiwan's current policy context provided us with a suitable site of investigation for this study.

Chapters 5 and 6 respectively presented the empirical results from the interview data and bibliometric analysis. Chapter 5 investigated nanomaterials scientists' perceptions and their research behaviours in terms of research orientation, industry involvement and interdisciplinary collaboration. We found that, firstly, scientists are rather flexible at positioning their research orientation, regardless of the nature of research. There was no consistency in how scientists understand the notions of basic and applied research. Secondly, industry involvement in the research process is not a conventional practice in Taiwan's universities. While a few scientists have just started to be involved with industrial partners in the research process, the main motivation for scientists has been to realise their research ideas. Thirdly, we found that scientists implicitly embrace different conceptions of interdisciplinary collaboration, although

they tend to use the term 'interdisciplinarity' uncritically. Two patterns of collaboration emerged from the interviews. One concerned regular research collaboration in a disciplinary nature; the other had scientists with different disciplinary backgrounds involved in the entire research process and is more interactive. In general, the scientists perceived that interdisciplinary collaboration is a necessary condition for realising applications and that the research results tend to be published in high impact journals. Throughout this chapter, we also showed that seniority and publication-based reward systems have played major roles in affecting scientists' perceptions and behaviours when organising relevant research.

Chapter 6 investigated the relationship between scientists' research behaviour and their scientific performance by analysing publication outputs. We examined the overall pattern and compared scientists with different levels of seniority. The analysis found that, overall, nanomaterials research is oriented towards applied and targeted basic research, and involves more interdisciplinary collaboration. Moreover, the proportion of university-industry papers has been rather stable over time. The results of the bibliometric analysis broadly accord with our interview findings. Nevertheless, the analysis and scientists' research experiences present a rather complex result.

The following discusses the main findings from the previous chapters and answers the research questions posed in the thesis (section 7.2). It then addresses the overall conclusion (section 7.3), the contributions (section 7.4), policy implications (section 7.5) and the generalisation of the results of this study and directions for future research (section 7.6).

7.2 Synthesis of the key findings

7.2.1 The ambiguous notion of relevance and its dichotomous assumption

It is unsurprising that scientists denoted the socio-economic relevance of nanomaterials research straightforwardly as 'application' to industry. What is interesting is how scientists interpreted 'application' and associated their research with it in various ways, even though they may not actually engage in achieving the envisaged application of their research (see Table 5.5 in Chapter 5). On the one hand, our study shows that a number of scientists referred to their disciplines as applied in nature, under which they investigate new phenomena in their research subject at the nanoscale. Medical and engineering fields seem to benefit in the current research environment. However, basic-oriented scientists also argued that their research field has an applied dimension. One scientist explained that a feasible application is conducting research rigorously (Scientist 32). On the other hand, most scientists perceived a linear division of labour and expressed the view that research involves applications or that industry does not provide valuable input to their research. Our study reveals that scientists perceive a dichotomy between basic and applied research, even though this classical distinction has been criticised by a number of policy analysts (see section 2.2.1).

The discrepancy between scientists' perceptions of relevance and their actual research behaviour can be explained by boundary work theory (Gieryn, 1983, see section 2.4.2). As Gieryn (1983) puts it, public scientists construct a boundary between knowledge production and its consumption by external actors in order to pursue two professional goals: autonomy and public support. In our study, scientists tended to produce a self-image to gain public support by flexibly associating their research with application. On the other hand, some scientists justified their research behaviour of not being involved in realising application by referring to a number of features related to the notion of basic research. This study suggests that the underlying concern behind the

goal of protecting professional autonomy is to secure scientific credibility[33] (Latour & Woolgar, 1979). In particular, the publication-based reward system in the current research environment further reinforces scientists' behaviour of pursuing scholarly performance, rather than making their research relevant. A number of scientists report that research involving applications tends to be less publishable or less creative. What these remarks of scientists reveal is that scientific credibility remains their core interest in the institution of science.

Three implications for the intellectual debate on the nature of university research and for policy practices need to be highlighted. First, although previous studies propose alternative terms that incorporate considerations of both fundamental understandings and potential applications into research (European Commission, 2005; Gibbons et al., 1994; Irvine & Martin, 1984; Rip, 1997; Stokes, 1997), the applied dimension of scientific research is open to various interpretations by different groups. Our study shows that the gap between basic research and its applications remain a source of tension to most scientists. Inevitably, scientists tend to make their research fit policy requirements to secure funding, whilst making sure their research agenda is less affected.

Second, this finding challenges the assumption that research addressing socio-economic considerations will help ensure the likelihood of solving practical problems. This assumption is based on the premise that scientists are the people who best know the practical problems and will fulfil the promise. We have shown that scientists tend to articulate 'application' in a way that is meaningful to them, even though their research behaviours may not necessarily be guided by the envisaged application. This gives rise to a question about whether it is necessary to ask scientists to identify potential applications beforehand. Nelson (2004) argues that the path to practical application is

---

[33] Latour and Woolgar (1979) defined credibility as scientists' ability to actually do science (see section 2.4.)

generally unpredictable and that resource allocation for science should not be guided by potential application perceptions. His main point concerns the dissemination of research results, suggesting that scientific results should be open to a wider range of users. In contrast, Rip (1997) proposes a promise-requirement cycle, suggesting that promises, once made by scientists, create credibility pressure that enables scientists to fulfil the promise. However, in the process of reviewing grant proposals, it is almost impossible for reviewers to accurately identify scientists' intentions. Our study shows that, while the stated research goal is a vital element to demonstrate what is expected to be achieved, scientists have a measure of freedom to articulate that goal in order to meet the external requirements.

In the light of the above concern, the third implication of the finding is that policy makers, scientists and stakeholders may work together to reframe the notion of 'relevance' in a broader sense, rather than solely focusing on the *ultimate* goal of commercialising research. As addressed in Chapter 4, the economic logic of publicly funded research has always been dominant in science and technology policy in Taiwan. The current policy rationale for funding university research assumes that the socio-economic value of university research is mainly fulfilled through the application of research in industry. Our interviews reveal that the notion of relevance, interpreted as the ultimate goal of practical applications, tends to overlook the variety of benefits that might be yielded by the knowledge production process. As Table 5.5 in Chapter 5 shows, while scientists interpret 'relevance' as application in terms of the goal, they point out several 'channels' for realising relevance, which can be compared with the analytical framework for the economic benefits of basic research (Martin & Tang, 2007; Salter & Martin, 2001; Scott et al., 2001).

The most frequent channel for achieving relevance that the scientists highlight concerns the training of graduates. This is particularly important in carrying out

interdisciplinary collaborations. As the disciplinary structure tends to be highly specialised, participation in interdisciplinary projects is the major way that students can gain knowledge beyond their disciplinary training and interact with their peers from different educational backgrounds during their early careers. The second channel is the various informal linkages through which scientists interact with industry. Although most scientists expressed the view that they would not get industry involved in their research process, several scientists have had interactions with industry through consultancy, exhibitions and meetings. They considered that such interactions enable them to make more sense of industry and that this indirectly benefits their research ideas, despite being less well rewarded. The third channel for realising relevance is the commercialisation of knowledge through engaging in patenting and technology transfer activities. A few scientists highlighted the importance of patenting in the application fields. Moreover, filed patents attract industry interest to interact with scientists. Lastly, just one interviewee had established a spin-off company. The above channels show that the realisation of 'relevance' tends to occur in various ways. Furthermore, tacit knowledge embedded in scientists and students plays a major role.

If we map the three ways of organising relevant research with the exploitation channels, and although difficult to quantify, our study suggests that there is no evident relationship between a scientist's research orientation and the possible exploitation channels. For instance, two basic-oriented junior scientists have provided knowledge and expertise to industrial actors through consultancy and formal projects (section 5.3.1). In contrast, application-oriented scientists may not have any interaction with industry. It is worth noting that interdisciplinary collaboration and joint R&D with industry help stimulate new forms of interaction among scientists and industry. Several scientists referred to the launch of the Nano Programme in triggering the collaborative culture.

The argument derived from the finding is that organising 'relevance' in the research process is often interpreted ideologically, in a way that the ambiguity of the term relevance enables scientists to manipulate the notion for their own interests at different circumstances. In addition, the interpretation of relevance as the ultimate commercialisation of research hinders effective policy discussions concerning the socio-economic values and benefits of science. As indicated previously, commercialising research is just one of the various exploitation channels for achieving relevance. Especially in a scientific-technical field, such as nanotechnology research, policy discourses tend to focus on the high expectation of industrial applications, thereby providing a misleading image of a direct relationship between science and practical applications. As a result, they create tension in regard to demonstrating relevance, which appears to be an unproductive narrative. As Pavitt (1991, p.117) suggests, "the objectives of many policies seeking to make basic research more useful may turn out to have been badly misconceived." According to the interviews, we have demonstrated that there are alternative ways of addressing 'relevance' that occur in the research process. Our study suggests that the conceptualisation of the relationship between the ways of organising relevant research and the exploitation of the research results could serve as a point of departure for addressing 'relevance' more effectively.

7.2.2 Research category as a context-dependent scheme

Our study finds that several scientists denote their research orientation in a relative way, although they characterise the goal of their research in a certain direction. Whether a piece of research work is basic or applied oriented is relative to what one compares it with, whom a scientist talks to and whose perspective, regardless of the nature of research. Such a response implies that, from a scientist's perspective, research categorisation is not really so meaningful. Our study did not investigate whether and

how scientists use the terms of basic and applied in their daily work. Nonetheless, their responses accord with a prior study by Calvert (2001), who suggests that scientists mainly use the term 'basic research' when there is an interaction with external groups. Our interviews further show that scientists flexibly characterise their research orientation according to the context of interaction. As one scientist stated, "materials science is application-oriented relative to physics and chemistry and is basic-oriented relative to mechanical and electrical engineering… From the perspective of the NSC, we are on the applied side" (Scientist 11).

The above scientist's remark implies that the distinction between basic and applied research depends more on the context of the interaction between different interest groups than on the nature of research. Scientists are aware of what external groups expect from them. If the interaction might affect their intellectual authority, resources or autonomy, such as when seeking research grants, they will adapt to the funding criterion. According to this line of thought, we expect that in the current trend of demanding science to be relevant, what is meant by the terms basic, strategic or applied research does not make a major difference. Scientists make use of any opportunity to gain external resources. As one scientist expressed, nanotechnology is a political term and he goes where the money is (Scientist 2). Other scientists shared a similar opinion that nanotechnology is a campaign slogan by the government. Once public resources are mobilised towards the next 'star industry,' such as energy, nanotechnology research will decline.

The point in need of clarification is that the political term is powerful but also can be vulnerable. In the current research context, the notion of relevance is powerful because it directly connects to funding decisions, especially when national budgets are constrained. On the other hand, it can be vulnerable if the institutional structure and culture do not reconfigure to support and sustain it. The investigation of nanomaterials

research in this study concern this and will be discussed in the following.

