The societal footprint of large research facilities
A literature review

Edwin Horlings [a)], Thomas Gurney [a)], André Somers[c)], Peter van den Besselaar [b)]

[a)] Rathenau Institute, Science System Assessment Department, The Hague, the Netherlands

[b)] Department of Organisation Sciences & Network Institute, Vrije Universiteit, Amsterdam, the Netherlands

[c)] i-Optics, Mauritskade 35, The Hague, The Netherlands

Abstract: Large research facilities are among the most expensive items of scientific expenditure. Any decision to invest in the knowledge infrastructure should be based on sound evidence. There is, however, a lack of evidence on the nature and extent of the societal impacts of large research facilities and on the mechanisms that generate such effects. We review the literature to determine whether or not and, if so, through which mechanisms large research facilities produce economic and social impacts. The literature provides no direct, empirical evidence to show that such impacts actually occur around large research facilities. There is insufficient evidence to support the claim that they attract and retain talent and promote innovation. More evidence exists that large research facilities forge new networks and communities. Empirical research on large research facilities and their effects on science, economy and society is sorely needed.

Keywords: large research facilities; research infrastructures; big science; evaluation; knowledge spillovers; science parks, innovation; collaboration; social interaction; research collaboration

1. Introduction

Large research facilities are considered of vital importance for continued scientific progress and tackling the grand challenges (ESFRI, 2010). Large facilities call for large investments. The European Strategy Forum on Research Infrastructures (ESFRI) foresees investments of around €13 billion to build 37 multinational research facilities in seven areas of science (ESFRI, 2010). Since science funding is predominantly a national matter, countries are developing national roadmaps for investment in national and international research facilities, each planning for the expenditure of tens or hundreds of millions of euros per year. In a context of scarce public resources, the financial needs of public science compete with alternative expenditure options that may produce more predictable and visible benefits in the shorter run, such as improvements in education, public health care, and transport infrastructure. Opportunity costs are at the heart of issue. Decisions about investments in research facilities may therefore not only depend on the scientific benefits but also – and sometimes even predominantly – on the expected direct societal benefits of those investments (Stephan 2012). The societal benefits of scientific research are, however, more uncertain, take longer to materialise, and are more difficult to substantiate (Martin & Tang, 2007).

The need for a comparison of available options was voiced as early as the 1960s, when Weinberg called for a consideration of the likely impact on society of different patterns of investment in big science projects (Weinberg, 1961). Since then, the need for studies that focus on the effects of scientific infrastructures as such has been repeated (Autio, Hameri, & Vuola, 2004; Galison & Hevly, 1992; Pavitt, 1991; Valentine, 2010), both to support decisions with respect to public investments in scientific capital goods and to better understand the dynamics of the science system. Policy makers share this need as was, for example, stated in the evaluation of support for research infrastructures in FP6: “there is little demonstration of actual impacts systematically being achieved beyond a few ad hoc examples” (EC, 2009).

Considerable attention has been paid to the impact of *research* on economic innovation. There is an extensive literature on R&D performance and collaboration (e.g. Adams, 2004; Archibugi & Coco, 2004; Arranz & de Arroyabe, 2008), technology transfer (e.g. Bozeman, 2000; Djokovic & Souitaris, 2008), knowledge spillovers (e.g. Audretsch, Lehmann, & Warning, 2005; Henderson, 2007), and the effects of science parks (e.g. Link & Scott, 2003; Phan, Siegel, & Wright, 2005; Phillimore, Joseph, & Larisa, 2003).

In this paper we focus on *large research facilities.* Investments in large, state-of-the-art research facilities are expected to provide critical support to the advancement of science on the national and international levels. Do they also generate *social and economic impacts?* We review the literature to summarize what is currently known about the economic and social impacts produced by large research facilities and, where such impacts are found, about the mechanisms that produce them.

The remainder of the paper is structured as follows. In section 2 define, characterise and classify large research facilities and describe the impacts they are expected to generate. In section 3, we briefly describe the method used to collect and analyse the literature on large research facilities and similar large concentrations in research. In section 4 we review the literature on the economic and social impacts of large research facilities with a scientific mission. As the available literature is rather limited, in section 5 we review literature about the societal and economic impact of other concentrations of research resources, that may be comparable to large research facilities. In this way we may learn about the problem in an indirect way. In section 6 we briefly discuss virtual research facilities. Finally in section 7, we draw conclusions and discuss further research.

2. Definition and impacts of large research facilities

In this section we define, characterise and classify large research facilities and describe the impacts they are expected to generate.

2.1. Defining characteristics

There is no common definition of a large research facility. Science has not developed one and every roadmap for large research facilities uses its own definition. The US National Science Foundation provides a generic definition of a research facility as the ensemble of tools, resources and services that enable research:

> “the tools, services, and installations that are needed for the science and engineering (S&E) research community to function and for researchers to do their work. [It] includes: (1) hardware (tools, equipment, instrumentation, platforms and facilities), (2) software (enabling computer systems,

> libraries, databases, data analysis and data interpretation systems, and communication networks), (3) the technical support (human or automated) and services needed to operate the infrastructure and keep it working effectively, and (4) the special environments and installations (such as buildings and research space) necessary to effectively create, deploy, access, and use the research tools." (NSF, 2003)

Two general characteristics can be deduced from the various definitions and descriptions in roadmaps and other policy documents.