7.2.3 Mode-2 knowledge production at the interplay of the institutional division of labour

The third finding is that the institutional boundaries between university, industry and research institutes are not co-evolving or converging to produce 'Mode 2' knowledge in nanomaterials research. Even the division of labour among disciplines is still compartmentalised. Our study shows that some researchers do organise research in a more interactive and 'interdisciplinary' way, as defined by prior studies (Klein, 1996; Porter & Rossini, 1984). We did not, however, observe the emergence of transdisciplinarity that transcends organisational and disciplinary structures (Gibbons et al., 1994). A few scientists have had got industry involved in their research process. Nevertheless, scientists still maintain their own research agenda. In addition, the organisational division of labour and cultural boundaries remain clear. In a broader sense, our interviews show that Mode-2 knowledge production takes place in a Mode-1 research environment and tends to involve the interplay of the institutional division of labour.

Our study suggests that Mode-2 knowledge appears to be an extension of the current Mode-1 knowledge production, rather than a replacement or an entire transformation of science. Firstly, scientists' research orientation tends to be path-dependent. Several interviewees expressed the view that their research focus has shifted and become more applied due to prior knowledge of the fundamental aspects. Moreover, the lack of R&D capabilities in industry and the different cultures between university and industry are major obstacles to getting industry involved in the research process. Interaction with industry still lies in knowledge transfer activities, activities that most scientists consider a public service of academia rather than a major mission. Lastly,

interdisciplinary collaboration often takes place when a scientist's academic status is more established in their disciplinary community. Scientists who have been involved in interdisciplinary collaboration indicate that it is "a step further out of their disciplines." They still maintain their own disciplinary identity. This evidence highlights that scientists are guided by the traditional norms of academia to a large extent, even though several scientists have actively participated in realising relevant research.

The above finding also suggests that a profound normative change in science asserted by the proponents of entrepreneurial university (Etzkowitz, 1989; Etzkowitz et al., 2008) does not seem empirically grounded. As addressed in the literature review (Chapter 2), the innovation system, triple helix model, entrepreneurial university and Mode-2 thesis tend to focus on the macro-level interaction between different institutional actors, while overlooking the diversity amongst disciplines in universities. The triple helix model (Etzkowitz & Leydesdorff, 2000; Etzkowitz et al., 2000) suggests that the university, in taking on the mission of economic development, goes through an internal transformation. In this model, research universities are undergoing a profound transition to entrepreneurial universities and reshape university-industry relationships by the capitalisation of knowledge (Etzkowitz, 1998). Our analysis of the changing rationale for university funding in Taiwan (Chapter 4) indicates that university funding has been closely linked to economic development over time. In the last decade, the government did establish several regulations and intermediary organisations concerning the commercialisation of university research. These new mechanisms helped facilitate knowledge transfer activities, but did not exert a major influence on scientists' behaviour when conducting research. The provision of human capital through education and research remains the major mission of the university. Even when scientists have industrial partners involved in their research process, the major motivation for scientists is to fulfil their research ideas rather than seeking external funds or making profits.

194

Scientists remain in control of their research agenda.

In addition, the Mode-2 thesis and triple helix model assert that a new form of interface is being created to stimulate interaction between different actors. However, our study finds that the interactive relationship with other academics and industry tends to be organised informally and is often project-based. The reason might be that the demand for a more interactive collaboration among heterogeneous actors remains rather weak. Part of the reason is also related to the absorptive capacity of industry. The triple helix model assumes that industry has the capability to monitor and negotiate during the process of interaction (Etzkowitz et al., 2000). As discussed earlier, scientists tend to perceive a lack of R&D capabilities in industry.

Based on the above discussions, our study argues that research practices aiming to be relevant are fragmented and not fully institutionalised. While observing an emerging culture of interaction and collaboration, such activities are often unequally distributed. In particular, we find that interaction tends to occur among academics undertaking interdisciplinary collaborations. The bibliometric analysis supports this finding and will be addressed in the next section.

7.2.4 Interdisciplinary collaboration as a strategic device for relevance and excellence

Despite the inertia of institutional arrangements, our study finds that scientists have been rather active in forming interdisciplinary collaborations. Several scientists state that this is a way of organising research that substantially differs from what they did before. Our analysis also finds that scientists implicitly embrace different conceptions of interdisciplinary collaboration. A distinctive feature concerns the degree of interaction during the collaboration. This finding accords with several prior studies (Klein, 1990; Porter & Rossini, 1984), suggesting that interdisciplinary research should be defined as synthetic rather than additive. While existing literature discusses

interdisciplinarity from various aspects, such as the evolution of disciplines and specialities, and the cognitive content of interdisciplinary research (section 2.2.3, Chapter 2), we will relate our findings to the institutional aspects of collaboration in this section.

As Brewer's study (1999, p. 328) notes, "The world has problems, but universities have departments"; in other words, the disciplinary structure is considered one of the main obstacles to interdisciplinary collaboration. Our interviews did show that disciplinary structures hinder collaboration among different disciplines (see section 5.4.1.3). Nonetheless, our study suggests that interdisciplinary collaboration can serve as a strategic device to fulfil the demand for both scientific excellence and socio-economic relevance, which is supported by a number of findings.

Firstly, we find that interdisciplinary collaboration in nanomaterials research is a policy-driven phenomenon related to the global trend of public investment in nanotechnology research. While most of the interviewees have been involved in nano-related studies since their doctoral training, several scientists point to the role of the Nano Programme in stimulating interdisciplinary collaboration. As noted earlier, scientists' academic training and departmental structures are both highly disciplinary oriented, which hinders interaction among scientists. The norms and practices within a discipline still serve as an important source of identity to scientists. The funding scheme of the Programme helps break down disciplinary boundaries, thereby enabling scientists to form interdisciplinary teams in order to seek large-scale funds.

Secondly, interdisciplinary collaboration provides various benefits for scientists to serve their own purposes, thereby helping to cross the boundaries between disciplines. While previous studies present a number of reasons for forming a collaboration (e.g. Beaver, 1978; Katz & Martin, 1997), one distinctive reason in our study is that scientists perceive interdisciplinary collaboration as a necessary requirement to facilitate the

potential application of nanomaterials research (see Table 5.4 in Chapter 5). Moreover, interdisciplinary collaboration helps scientists gain a comprehensive understanding of the research subject and enhance the quality of their research. As noted in section 5.4.1, the reason why scientists engage in interdisciplinary collaboration is not only to facilitate application but also for intellectual and instrumental demands, such as publishing in top journals. The various benefits and resources of collaboration outweigh the disciplinary barriers, thereby creating different incentives for scientists to form collaborations for different purposes.

Thirdly, newly established journals in nano-related topics have helped scientists gain recognition and scientific credibility from interdisciplinary work. As journal publications have become the major criterion for the recruitment and promotion of scientists, the new nano-related journals with their high impact have been widely accepted as a source of recognition in interdisciplinary research since their launch. Our bibliometric analysis shows that several newly established journals have been the targeted journals for scientists in recent years (see Figure 6.2 in Chapter 6). This result demonstrates how interdisciplinary work can be built into the disciplinary structure and become the norm in the institution of science.

As noted by Morris and Rip (2006, p.257), "scientists often refer to 'science' as the main influence and driver of their professional lives." Their study shows that 'Science' is used as an abstract sponsor of research in the negotiation between scientists and the funding agency, thereby reducing the threat to scientific independence. Likewise, the notion of 'collaboration' has long been considered a conventional practice and is often perceived as a way to produce 'good research.' In our study, most scientists had a positive attitude towards collaboration, considering it a natural research practice. They internalised 'interdisciplinary collaboration' uncritically. However, our analysis reveals two distinctive forms, one of which tends to be a regular form of collaboration rather

than a interdisciplinary collaboration as suggested in the existing literature (Klein, 1990; Porter & Rossini, 1984). The present study shows that, like the term relevance, the ambiguous notion of interdisciplinarity can serve as a boundary concept, which creates a space for scientists to meet policy requirements as well as to fulfil their own purposes. In this line of thought, this study suggests that the Nano Programme has had a modest effect in terms of making research relevant by promoting interdisciplinary collaboration among scientists. Our bibliometric analysis supports this argument, showing that two-discipline collaborative papers emerged as the norm in interdisciplinary work (see Figure 6.7 in Chapter 6), although nanomaterials research tended to extend beyond the boundary of a single departmental discipline over time (see Figure 6.6 in Chapter 6).

Among the three research practices (research orientation, industry involvement and interdisciplinary collaboration), scientists shared their support for interdisciplinary collaboration. We argue that a well-articulated interdisciplinary vision can serve as a guiding framework for achieving relevant and excellent research, as well as helping shape a common perception of the research agenda between policy makers and scientists.

7.2.5 Scientists' behaviour in response to relevance: adaptation and persistence

Building on the above four main findings, this section presents the response to our first research question:

How do scientists perceive and organise research that aims to be relevant?

Given the ambiguous notion of relevance and the institutional environment perceived by the interviewees, our study finds that scientists' research behaviour in response to research orientation, industry involvement and interdisciplinary collaboration is partly adaptive and partly persistent. Although most of the scientists consider their nano-related research as being relevant to application and

interdisciplinary, the actual research behaviour was not entirely oriented towards achieving relevance. Moreover, seldom did industry play a role in their research activities.

In what follows, we discuss scientists' behavioural patterns and elaborate on why they behaved differently concerning the socio-economic relevance of their research from a resource-based perspective. Our study suggests that scientists' behaviours are mainly shaped by their concern for scientific credibility and the resources provided by the institutional environments they perceived themselves to be part of. As we addressed in Chapter 2, the resource-based perspective is based on the theories of boundary work (Gieryn, 1983), principal-agent relationship (Braun & Guston, 2003; Guston & Keniston, 1994) and credibility cycle (Latour & Woolgar, 1979). These theories deal with scientists' behaviours and their interactions with external groups when securing resources to conduct research. In section 7.2.1, we introduced boundary work theory to explain the inconsistency between scientists' perceptions of relevant research and their actual research behaviours. In addition, the credibility cycle model helped us understand the mechanisms for scientists to convert different resources into credits. Nevertheless, it would be wrong to suggest that scientists only manipulate the term relevance without taking any action to fulfil the promised relevance of their research. Some scientists expressed an explicit intention to make their research relevant to industrial needs and have been involved in different forms of knowledge-transfer activities.

To better understand scientists' research behaviours, this section provides an explanation of the behavioural patterns from a principal-agent perspective. Principal-agent theory deals with the design of incentive structures in a contractual relationship. In science policy, this theory tends to look at the problems of delegation from the government's point of view. One drawback is that it does not take into account scientists' actions and strategies (van der Meulen, 1998). This study provides empirical

evidence from a scientist's point of view. Specifically, we look at scientists' research behaviours in response to the incentive mechanisms and resources in the principal-agent interaction.

Behavioural patterns of scientists

Among the three ways of organising research, scientists tended to show their adaptation in terms of research orientation and interdisciplinary collaboration, while revealing a rather persistent view in regard to interacting with industry. Scientists' showed their adaptive behaviour in writing grant proposals by demonstrating the potential application of their research in order to seek research grants. Several scientists expressed reservations about this requirement, but tended to compromise. As one scientist noted, "we can write a grant proposal oriented towards application, but it is not necessarily meaningful" (Scientist 32). This behaviour implies that basic research (as in the pursuit of knowledge for its own sake) is less well positioned to seek funding and indeed appears under threat. Nonetheless, the adaptive behaviour may not extensively affect scientists' research agendas. A similar adaptive behaviour has also been observed in previous studies (Calvert, 2001; Leisyte, 2007; Morris, 2003; Morris & Rip, 2006).

Scientists also showed their adaptive behaviour by outlining how their research is of relevance in different ways. [34] In general, they flexibly depicted their research orientation, regardless of the nature of their research. On the other hand, they implicitly attribute value to some of the characteristics of basic research to justify their behaviour of not engaging in realising relevance (see Chapter 5, Table 5.5). They usually refer to a linear view of research, a distance from application and a division of labour, factors that are outside of scientists' control.

---

[34] They tend to point to an industry, a technological area, the disciplines they are affiliated to or the relative position of a discipline (see Chapter 5, Table 5.5).

The finding concerning the various ways that scientists address and justify their research behaviour accords with a previous study that suggests scientists retain an idealised view of basic research even in a changing research environment (Calvert, 2001). Nonetheless, in the context of my interviews, they generally play down the notion of basic research.

This adaptive behaviour was also observed when they addressed their interdisciplinary collaborations. This behaviour is mainly due to the high funding levels available for interdisciplinary projects in nanotechnology, as well as the scientists' uncritical acceptance of interdisciplinary collaboration. Most scientists had a positive attitude about forming interdisciplinary collaborations. Some stated that it has been a common research practice for them. Our analysis, however, shows that the ways in which scientists describe their interdisciplinary collaboration practices are rather ambiguous. Firstly, some forms of interdisciplinarity appear to be just regular collaborations based on the scientists' own disciplinary traditions. Secondly, the goal of application is not necessarily the main reason why scientists engage in interdisciplinary collaborations (see Chapter 5, Table 5.4). Nonetheless, the ambiguous notion of interdisciplinarity allows them to articulate their projects in order to meet policy requirements.

Scientists' adaptive behaviour reflects how they reduced the tension between policy requirements for relevance and their own interests by doing boundary work (Gieryn, 1983). As we addressed in section 7.2.1, the flexible features of science enabled the interviewees to gain public support, either symbolically or financially, while protecting their independence when conducting research.

We find a more persistent form of behaviour when scientists address the issue of interaction with industry. Our study finds that industry involvement in the research process is not a main concern to scientists conducting nanomaterials research. Although

44% of the scientists interviewed (15 out of 34 scientists) have interacted with industry to some extent, very few considered industry to be an important partner in their research process. A majority of the interactions with industry have been based on scientists' existing expertise and knowledge, with such interactions mainly considered as a service provided by universities. Only three scientists conducting biomedical research formed joint R&D projects with industry, with the research problems initiated by the academic scientists. This study suggests that scientists remain in control of their research agenda when interacting with industry.

Explaining the behaviour from a principal-agent perspective

As discussed in section 2.1.2, principal-agent theory focuses on the social relationship of two actors involved in the exchange of resources. In this study, the principal is mainly the National Science Council (NSC), the major government funding source of scientists' research projects (although private industry may also be included through co-funded projects); the agent is usually the scientist. Scientists' behaviour can be conceptualised in terms of mobilising financial, intellectual and symbolic resources.

Compared with private funding, government funding provides more financial resources. Despite the government having adopted market-style funding mechanisms from the year 2000 onwards, the level of private funding remains considerably lower than that of government funding (section 4.1.4). In addition, our interviews highlight that there is generally a lack of institutional support for engaging in interdisciplinary collaborations, except when a larger scale of financial resources is required than regular research projects (section 5.4.3). Symbolic and intellectual capital is accompanied by large research grants. Several interviewed scientists acknowledged that the Nano Programme not only provides large funding resources but has also served as a symbol of recognition, thereby attracting more talented researchers to become involved (section

5.4.3). Although scientists recognise the policy concern about the potential application of research, this concern is most evident when reviewing grant proposals. All these conditions show that government funding provides not only financial resources but also the symbolic and intellectual resources that have driven scientists, to some extent, to make their research appear to be more applied and to engage in interdisciplinary collaborations.

In contrast, there are relatively few incentives for scientists to interact with industry due to industry lacking the above resources. A number of scientists share a similar view that industry in Taiwan generally lacks sufficient knowledge about nanotechnology and that the level of R&D capabilities is rather low (section 5.3.2). Moreover, several scientists regard interaction with industry as a public service of academia, which is of little benefit to their publication performance. In other words, there appears to be a lack of incentive for scientists to exchange financial or intellectual resources with industry. While a few scientists have had industrial partners involved in their research processes, the main motivation is the realisation of their research ideas rather than making profits. Our study suggests that intellectual challenges remain a major motive for scientists to interact with industry.

However, we should note that the current reward scheme has placed far more emphasis on scientific excellence than on the industrial relevance of research, a mechanism that exerts a major influence on scientists' research behaviours. Our interviews show that the ways of organising research are somewhat different between junior and senior scientists. Furthermore, some scientists have been involved in activities for realising the application or relevance of research, despite the demand for publication performance. Our interviews suggest that the behavioural balance between adaptation and persistence depends on the extent of scientists' concern with academic credibility, which will be discussed in the next section.

7.2.6 The demand for relevance, autonomy or credibility

This section addresses the second research question:

What is the relationship between scientists' research behaviour and their publishing activities?

Throughout the interviews, we find that the publication-based reward system exerts a major influence on scientists' intention to be involved in relevant research, which in turn shapes the publishing behaviour of scientists. Our study suggests that the concern for credibility mainly affects scientists' intention to be involved in relevant research.

In general, scientists tend to perceive that research involved in application and in industry is less publishable or less creative. On the other hand, they consider that interdisciplinary collaboration helps them produce high quality articles. Moreover, inconsistency between the demand for relevance and the publication-based reward system creates more tensions for junior scientists. Since their academic career is more directly influenced by the reward system, they tend to focus on establishing scientific credibility in their research fields and are less motivated in interacting with scientists from other disciplines or actors outside the scientific community. As one junior scientist put it, he has shifted his research focus from the perspective of industry to more academic aspects for the purpose of academic promotion (Scientist 29). Senior scientists tend to follow their own research agenda and are rarely affected by the demand for relevance.

Evidence from the bibliometric data broadly confirms the main findings on scientists' research behaviours obtained from the interviews. Firstly, the bibliometric analysis shows that scientists tend to publish their research in applied and targeted basic journals, and engage in more interdisciplinary collaborations over time. In contrast, the share of university-industry co-authored papers has remained stable during the last two

decades. Secondly, the publication behaviour of junior scientists is different from their senior counterparts. While junior scientists consider their research to be basic oriented, they tend to publish in applied oriented journals. In addition, senior scientists (those with research experience of over 16 years) are the main actors who carry out interdisciplinary collaboration, particularly with scientists from other universities. These results support our argument that research experience tends to exert an influence on scientists' behaviour when organising relevant research and shapes their publishing activities.

The citation impacts of the three research practices also align with the interview findings, showing that the more disciplines and the more heterogeneous the organisations involved in a paper, the more basic-oriented it is, and the more citations a paper receives. The analysis suggests that interdisciplinary collaboration helps scientists achieve scientific excellence (in terms of citation impact). Even collaboration with applied-oriented research institutes does not come at the expense of scientific performance. On the other hand, university-industry papers tend to receive a lower citation impact than other types of collaborative papers.

The interview and bibliometric results reveal that scientists are concerned more about pursuing scholarly performance than making their research relevant. This finding challenges the conventional perspective of the principal-agent relationship between scientists and funding agency (Braun & Guston, 2003; Guston, 1996; van der Meulen, 1998), a theory suggesting that the policy problem concerning the relevance of research mainly lies in the balance between accountability and autonomy. Our study shows that the policy requirement for relevance tends to be ideological on the grounds that the notions related to relevance are rather ambiguous, thereby creating a space for scientists to associate their research with application in some ways and to conduct research in other ways. Although scientists perceive increasing pressure for relevance in the current

research environment, they can cope with the demand without much difficulty. The interviews imply that scientists are still in control of their research agenda to a large extent and scientific performance remains their core interest in the conduct of research.

In addition, scientists do sometimes restrict their autonomy for their own purposes, especially when establishing academic credibility. Involvement in interdisciplinary collaboration for realising relevance is an evident example. Although there are institutional barriers and obstacles concerning communication and coordination between different actors, scientists tend to perceive these barriers as a learning process. The ultimate benefits outweigh the costs. Several scientists indicate that being involved in interdisciplinary collaborations is a personal choice and that there is no pressure for scientists to do so. In addition, while scientists often criticise the publish-or-perish imperative, they tend to comply with it. As one scientist argued, the reward system based on SCI publications limited scientists' freedom to be involved in activities other than publishing academic articles (Scientist 30). Furthermore, a few interviewees have had industrial actors involved in their research process in order to realise their research ideas.

The above evidence suggests that scientists' autonomy is not an absolute concept. The values and interests attached to the notion are dependent on different scientists in a variety of circumstances. Our study suggests that the notion of autonomy in principal-agent theory applied to science policy needs to be refined in accordance with the changing research context.

7.3 Conclusion

This study has aimed to gain a better understanding of scientists' research behaviours when organising research aimed at being relevant. Our study shows that their behaviour is influenced by concern for credibility and the institutional environment

they perceive around them. While the funding environment places an emphasis on the potential applications of nanomaterials research, the institutional arrangements and the norms that govern scientists' behaviour have not co-evolved to align with the demand for relevance.

From a resource-based perspective, this thesis suggests that the demand for relevance is very much concerned with mobilising financial, intellectual and symbolic resources among the funding body, scientists and industry. Policy requirements for relevance mainly exert an influence on financial resources. The activities of realising relevance are in fact less well rewarded. The current reward system dominated by scholarly publication is a driving force for scientists to pursue intellectual recognition and rarely provides any incentive for fulfilling the socio-economic relevance of research. Therefore, scientists tend to partly adapt to external requirements in certain ways in order to receive financial resources but without jeopardising their research independence and academic credibility.

The behavioural balance between adaptation and persistence in organising nanomaterials research reflects scientists' concerns between academic excellence and the socio-economic relevance of their research subjects. While the ambiguous notion of relevance allows scientists to demonstrate their compliance with policy requirements, this study argues that the real pressure comes from the demand for scientific excellence.

7.4 Contribution to literature

Based on the above empirical findings, this thesis makes various contributions to existing knowledge. It contributes to existing knowledge in the changing science system by providing an alternative perspective from the point of view of individual scientists, an aspect that is usually overlooked in existing literature. Firstly, this study introduced a resource-based perspective to the notion of relevance and has conceptualised this notion

in terms of three major dimensions that tend to occur in the research process in order to better understand scientists' behaviours. The three dimensions of organising relevant research concern research orientation, industry involvement and interdisciplinary collaboration. Our analysis suggests that, rather than looking at university as a unified social organisation, we should consider the heterogeneity of scientific disciplines and treat each research practice separately.

This thesis contributes to a number of studies that have revealed a multiplicity of responses to the changing institutional environments at the level of individual scientists (Dzisah, 2006; Hessels, 2010; Owen-Smith & Powell, 2001). Dzisah (2006) found that scientists who received commercial research funding tend to have positive views about university-industry relations. Nevertheless, it is oversimplified to conclude that commercialising research is harming the core functions of the university. Owen-Smith and Powell (2001) investigated faculty responses to the commercialisation of life sciences, arguing that a dichotomy between scientist-entrepreneurs and ivory-tower traditionalists misses the interesting variation in scientists' behaviour. This thesis adds to our understanding of scientists' research behaviour by introducing a resource-based concept to the notion of relevance. We have shown that scientists' behaviour towards organising relevant research reflects their concern with securing financial, symbolic and intellectual resources in order to establish their academic credibility, and may not be entirely oriented towards the concern of relevance. The behavioural patterns of scientists can be better understood by introducing the concepts of adaptation and persistence. This thesis suggests that 'Mode 1' knowledge remains a core research practice to a large extent, even though research is partly oriented towards more applied and interdisciplinary orientations.

Furthermore, life-cycle effects highlighted in this study add to our understanding of scientists' research behaviours towards organising relevant research. We have shown

that a generation gap exists in scientists' approaches of organising research practices as well as in their publishing activities. A number of studies have investigated the relationship between publishing and entrepreneurial activities at the level of individual scientists (Azoulay et al., 2009; Blumenthal et al., 1996; Calderini et al., 2007; Crespi et al., 2011; Geuna & Nesta, 2006; Landry et al., 2006; Thursby et al., 2007; Van Looy et al., 2006; Van Looy et al., 2004), some of which pointed out that academic status is positively associated with research outputs (Crespi et al., 2011; Thursby et al., 2007). According to the distinction between relevance and impact defined in this thesis, previous studies often focus on the relationship between different research results produced by scientists. Our analysis complements the existing literature by showing that academic status, which partly reflects scientific credibility, also differentiates scientists' behaviours towards organising relevant research.

Related to the first contribution, this thesis contributes to the heated debate about the relationship between scientific excellence and socio-economic relevance. Our study shows that collaboration with applied research institutes tends to reinforce scientists' citation impact, while that with industry does not have this effect. The latter finding challenges conventional wisdom that university-industry collaborative papers are well cited (Godin & Gingras, 2000; Hicks & Hamilton, 1999). In terms of co-authored publications, we need to consider the effect of collaborators' research capabilities, the level of a scientist's academic credibility and the industrial features in different national contexts.

The effect of publication-based performance measuring the relationship between excellence and relevance needs to be underlined. Existing literature suggests that the demand for relevance, along with quantitative-based performance measures, may lead scientists to pursue short-term and applied research, as well as potentially undermine the long-term development of science (Geuna, 2001; Nelson, 2004). Our study shows that

performance indicators play a dominating role in terms of exerting a direct influence on scientists' behaviour. Although scientists perceived an increasing demand for relevance, the emphasis is still on scientific performance. The dominance of publication performance seems to have negative effects both on achieving excellence and relevance. While some scientists argue that publication performance pushes scientists away from making research relevant to socio-economic needs, others argue that it only makes scientists produce more papers that do not push forward the frontiers of knowledge. Both concerns reflect the fact that scientists feel more pressure to demonstrate their academic performance so that they fit in with the current reward system.

The third contribution concerns interdisciplinary collaboration in terms of methodology and the concept itself. Instead of looking at the cognitive aspect of research outputs, this study focuses on the social process of interaction among actors with different disciplinary institutions. Seldom have studies investigated this issue from this perspective, perhaps due to difficulties in the operationalisation of the term 'discipline.' Our methodology shows that the affiliated departments of scientists can serve as a satisfactory, although by no means perfect, indicator of their scientific discipline. This is subject to the degree of scientists' mobility and the change of their broader research trajectories being rather low, as in the case of Taiwan, China and Japan.

Our study supports previous studies that argue that 'interdisciplinary research' is more interactive and integrates knowledge from different disciplines (Klein, 1996; Rossini & Porter, 1979). Moreover, it suggests that disciplinary structure and geographical proximity may not necessarily be factors hindering interdisciplinary collaboration. We show that scientists tend to look for collaborators through their personal networks, with social proximity able to reduce physical distance concerns.

7.5 Policy implications

The empirical findings of this thesis raise two main policy implications for government and funding agencies to further discuss with regard to certain related issues in developing science policies. A first general implication is that, given the ambiguous notion of relevance, should policy makers consolidate the criteria for relevance? For example, should policy makers specifically identify the forms of interdisciplinary collaboration that they prefer to support? This study suggests that it is important for policy makers, stakeholders and scientists to 'unpack' the buzzword of relevance and reframe the notion into a more effective concept in order to shape the common vision of scientific development and help achieve the intended policy goal.

The empirical findings highlight that scientists remain persistent in some aspects of their behaviour to gain intellectual recognition. Nevertheless, their research agendas do not emerge from a social vacuum. A number of scientists state that the ultimate goal is to solve an industrial problem, for which they first have to make a scientific breakthrough in order to realise that objective. In short, their research agenda appears to be developed "in the context of application" (Gibbons et al., 1994) or in "Pasteur's Quadrant" (Stokes, 1997). Moreover, the demand for good scientific performance has constrained many junior scientists from becoming involved in realising relevance. In our empirical study, financial resources are the main incentive for scientists to become involved in interdisciplinary collaborations. However, there are a lack of other incentives and institutional support for scientists to realise the goal of application. This means that scientists tend to limit their activities in diffusing their research. This thesis suggests that policy practices for ensuring relevance would do better to focus more on providing pluralistic incentives rather than monitoring or managing how scientists *should* organise their research.

The second policy implication concerns the national context in newly industrialised countries, which often tend to follow the US model. In the case of Taiwan, we can see that its higher education system and the policy instruments emulate those from the US. There is generally a lack of policy debate on the substance of policy instruments due to the rather top-down approach to science-policy making. The literature review showed that the notions of basic research and interdisciplinarity are deeply rooted in the development of science in Western countries. Their meanings have also evolved and been re-interpreted at different stages. The conceptions of the above notions in Taiwan seem to ignore this historical perspective. The idea of basic research in Taiwan tends to follow the definition set by the OECD for statistical purposes. In addition, both scientists and policy makers seem to accept the notion of interdisciplinarity uncritically, even though our findings show that there are different forms of interdisciplinary collaboration.

Our suggestion here is that it would be helpful for policy makers and related stakeholders to discuss and perhaps reconceptualise certain taken-for-granted notions, such as the notions of socio-economic relevance and interdisciplinarity. We have shown that the notions of relevance and impact, despite having been used interchangeably in policy practices, are conceptually distinctive (see section 2.1.1). Our analysis also reveals that the major ways of organising research, in terms of research orientation, industry involvement and interdisciplinary collaboration, to ensure the socio-economic relevance of science are not so straightforward. This thesis provides an alternative perspective of the term 'relevance' from a scientist's point of view, which can serve as a starting point for the reconceptualisation of related notions. For example, we have shown how scientists distinguish the term 'interdisciplinarity' based on their collaborative research experiences (see Table 5.3) and the main reasons for such interdisciplinary collaborations (Table 5.4). In addition, we have identified two

distinctive patterns of interdisciplinary collaboration that emerged from our interviews, patterns that generally accord with the assertions in existing literature (e.g. Klein, 1990; Rossini & Porter, 1979, see section 5.4.2). The above analysis provides a set of analytical categories for policy makers and scientists to refine the discussions and debates about what is meant by 'relevance.' These debates will help enrich our understanding of current research practices, an essential first step towards formulating a common vision for the direction of research.

7.6 Generalisations and future research directions

This thesis is based on empirical evidence from one scientific domain (nanomaterials) in a specific national context (Taiwan). Apart from the methodological limitations addressed in Chapter 3, any attempt at generalising the findings should be subject to several criteria. The first criterion concerns the socio-political context, while the second concerns the scientific discipline. As shown in Chapters 2 and 4, the notion of relevance can refer to different aspects in different fields. In practice, this notion is embodied in a national context with its own socio-political development. For example, our study shows that industry involvement is not currently a major concern for nanomaterials science in Taiwan. This finding may therefore not be applicable in an area like pharmaceutical research, where scientists may exhibit a rather different pattern in their research behaviour.

In the light of above limitations, this study suggests that future research could investigate the applicability of the conceptual framework by focusing on researchers in applied-oriented public research institutes and by examining different scientific disciplines. Furthermore, this study only investigated scientists' publications in international journals, which are only one part of their research output. Incorporating other indicators such as patents, technology-transfer activities and major conference

proceedings into the framework could help enrich our understanding of the relationship between scientists' research behaviour and the diffusion of their research outputs.

7.7 Concluding remarks

In the contemporary policy agenda, how research can be best organised in order to ensure the socio-economic relevance of science is a central issue. This thesis tackles this problem by introducing a resource-based perspective concerning the notion of relevance as implemented in the knowledge production process. We have focused on scientists' research behaviour in dealing with the notion of relevance. To summarise the main points, scientists' research behaviour is partly adaptive in response to the external requirements for relevance but is persistent in certain other ways in order to enable scientists to retain their academic credibility. Given the ambiguous notion of relevance, the lack of incentives for realising practical applications and a reward system dominated by scientific publications, this study suggests that the real pressure on scientists is more to do with the demand for pursuing excellence than for relevance.

References

Acosta, M., Coronado, D., Ferrandiz, E., & Leon, M. D. (2011). Factors affecting inter-regional academic scientific collaboration within Europe: the role of economic distance. *Scientometrics, 87*, 63-74.

Arundel, A., & Geuna, A. (2004). Proximity and the use of public science by innovative European firms. *Economics of Innovation and New Technology, 13*, 559-580.

Azoulay, P., Ding, W., & Stuart, T. (2009). The impact of academic patenting on the rate, quality and direction of (public) research output. *Journal of Industrial Economics*, 57, 637-676.

Böhme, G., Van Den Daele, W., Hohlfeld, R., Krohn, W., & Schäfer, W. (1983). *Finalization in Science: The Social Orientation of Scientific Progress*. Dordrecht: Reidel.

Böhme, G., Van Den Daele, W., & Krohn, W. (1976). Finalization in science. *Social Science Information, 15*, 307-330.

Balsiger, P. W. (2004). Supradisciplinary research practices: history, objectives and rationale. *Futures, 36*, 407-421.

Beaver, D. D. (1978). Studies in scientific collaboration. *Scientometrics, 1*, 65-84.

Bercovitz, J., & Feldman, M. (2008). Academic entrepreneurs: organizational change at the individual level. *Organization Science, 19*, 69-89.

Blumenthal, D., Causino, N., Campbell, E., & Louis, K. S. (1996). Relationships between academic institutions and industry in the life sciences: an industry survey. *New England Journal of Medicine, 334*, 368-374.

Bordons, M., Gomez, I., Fernandez, M. T., Zulueta, M. A., & Mendez, A. (1996). Local, domestic and international scientific collaboration in biomedical research. *Scientometrics, 37*, 279-295.

Bordons, M., Zulueta, M. A., Romero, F., & Barrigon, S. (1999). Measuring interdisciplinary collaboration within a university: the effects of the Multidisciplinary Research Programme. *Scientometrics, 46*, 383-398.

Borgman, C. L. (1990). Editor's Introduction. In C. L. Borgman (Ed.), *Scholarly Communication and Bibliometrics*. Newbury Park, CA: Sage.

Borup, M., Brown, N., Konrad, K., & Van Lente, H. (2006). The sociology of expectations in science and technology. *Technology Analysis & Strategic*

Management, 18, 285-298.

Boschma, R. (2005). Promixity and innovation: a critical assessment. *Regional Studies, 39*, 61-74.

Braun, D. (1998). The role of funding agencies in the cognitive development of science. *Research Policy, 27*, 807-821.

Braun, D., & Guston, D. (2003). Principal agent theory and research policy: an introduction. *Science and Public Policy, 30*, 302-308.

Brewer, G. D. (1999). The challenges of interdisciplinarity. *Policy Sciences, 32*, 327-337.

Bronmann, L., & Daniel, H. D. (2008). What do citation counts measure? A review of studies on citing behaviour. *Journal of Documentation, 64*, 45-80.

Brooks, H. (1978). The problem of research priorities. *Daedalus, 107*, 171-190.

Brooks, H. (1994). The relationship between science and technology. *Research Policy, 23*, 477-486.

Brooks, H. (1996). The evolution of US science policy. In L. R. Smith & C. E. Barfield (Eds.), *Technology, R&D, and the Economy* (pp. 15-47). Brookings: Brookings Institution.

Calderini, M., Franzoni, C., & Vezzulli, A. (2007). If star scientists do not patent: The effect of productivity, basicness and impact on the decision to patent in the academic world. *Research Policy, 36*, 303-319.

Calvert, J. (2001). *Goodbye Blue Skies?: The Concept of 'Basic Research' and Its Role in a Changing Funding Environment.* DPhil Thesis, University of Sussex, Brighton, UK.

Carayol, N., & Thi, T. U. N. (2005). Why do academic scientists engage in interdisciplinary research? *Research Evaluation, 14*, 70-79.

Chang, Y. C., Chen, M. H., Hua, M., & Yang, P. Y. (2005). Industrializing academic knowledge in Taiwan. *Research-Technology Management, 48*, 45-50.

Cohen, W. M., & Levinthal, D. A. (1990). Absorptive capacity: a new perspective on learning and innovation. *Administrative Science Quarterly, 35*, 128-152.

Cohen, W. M., Nelson, R. R., & Walsh, J. P. (2002). Links and impacts: the influence of public research on industrial R&D. *Management Science, 48*, 1-23.

Crane, D. (1972). *The Invisible College: Diffusion of Knowledge in Scientific*

Communities. Chicago: University of Chicago Press.

Crespi, G., D'Este, P., Fontana, R., & Geuna, A. (2011). The impact of academic patenting on university research and its transfer. *Research Policy, 40*, 55-68.

Creswell, J. W. (2007). *Qualitative Inquiry and Research Design: Choosing among Five Approaches*. Thousand Oaks, CA: Sage.

Davenport, S., Leitch, S., & Rip, A. (2003). The 'user' in research funding negotiation processes. *Science and Public Policy, 30*, 239-250.

Debackere, K., & Rappa, M. A. (1994). Institutional variations in problem choice and persistence among scientists in an emerging field. *Research Policy, 23*, 425-441.

Dunleavy, P., & Hood, C. (1994). From old public administration to new public management. *Public Money & Management, 14*, 9-16.

Dzisah, J. S. (2006). *Scientific Research and Economic Activity: The Perceptions of Academic and Industrial Scientists of the Production and Capitalisation of Knowledge.* DPhil Thesis, University of Saskatchewan, Saskatoon, Canada.

Edquist, C. (Ed.). (1997). *Systems of Innovation: Technologies, Institutions, and Organisations*. London: Pinter.

Elzinga, A. (1997). The science-society contract in historical transformation: with special reference to "epistemic drift". *Social Science Information, 36*, 411-445.

Economic and Social Research Council [ESRC]. (1995). *Thematic Priorities*. Swindon: ESRC.

Etzkowitz, H. (1989). Entrepreneurial science in the academy: a case of the transformation of norms. *Social Problems, 36*, 14-29.

Etzkowitz, H. (1998). The norms of entrepreneurial science: cognitive effects of the new university-industry linkages. *Research Policy, 27*, 823-833.

Etzkowitz, H. (2003). Research groups as 'quasi-firms': the invention of the entrepreneurial univeristy. *Research Policy, 32*, 109-121.

Etzkowitz, H., & Leydesdorff, L. (1998). The endless transition: a "triple helix" of university-industry-government relations. *Minerva, 36*, 271-288.

Etzkowitz, H., & Leydesdorff, L. (2000). The dynamics of innovation: from national systems and "mode 2" to a triple helix of university-industry-government relations. *Research Policy, 29*, 109-123.

Etzkowitz, H., Ranga, L. M., Benner, M., Guaranys, L., Maculan, A. M., & Kneller, R. (2008). Pathways to the entrepreneurial university: towards a global convergence. *Science and Public Policy, 35*, 681-695.

Etzkowitz, H., Webster, A., Gebhardt, C., & Terra, B. R. C. (2000). The future of the university and the university of the future: evolution of ivory tower to entrepreneurial paradigm. *Research Policy, 29*, 313-330.

European Commission [EC]. (2005). *Frontier Research: The European Challenge*. Luxembourg: Office for Official Publications of the European Communities.

EC. (2009). *Challenging futures of science in society- emerging trends and cutting-edge issues*. Brussels: EU DG-Research.

EC. (2010). *European Commission Directorate General for Research Seminar: "How Ways of Doing Research are Evolving in Order to Address Soceital Challenges"*. Brussels: EU DG-Research.

Feller, I., Ailes, C. P., & Roessner, J. D. (2002). Impacts of research universities on technological innovation in industry: evidence from engineering research centers. *Research Policy, 31*, 457-474.

Ferné, G. (1995). Science and technology in the new world order. In S. Schwartzman (Ed.), *Science and Tecnology in Brazil: New Policy for a Global World*. Rio de Janeiro: Fundação Getúlio Vargas.

Florida, R., & Cohen, W. M. (1999). Engine or infrastructure? The university role in economic development. In L. M. Branscomb, F. Kodama & R. Florida (Eds.), *Industrializing Knowledge: University-Industry Linkages in Japan and the United States* (Vol. 589-610). Cambridge, MA, USA: The MIT Press.

Funtowicz, S. O., & Ravetz, J. R. (1993). Science for the post-normal age. *Futures, 25*, 739-755.

Geuna, A. (2001). The changing rationale for European university research funding: are there negative unintended consequences? *Journal of Economic Issues, 35*, 607-632.

Geuna, A., & Nesta, L. J. J. (2006). University patenting and its effects on academic research: The emerging European evidence. *Research Policy, 35*, 790-807.

Gibbons, M., & Johnston, R. (1974). The roles of science in technological innovation. *Research Policy, 3*, 220-242.

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., & Scott, P. (1994). *The New

Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies. London: Sage Publications.

Gieryn, T. F. (1983). Boundary-work and the demarcation of science from non-science: strains and interests in professional ideologies of scientists. *American Sociological Review, 48*, 781-795.

Glanzel, W., Meyer, M., Du Plessis, M., Thijs, B., Magerman, T., Schlemmer, B., et al. (2003). *Nanotechnology: Analysis of an emerging domain of scientific and technological endeavour*. Leuven: K.U. Leuven, Steunpunt O&O Statistieken, Report.

Godin, B. (1998). Writing performative history: the new new Atlantis? *Social Studies of Science, 28*, 465-483.

Godin, B., & Gingras, Y. (2000). Impact of collaborative research on academic science. *Science and Public Policy, 27*, 65-73.

Gulbrandsen, M. (2005). Tensions in the research council-research community relationship. *Science and Public Policy, 32*, 199-209.

Gulbrandsen, M., & Kyvik, S. (2010). Are the concepts basic research, applied research and experimental development still useful? An empirical investigation among Norwegian academics. *Science and Public Policy, 37*, 343-353.

Gulbrandsen, M., & Langfeldt, L. (2004). In serach of 'Mode 2': the nature of knowledge production in Norway. *Minerva, 42*, 237-250.

Guston, D. (1996). Principal-agent theory and the structure of science policy. *Science and Public Policy, 23*, 229-240.

Guston, D. (1999). Stabilizing the boundary between US politics and science: the role of the Office of Technology Transfer as a boundary organization. *Social Studies of Science, 29*, 87-111.

Guston, D., & Keniston, K. (Eds.). (1994). *The Fragile Contract: University Science and the Federal Government*. Cambridge, MA, USA: The MIT Press.

Hagstrom, W. O. (1965). *The Scientific Community*. New York; London: Basic Books.

Hessels, L. K. (2010). *Science and the Struggle for Relevance.* DPhil Thesis, University of Utrecht, the Netherlands.

Hessels, L. K., Grin, J., & Smits, R. (2011). The effects of a changing institutional environment on academic research practices: three cases from agricultural

science. *Science and Public Policy, 38*, 555-568.

Hessels, L. K., & van Lente, H. (2008). Re-thinking new knowledge production: a literatue review and a research agenda. *Research Policy, 37*, 740-760.

Hessels, L. K., van Lente, H., & Smits, R. (2009). In search for relevance: the changing contract betweeen science and society. *Science and Public Policy, 36*, 387-401.

Hicks, D., & Hamilton, K. (1999). Does university-industry collaboration adversely affect university research? *Issues in Science and Technology, 15*, 74-75.

Hicks, D. M., & Katz, J. S. (1996). Where is science going? *Science Technology and Human Values, 21*, 379-406.

Higher Education Evaluation & Accreditation Council of Taiwan [HEEACT]. (2010). *Self-evaluation Report of HEEACT*. Taipei: HEEACT.

Her Majesty's Stationery Office [HMSO]. (1971). *Rothschild report: The organisation and management of government research and development, Cmnd 4814*. London: HMSO.

HMSO. (1993). *Realising Our Potential: A Strategy for Science, Engineering and Technology*. London: HMSO.

Holbrook, J. B. (2005). Assessing the science-society relation: the case of the US National Science Foundation's second merit review criterion. *Technology in Society, 27*, 437-451.

Huang, C., Notten, A., & Rasters, N. (2011). Nanoscience and technology publications and patents: a review of social science studies and search strategies. *Journal of Technology Transfer, 36*, 145-172.

Huutoniemi, K., Klein, J. T., Bruun, H., & Hukkinen, J. (2010). Analyzing interdisciplinarity: typology and indicators. *Research Policy, 39*, 79-88.

Illinois Institute of Technology [IIT]. (1968). *Technology in Retrospect and Critical Events in Science* (TRACES). Chicago: IIT Research Institute.

Irvine, J., & Martin, B. R. (1984). *Foresight in Science: Picking the Winners*. London: Pinter.

Jacob, M. (2005). Boundary work in contemporary science policy: a review. *Prometheus, 23*, 195-207.

Jaffe, A. B. (1989). Real effects of academic research. *The American Economic Review, 79*, 957-970.

Kanninen, S., & Lemola, T. (2006). *Methods for Evaluating the Impact of Basic Research Funding: An Analysis of Recent International Evaluation Activity.* Helsinki: Academy of Finland.

Katz, J. S. (1994). Geographical proximity and scientific collaboration. *Scientometrics, 31*, 31-43.

Katz, J. S., & Hicks, D. (1997). How much is a collaboration worth? A calibrated bibliometric model. *Scientometrics, 40*, 541-554.

Katz, J. S., & Martin, B. R. (1997). What is research collaboration? *Research Policy, 26*, 1-18.

Klein, J. T. (1990). *Interdisciplinarity: History, Theory, and Practice.* Detroit: Wayne State University Press.

Klein, J. T. (1996). Interdisciplinary needs: the current context. *Library Trends, 45*, 134-154.

Kline, S. J., & Rosenberg, N. (1986). An overview of innovation. In R. Landau & N. Rosenberg (Eds.), *The Positive Sum Strategy: Harnessing Technology for Economic Growth* (pp. 275-306). Washington, D.C.: National Academy Press.

Knorr-Cetina, K. D. (1982). Scientific communities or transepistemic arenas of research? A critique of quasi-economic models of science. *Social Studies of Science, 12*, 101-130.

Kostoff, R. N. (2007). Global nanotechnology research metrics. *Scientometrics, 70*, 565-601.

Landry, R., Amara, N., & Lamari, M. (2001). Utilization of social science research knowledge in Canada. *Research Policy, 30*, 333-349.

Landry, R., Amara, N., & Rherrad, I. (2006). Why are some university researchers more likely to create spin-offs than others? Evidence from Canadian universities. *Research Policy, 35*, 1599-1615.

Larsen, M. T. (2011). The implications of academic enterprise for public science: an overview of the empirical evidence. *Research Policy, 40*, 6-19.

Latour, B., & Woolgar, S. (1979). *Laboratory Life: The Construction of Scientific Facts.* Princeton, NJ: Princeton University Press.

Latour, B., & Woolgar, S. (1986). *Laboratory Life: The Construction of Scientific Facts* (2 ed.). Princeton, NJ: Princeton University Press.

Laudel, G. (2006). The art of getting funded: how scientists adapt to their funding conditions. *science and Public Policy, 33*, 489-504.

Law, W. W. (1995). The role of state in higher education reform: Mainland China and Taiwan. *Comparative Education Review, 39*, 322-355.

Leisyte, L. (2007). *University Governance and Academic Research: Case Studies of Research Units in Dutch and English Universities.* DPhil Thesis, University of Twente, the Netherlands.

Lewison, G., & Paraje, G. (2004). The classification of biomedical journals by research level. *Scientometrics, 60*, 145-157.

Leydesdorff, L. (1989). The relations between qualitative theory and scientometric methods in science and technology studies: introduction to the topical issue. *Scientometrics, 15*, 333-347.

Lin, O. C. C. (1998). Science and technology policy and its influence on economic development in Taiwan. In H. S. Rowen (Ed.), *Behind East Asian Growth: The Political and Social Foundation of Prosperity* (pp. 185-207). New York: Routledge.

Lundberg, J., Tomson, G., Lundkvist, I., Skar, J., & Brommels, M. (2006). Collaboration uncovered: exploring the adequacy of measuring university-industry collaboration through co-authorship and funding. *Scientometrics, 69*, 575-589.

Lundvall, B. A. (Ed.). (1992). *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning*. London: Pinter.

Luo, Y. L., & Wang, W. J. (2001). Highly skilled migration and Chinese Taipei's industrial development *International Mobility of the Highly Skilled* (pp. 253-269). Paris: OECD.

Maclean, M., Anderson, J., & Martin, B. R. (1998). Identifying research priorities in public sector funding agencies: mapping science outputs on to user needs. *Technology Analysis & Strategic Management, 10*, 139-155.

Mansfield, E. (1991). Academic research and industrial innovation. *Research Policy, 20*, 1-12.

Martin, B. R. (1996). The use of multiple indicators in the assessment of basic research. *Scientometrics, 36*, 343-362.

Martin, B. R. (2003). The changing social contract for science and the evolution of the university. In A. Geuna, A. J. Salter & W. E. Steinmueller (Eds.), *Science and*

Innovation: Rethinking the Rationales for Funding and Governance. Cheltenham: Edward Elgar.

Martin, B. R., & Johnston, R. (1999). Technology foresight for wiring up the national innovation system: a review of recent government exercises. *Technological Forecasting and Social Change, 60*, 37-54.

Martin, B. R., Salter, A., Hicks, D., Pavitt, K., Senker, J., Sharp, M., et al. (1996). *The Relationship Between Publicly Funded Basic Research And Economic Performance: A SPRU Review*. London: HM Treasury.

Martin, B. R., & Tang, P. (2007). *The Benefits from Publicly Funded Research*. Brighton: SPRU.

Meyer, M., & Persson, O. (1998). Nanotechnology - Interdisciplinarity, patterns of collaboration and differences in application. *Scientometrics, 42*, 195-205.

Mok, K. H. (2000). Reflecting globalization effects on local policy: higher education reform in Taiwan. *Journal of Education Policy, 15*, 637-660.

Molas-Gallart, J., Tang, P., & Morrow, S. (2000). Assessing the non-academic impact of grant-funded socio-economic research: results from a pilot study. *Research Evaluation, 9*, 171-182.

Morris, N. (2000). Science policy in action: policy and the researcher. *Minerva, 38*, 425-451.

Morris, N. (2003). Academic researchers as 'agents' of science policy. *science and Public Policy, 30*, 359-370.

Morris, N., & Rip, A. (2006). Scientists' coping strategies in an evolving research system: the case of life scientists in the UK. *Science and Public Policy, 33*, 253-263.

Narin, F., Pinski, G., & Gee, H. H. (1976). Structure of the biomedical literature. *Journal of the American Society for Information Science, 27*, 25-45.

National Long-term Science Development Council. (1965). *Annual Report of National Long-term Science Development Council*. Taipei.

National Science and Technology Council. (2000). *National Nanotechnology Initiative: The Initiative and Its Implementation Plan*. Washington, DC.

National Science Council [NSC]. (1997). *White Paper on Science and Technology*. Taipei: NSC.

NSC. (2003). *White Paper on Science and Technology*. Taipei: NSC.

NSC. (2012). *Indicators of Science and Technology Taiwan*. Taipei: NSC.

Nelson, R. R. (1959). The simple economics of basic scientific research. *The Journal of Political Economy, 67*, 297-306.

Nelson, R. R. (2004). The market economy, and the scientific commons. *Research Policy, 33*, 455-471.

Nelson, R. R. (Ed.). (1993). *National Innovation Systems: A Comparative Analysis*. New York: Oxford University Press.

Nelson, R. R., & Winter, S. G. (1982). *An evolutionary theory of economic change*. Cambridge: Harvard University Press.

O'Brien, H. L., & Toms, E. G. (2008). What is user engagement? A conceptual framework for defining user engagement with technology. *Journal of the American Society for Information Science and Technology, 59*, 938-955.

Organisation for Economic Co-operation and Development [OECD]. (1971). *Science, Growth and Society - A New Perspective: Report of the Secretary-General's Ad Hoc Group on New Concepts of Science Policy*. Paris: OECD.

OECD. (1972). *Interdisciplinarity: Problems of Teaching and Research in Universities*. Paris: OECD.

OECD. (2002a). *Frascati Manual 2002: Proposed Standard Practices for Surveys on Research and Experimental Development*. Paris: OECD.

OECD. (2002b). *Glossary of Key Terms in Evaluation and Results Based Management*. Paris: OECD.

OECD. (2007). *Performance Budgeting in OECD Countries*. Paris: OECD.

Owen-Smith, J., & Powell, W. W. (2001). Careers and contradictions: faculty responses to the transformation of knowledge and its uses in the life sciences. *Research in the Sociology of Work, 10*, 109-140.

Pavitt, K. (1991). What makes basic research economically useful? *Research Policy, 20*, 109-119.

Pavitt, K. (2001). Public policies to support basic research: what can the rest of the world learn from US theory and practice? (And what they should not learn). *Industrial and Corporate Change, 10*, 761-779.

Pfetsch, F. R. (1979). The 'Finalization' debate in Germany: some comments and explanations. *Social Studies of Science, 9*, 115-124.

Polt, W., & Rojo, J. (2002). 2. Policy instruments. In G. Fahrenkrog, W. Polt, J. Rojo, A. Tubke & K. Zinocker (Eds.), *RTD Evaluation Toolbox: Assessing the Socio-Economic Impact of RTD-Policies*. Seville, Spain.

Porter, A. L., Cohen, A. S., Roessner, J. D., & Perreault, M. (2007). Measuring researcher interdisciplinarity. *Scientometrics, 72*, 117-147.

Porter, A. L., & Rafols, I. (2009). Is science becoming more interdisciplinary? Measuring and mapping six research fields over time. *Scientometrics, 81*, 719-745.

Porter, A. L., Roessner, J. D., Cohen, A. S., & Perreault, M. (2006). Interdisciplinary research: meaning, metrics and nurture. *Research Evaluation, 15*, 187-195.

Porter, A. L., & Rossini, F. A. (1984). Interdisciplinary research redefined - multi-skill, problem-focused research in the STRAP framework. *R & D Management, 14*, 105-111.

Price, D. J. d. S. (1963). *Little Science, Big Science*. New York and London: Columbia University Press.

Qin, J., Lancaster, F. W., & Allen, B. (1997). Types and levels of collaboration in interdisciplinary research in the sciences. *Journal of the American Society for Information Science, 48*, 893-916.

Rafols, I., Leydesdorff, L., O'Hare, A., Nightingale, P., & Stirling, A. (2012). How journal rankings can suppress interdisciplinary research: A comparison between Innovation Studies and Business & Management. *Research Policy, 41*, 1262-1282.

Rafols, I., & Meyer, M. (2007). How cross-disciplinary is bionanotechnology? Explorations in the specialty of molecular motors. *Scientometrics, 70*, 633-650.

Rafols, I., & Meyer, M. (2010). Diversity and network coherence as indicators of interdisciplinarity: case studies in bionanoscience. *Scientometrics, 82*, 263-287.

Rappa, M. A., & Debackere, K. (1995). An analysis of entry and persistence among scientists in an emerging field of science - the case of neural networks. *R & D Management, 25*, 323-341.

Rappert, B. (1997). Irreconcilable difference? The business of social science research and users. *Higher Education Quarterly, 51*, 239-250.

Richardson, S. A., Dohrenwend, B. S., & Klein, D. (1965). *Interviewing. Its Forms and Functions*. New York: Basic Books Inc.

Rip, A. (1994). The republic of science in the 1990s. *Higher Education, 28*, 3-23.

Rip, A. (1997). A cognitive approach to relevance of science. *Social Science Information, 36*, 615-640.

Rip, A. (2002). Regional innovation systems and the advent of strategic science. *Journal of Technology Transfer, 27*, 123-131.

Rosenberg, N., & Nelson, R. R. (1994). American universities and technical advance in industry. *Research Policy, 23*, 323-348.

Rossini, F. A., & Porter, A. L. (1979). Frameworks for integrating interdisciplinary research. *Research Policy, 8*, 70-79.

Salter, A., D'Este, P., Pavitt, K., Scott, A., Martin, B. R., Geuna, A., et al. (2000). *Talent, Not Technology: Publicly Funded Research and Innovation in the UK*. London: Committee of Vice-Chancellors and Principals (CVCP).

Salter, A., & Martin, B. R. (2001). The economic benefits of publicly funded basic research: a critical review. *Research Policy, 30*, 509-532.

Schmidt, J. C. (2008). Trancing interdisciplinarity of converging technologies at the nanoscale: a critical analysis of recent nanotechnosciences. *Technology Analysis & Strategic Management, 20*, 45-63.

Schroyer, T. (1984). Review: on finalization in science. *Theory and Society, 13*, 715-723.

Schummer, J. (2004). Multidisciplinarity, interdisciplinarity, and patterns of research collaboration in nanoscience and nanotechnology. *Scientometrics, 59*, 425-465.

Scott, A. (2004). *'Relevant' Social Science? The Case of Global Environmental Change Research in UK Universities*. DPhil Thesis, University of Sussex, Brighton, UK.

Scott, A. (2007). Peer review and the relevance of science. *Futures, 39*, 827-845.

Scott, A., Steyn, G., Geuna, A., Brusoni, S., & Steinmueller, W. E. (2001). *The Economic Returns to Basic Research and the Benefits of University-industry Relationships: A Literature Review and Update of Findings*. Brighton: SPRU.

Sherwin, C. W., & Isenson, R. S. (1967). Project Hindsight. *Science*, 156, 1571-1577.

Shove, E. (2003). Principals, agents and research programmes. *Science and Public Policy, 30*, 371-381.

Shove, E., & Rip, A. (2000). Users and unicorns: a discussion of mythical beasts in interactive science. *Science and Public Policy, 27*, 175-182.

Small, H., Kushmerick, A., & Benson, D. (2008). Scientists' perceptions of the social and political implications of their research. *Scientometrics, 74*, 207-221.

Song, M. M., & Tai, H. H. (2009). Taiwan's response to globalisation: internationalisation and questing for world class universities. *Asia Pacific Journal of Education, 27*, 323-340.

Sooryamoorthy, R. (2009). Do types of collaboration change citation? Collaboration and citation patterns of South African science publications. *Scientometrics, 81*, 177-193.

Stokes, D. E. (1997). *Pasteur's Quadrant: Basic Science and Technological Innovation*. Washington, D.C., USA: Brookings Institution Press.

The National Academies. (2004). *Facilitating Interdisciplinary Research*. Washington, D.C.: The National Academies Press.

Thursby, M., Thursby, J., & Gupta-Mukherjee, S. (2007). Are there real effects of licensing on academic research? A life cycle view. *Journal of Economic Behavior & Organization, 63*, 577-598.

Tsay, C. L., & Tai, P. F. (2001). The trend and impact of reverse brain drain in Taiwan: the case of high-tech industry, RCTED Working paper series No. 2001-0006. Chungli, Taiwan: National Central University.

van der Meulen, B. (1998). Science policies as principal agent games: institutionalization and path dependency in the relation between government and science. *Research Policy, 27*, 397-414.

van der Meulen, B., & Rip, A. (2000). Evaluation of societal quality of public sector research in the Netherlands. *Research Evaluation, 9*, 11-25.

van Lente, H., & Rip, A. (1998). The rise of membrance technology: from rhetorics to social reality. *Social Studies of Science, 28*, 221-254.

Van Looy, B., Callaert, J., & Debackere, K. (2006). Publication and patent behavior of academic researchers: Conflicting, reinforcing or merely co-existing? *Research Policy, 35*, 596-608.

Van Looy, B., Ranga, L. M., Callaert, J., Debackere, K., & Zimmerman, E. (2004). Combining entrepreneurial and scientific performance in academia: Towards a compounded and reciprocal Matthew-effect? *Research Policy, 33*, 425-441.

van Raan, A. F. J. (2005a). Fatal attraction: conceptual and methodological problems in the ranking of universities by bibliometric methods. *Scientometrics, 62*, 133-143.

Van Raan, A. F. J. (2005b). Measuring science. In H. F. Moed, W. Glanzel & U. Schmoch (Eds.), *Handbook of Quantitative Science and Technology Research* (pp. 19-49). Dordrecht: Kluwer Academic Publisher.

Van Raan, A. F. J., & Van Leeuwen, T. N. (2002). Assessment of the scientific basis of interdisciplinary, applied research Application of bibliometric methods in Nutrition and Food Research. *Research Policy, 31*, 611-632.

van Rijnsoever, F. J., & Hessels, L. K. (2011). Factors associated with disciplinary and interdisciplinary research collaboration. *Research Policy, 40*, 463-472.

Wang, R. J. (2003). From elitism to mass higher education in Taiwan: the problems faced. *Higher Education, 46*, 261-287.

Wanger, C. S., Roessner, J. D., Bobb, K., & Klein, J. T. (2011). Approaches to understanding and measuring interdisciplinary scientific research (IDR): a review of the literature. *Journal of Informetrics, 165*, 14-26.

Waterton, C. (2005). Scientists' conceptions of the boundaries between their own research and policy. *Science and Public Policy, 32*, 435-444.

Weingart, P. (1997). From "Finalization" to "Mode 2": old wine in new bottles? *Social Science Information, 36*, 591-613.

Weingart, P. (2008). How robust is "socially robust" knowledge. In M. Carrier, D. Howard & J. Kourany (Eds.), *The challenge of the social and the pressure of practice: Science and values revisited* (pp. 131-145). Pittsburgh: University of Pittsburg Press.

Wickham, J., & Collins, G. (2006). Involving users in social science research: a new European paradigm? *European Journal of Education, 41*, 269-280.

Wu, W. H., Chen, S. F., & Wu, C. T. (1989). The development of higher education in Taiwan. *Higher Education, 18*, 117-136.

Yang, T. H. (1999). Wang Shih-Chieh and Sino-American scientific and scholarly exchange, 1963-1978: aid or cooperation? *Journal of European and American Studies, 29*, 41-103.

Yang, T. H. (2003). Planning science and technology in Taiwan: Wu Ta-You and the Commission for Science Development. *Taiwan Historical Research, 10*, 67-110.

Yin, R. K. (2009). *Case Study Research: Design and Methods* (4th ed.). Thousand Oaks, London, New Delhi: Sage.

Ziman, J. (1984). *An Introduction to Science Studies: The Philosophical and Social Aspects of Science and Technology*. New York: Cambridge University Press.

Ziman, J. (1987). *Knowing Everything about Nothing: Specialization and Change in Scientific Careers*. New York: Cambridge University Press.

Ziman, J. (1994). *Prometheus Bound: Science in a Dynamic Steady State*. Cambridge, UK: Cambridge University Press.

Appendix 3.1: **Outline of the interview questions**

Background information:

Publicly funded research has played a key role in the development of new technological areas such as nanotechnology, which is expected to meet social and economic needs. This phenomenon gives rise to the challenges related to how best to organise scientific research and maintain a balance between research excellence and relevance. As part of the research, I am talking to academic scientists involved in nano-related research, seeking opinions on the characteristics of their research and factors affecting their research practices.

Outlines of the interview questions

1 Your involvement in nano-related research

- When did you become involved in nano-related research?

- Where do your research ideas generally come from?

- Where does your funding generally come from for your work?

- How would you characterise your research project? Has your research direction changed over time?

- Do you distinguish the features of nano-related research from your other research projects?

- To what extent do you expect the relevance of nano research to the socio-economic needs in your research subject?

2 The governing factors of conducting nano research

- How do you feel that the research environment is changing by emphasising the socio-economic relevance of science more? If yes, does it require you to do nano-related research in a way that is different from how you normally conduct research (e.g. more interdisciplinary, more interaction than other research)?

- Do you think that interdisciplinary research is more likely to address socio-economic problems? Why (or why not)?

- Would you say that your nano research is interdisciplinary? If yes, how do you

organise interdisciplinary research? What are the major difficulties? If not, why?

- If you have conducted interdisciplinary research, what are its effects on your publishing activities (e.g. more difficult to get published, higher impact results)?

- Who do you think are the potential users of your nano research results? Do you interact with other non-scientists when conducting nano-related research?

- What criteria do you think would be useful to identify the relevance of research? And by whom should relevance be assessed?

- How do you define "research excellence" in your discipline? How do you think "excellence" should be measured and rewarded?

- What do you think are the relationships between research excellence and relevance (e.g. complementary or conflicting)?

- Your overall comments or other things that you feel strongly about.

Appendix 3.2: The classification scheme of the Ministry of Education in Taiwan

The classification scheme contains three levels: there are 158 disciplines, which are aggregated into 23 fields and further into nine broad fields.

Nine broad fields	23 fields	158 disciplines			
1 Education	14 Teacher training and education science	1401 General education	3103 Sociology	4404 Meteorology	6210 Forestry
2 Humanities and Arts	21 Arts	1402 General teacher training programmes	3104 Demography	4405 Marine science	6211 Fisheries
3 Social sciences, business and law	22 Humanities	1403 Specialized teacher training programmes	3105 Psychology	4406 Astronomy and space sciences	6299 Other agriculture, forestry, and fishery
4 Science	23 Design	1404 Teacher training for pre-school	3106 Geography	4499 Other natural science	6401 Veterinary
5 Engineering, manufacturing and construction	31 Social and behavioural science	1405 Adult education	3107 Regional studies	4601 Mathematics	7201 Medicine
6 Agriculture	32 Journalism and information	1406 Teacher Trainers and for Handicapped	3108 Public adminstration	4602 Statistics	7202 Public health
7 Health and welfare	34 Communication	1407 Educational administration	3109 International Affairs	4699 Statistics and other allied fields	7203 Pharmacology
8 Services	38 Law	1408 Education science	3110 Comprehensive Social and Behavioral Science	4801 Computer sciences	7204 Rehabilitation
9 Security services	42 Life sciences	1409 Educational assessment	3201 General Mass Communication	4802 Networks	7205 Nutrition
	44 Natural sciences	1499 other education science	3202 Journalism	4803 Software development	7206 Nursing
	46 Mathematics and statistics	2101 Drawing; Painting	3203 Radio and TV Production	4804 Operating Systems	7207 Medical Laboratory and Technology
	48 Computing	2102 Sculpture	3204 Public relations	4805 Data Processing	7208 Dental services
	52 Engineering	2103 Craft skills	3205 Museums	4899 Other Computing	7299 Other Health
	58 Architecture and town planning	2104 Music	3206 Archival sciences	5201 Electronics engineering	7601 Care of the disabled
	62 Agriculture	2105 Drama and dance	3207 Graphic Arts Communication	5202 Mechanics engineering	7602 Gerontology
	64 Veterinary	2106 Graphic and audio-visual arts	3208 Advertising	5203 Civil engineering	7603 Social work
	72 Health	2107 General art	3299 Other Communication and Information	5204 Chemical engineering	7604 Child care
	76 Social services	2108 Folk art	3401 General Business	5205 Materials engineering	7699 Other social services
	81 Personal services	2109 Applied Arts	3402 Accounting	5206 Industrial Engineering	8101 Hotel and catering
	84 Transport services	2110 Arts Administration	3403 Business and administration	5207 Textiles engineering	8102 Tourism and leisure
	85 Environmental protection	2201 Taiwan Languages	3404 Trade	5208 Surveying Engineering	8103 Competitive Kinematics
	86 Security services	2202 Chinese language	3405 Finance, Banking	5209 Environmental engineering	8104 Sports science
	99 Not known or unspecified	2203 Foreign Languages	3406 Risk management	5210 Harbor and River Engineering	8105 Sports Leisure and Recreation Management
		2204 Miscellaneous Languages and Literature	3407 Finance	5211 Biomedical engineering	8106 Domestic Science
		2205 Translation	3408 Marketing and logistics	5212 Nuclear engineering	8107 Hair, Dressing, Beauty Treatment
		2206 Comparative literature	3409 Healthcare Administration	5213 General Engineering	8108 Cosmetic services
		2207 Linguistics	3499 Other business and management	5299 Other engineering	8199 Other Personal Services
		2208 Religion	3801 General law	5801 Architecture	8401 Railway Operations, Road Motor Vehicle Operations
		2209 History	3802 Specialised law	5802 landscape architecture	8402 Air Crew, Air Traffic Control
		2210 Anthropology	3899 Other law	5803 Urban planning	8403 Seamanship, Ship's Officer, Nautical Science, Ship's Officer
		2211 Philosophy	4201 Biology	5899 Other architechture and town planning	8499 Other Transport Services
		2212 Documentation Techniques	4202 Ecology	6201 Agriculture	8501 Environmental resources
		2299 Other Humanities	4203 Biotechnology	6202 Animal Husbandary	8502 Air and Water Pollution Control
		2301 Integrated Design	4204 Microbiology	6203 Horticulture	8599 Other environmental protection
		2302 Visual Communication Design	4205 Biochemistry	6204 Plant Protection	8601 Police work
		2303 Product Design	4206 Bioinformation	6205 Agronomy	8602 Military
		2304 Space Design	4299 Other life science	6206 Food science	8699 Other security
		2399 Other Design	4401 Chemistry	6207 Soil and Water Conservation	9901 Not known or unspecified
		3101 Economics	4402 Earth science	6208 Agricultural Chemistry	
		3102 political science	4403 Physics	6209 Crop and Livestock Production	

Source: Ministry of Education of Taiwan. Retrieved from the website http://www.edu.tw

Appendix Table 6.1 List of nano-titled journals published by Taiwanese scientists

Nano-titled-Journal	Year founded	Research level	no. of papers
NANOTECHNOLOGY	1990	3	285
JOURNAL OF NANOSCIENCE AND NANOTECHNOLOGY	2001	3	85
NANO LETTERS	2001	3	33
ACS NANO	2007	3	26
JOURNAL OF NANOPARTICLE RESEARCH	1999	Unassigned	26
NANOSCALE RESEARCH LETTERS	2006	Unassigned	24
IEEE TRANSACTIONS ON NANOTECHNOLOGY	2002	3	15
PHYSICA E-LOW-DIMENSIONAL SYSTEMS & NANOSTRUCTURES	1997	4	10
MICROFLUIDICS AND NANOFLUIDICS	2004	Unassigned	7
JOURNAL OF NANOMATERIALS	2005	Unassigned	6
MICRO & NANO LETTERS	2006	Unassigned	6
JOURNAL OF BIOMEDICAL NANOTECHNOLOGY	2005	Unassigned	5
NANO TODAY	2006	Unassigned	4
JOURNAL OF COMPUTATIONAL AND THEORETICAL NANOSCIENCE	2004	Unassigned	3
JOURNAL OF NANO RESEARCH	2008	Unassigned	3
MICROSYSTEM TECHNOLOGIES-MICRO-AND NANOSYSTEMS-INFORMATION STORAGE AND PROCESSING SYSTEMS	1994	2	3
NANOSCALE	2009	Unassigned	3
RECENT PATENTS ON NANOTECHNOLOGY	2007	Unassigned	3
CURRENT NANOSCIENCE	2005	Unassigned	2
JOURNAL OF MICRO-NANOLITHOGRAPHY MEMS AND MOEMS	2002	Unassigned	2
NATURE NANOTECHNOLOGY	2006	1	2
PRECISION ENGINEERING-JOURNAL OF THE INTERNATIONAL SOCIETIES FOR PRECISION ENGINEERING AND NANOTECHNOLOGY	2000	Unassigned	2
INTERNATIONAL JOURNAL OF NANOMEDICINE	2006	Unassigned	1
JOURNAL OF EXPERIMENTAL NANOSCIENCE	2006	Unassigned	1
JOURNAL OF LASER MICRO NANOENGINEERING	2005	Unassigned	1
JOURNAL OF NANOELECTRONICS AND	2006	Unassigned	1

| OPTOELECTRONICS | | | |
NANO	2006	Unassigned	1
NANOMEDICINE	2006	Unassigned	1
NANOMEDICINE-NANOTECHNOLOGY BIOLOGY AND MEDICINE	2005	Unassigned	1
NANOSCALE AND MICROSCALE THERMOPHYSICAL ENGINEERING	2006	2	1
SYNTHESIS AND REACTIVITY IN INORGANIC METAL-ORGANIC AND NANO-METAL CHEMISTRY	2005	4	1

Source: Computed by the author.

Appendix Table 6.2 Mann-Whitney Test of research level by types of collaboration

| Groups of comparison	z	p	Rank comparison
Single-Univ vs. Inter-Univ	-2.035	0.040	Single-U < Inter-Univ
Single-Univ vs. Univ-Industry	-3.104	0.002	Single-U > U-I
Single-Univ vs. U-Others	-2.441	0.015	U-Others > Single-U
Single-Univ vs. International	-6.176	0.000	Int'l > Single-U
Inter-Univ vs. Univ-Industry	-3.654	0.000	Inter-Univ > U-I
Inter-Univ vs. U-Others	-0.486	0.627	Inter-Univ = U-Others
Inter-Univ vs. International	-4.003	0.000	Inter-Univ < Int'l
Univ-Industry vs U-Others	-3.799	0.000	U-I < U-Others
Univ-Industry vs International	-5.214	0.000	U-I < Int'l
U-Others vs International	-3.389	0.001	U-Others < Int'l

Source: Computed by the author.

Appendix Figure 6.1 Trend of average citation of total nano-related papers
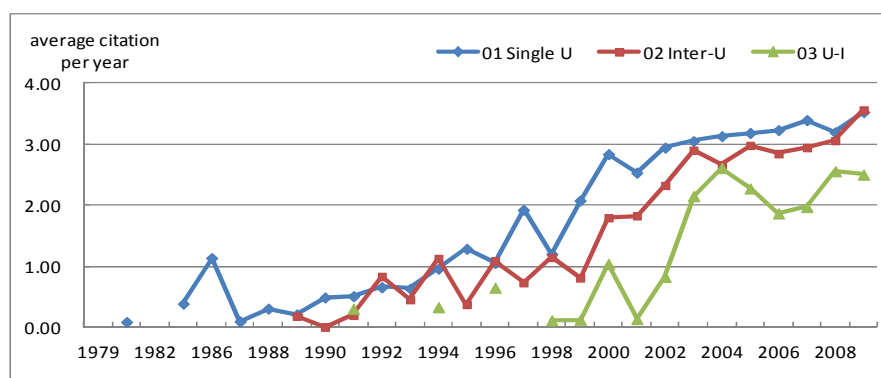
Source: Computed by the author.

Appendix Figure 6.2 Trend of research orientation by seniority
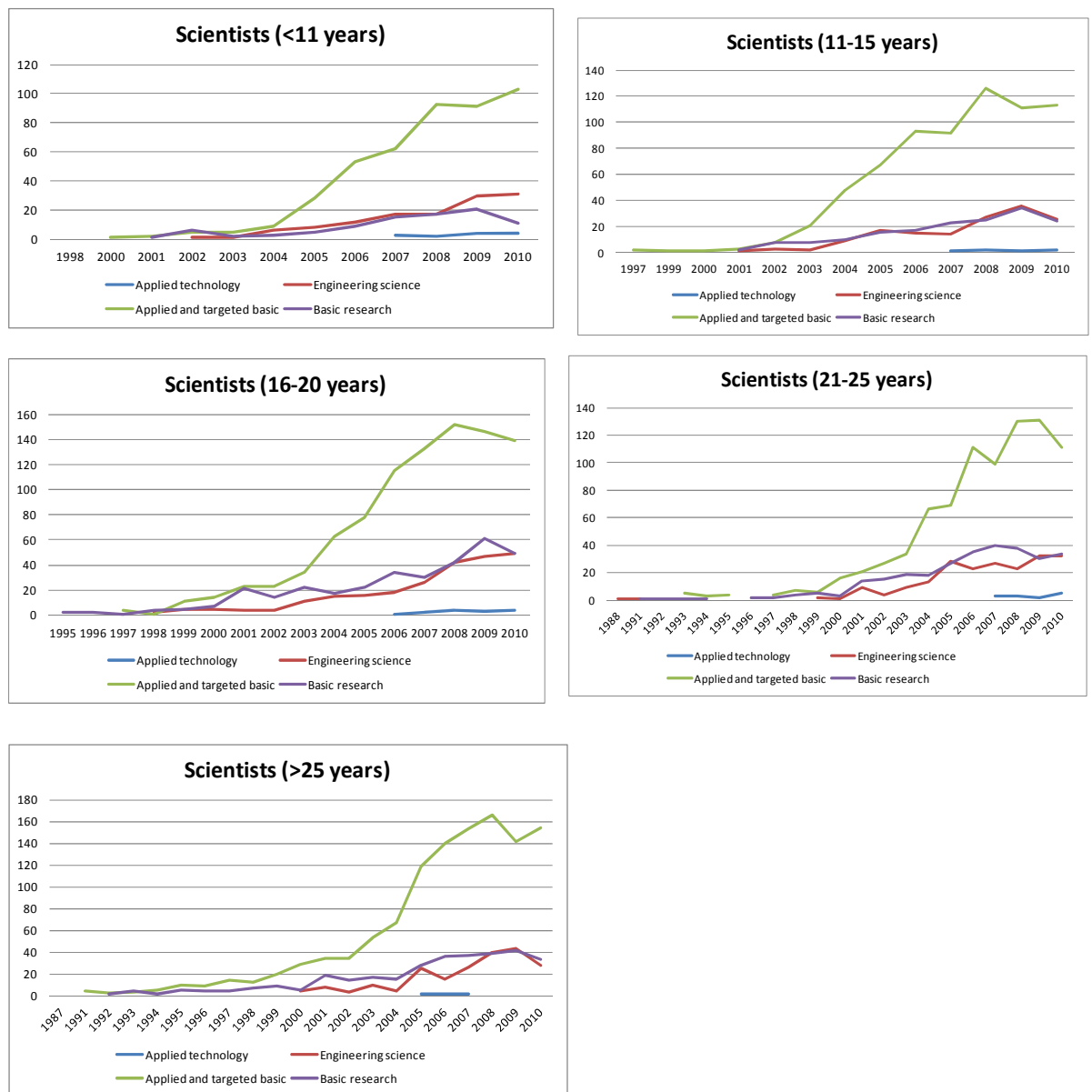
Source: developed by the authors.

Note: The unit of the vertical axis is the number of papers.