First, a large research facility is *a technological tool for science*. It is a complex set of interrelated, and usually advanced, technologies that enable scientists to do groundbreaking research that could not otherwise be done. Large research facilities tend to be technologically unique in the world or in a country, though countries may each want to have a specific type of facility to provide social or economic functions for which the country does not want to depend on other countries (e.g. national reference laboratories).

Second, a large research facility is *a social construct*. This characteristic has two dimensions. The first dimension is political. The development and construction of a facility often takes many years and significant amounts of funding, which is why facilities are generally designed for a long lifespan. Investments needed to build the facility as well as investments for renewal are usually too large to be carried by a single organization. Large facilities can generally only be realised by means of multi-institutional and sometimes multinational collaboration as well as with substantial public support, frequently from several funding sources. Mobilising such large resources involves negotiation between various actors, each with their own objectives, motivations, and expectations (Autio, Hameri, & Nordberg, 1996). The realisation of a new research facility is consequently both a technological and a social process; the interests and expectations of participating actors show up in its design. The second dimension is purely social. Research facilities are usually open to outside users, giving national and international scientists as well as researchers from industry access to state-of-the-art technologies. A large research facility is a meeting place and collaboration hub for researchers from different disciplines, nations, and sectors.

A research facility is in interaction with its environment. The development and use of research facilities depends on other complementary resources (Bonaccorsi, 2008; Carayol & Matt, 2004). For example, advanced technologies embedded in a research facility can only be used effectively, if there are sufficient researchers with the right skills. Thus, a new facility puts pressure on its institutional environment to subtly realign university curricula, encourages researchers to look for partners with complementary skills, and – when demand exceeds capacity – requires governance solutions to decide who gains access to a facility and who does not.

2.2. Types of facilities

Discussions about research facilities focus traditionally on hardware, such as large telescopes, research ships and big labs. These *single-sited* and *mobile* facilities are relatively clearly defined, for example in the classifications of ESFRI (2006) and NSF (2005). Technological development, mainly in information and communication technologies, has widened the definition. Increasingly, large data collections and other research collections, distributed (virtual) systems, and large software models are considered as research infrastructures (EC, 2007; NSF, 2003, 2005b). This leads to the following classes of facilities:

– *Single-sited facilities* for observation and experimentation, centred around a single piece of equipment (e.g. radio telescopes) or an integrated set of tools (e.g. a high-field magnet lab). CERN is the largest facility of this kind.
– *Mobile facilities* such as planes, ships, and other vehicles, specially designed for research.
– *Distributed facilities,* which are (national or international) networks of research collections, such as the European network of biobanks (BBMRI), or distributed sensor networks for observation, such as the global network of oceanic probes (ARGO). The individual nodes may be small, but the whole network is a large infrastructure. The rise of distributed facilities is enabled through e-science and ICT developments such as the grid, which is a large research facility itself.
– *Virtual facilities*, which are ICT and internet-based systems, such as software platforms for simulation and large linked databases, often accessible from a distance. Biodiversity data infrastructures, such as GBIF, are an example. These virtual facilities are becoming increasingly important as part of the development of e-science.[1]

2.3. Social and economic impacts

Impact relates to the effects of the design, construction, maintenance, usage, and renewal or decommissioning on science, economy and society. We distinguish between the impact of the scientific results produced in the facility (e.g. new medical treatments, new materials) and the impact of social and economic activities throughout a facility’s lifespan and in its environment. Our focus is on the latter.

Expected impacts listed in policy documents include innovation, attracting talented researchers, and job creation in (nearby) spin-off companies and equipment suppliers. For example, the French roadmap reads: “A research infrastructure is often a privileged place for collaboration with the economic sector, especially in the phases of design, of engineering and of implementation but also via the possibility to resolve technological barriers thus leading to innovation. This may also be achieved through education and dissemination of knowledge.” The Swedish roadmap states that “[w]orld-class infrastructures contribute to researcher mobility since they attract researchers from many nations and may be the single most important factor in researchers’ decisions to locate all or part of their research in other countries.”

Generating societal impacts is becoming endogenous to science. The debate about the economic and social impacts of science has long drawn sharp boundaries between public and private research and between fundamental and applied research (Dasgupta & David, 1994; Nelson, 1959). These boundaries are, however, becoming more diffuse. Joly and Mangematin (1996) refer to this development as the ‘hybridisation’ of fundamental and applied research: the borders between public and private and between fundamental and applied are becoming fuzzy (see also Salter & Martin, 2001). The interaction between fundamental and applied science is said to be intensifying (Stokes, 1997) and the organisation of knowledge production is becoming more heterogeneous in terms of the

---

[1] An example of large facilities are huge research collections created through digitalization, such as *Resource or community data collections* and *Reference collections*, serving one or more scientific and technical communities and depending heavily on processes of standardization. Budgets are generally large and guaranteed for long periods. These collections can be distributed (as in biodiversity) or concentrated in data centres (as in the life sciences) (NSF, 2005b).

nature and expertise of the parties involved (Hessels & van Lente, 2008). Scientists are increasingly collaborating with non-scientists in new organisational and social forms, such as Mode-2 research (Gibbons et al., 1994) and transdisciplinary research (Hoffmann-Riem et al. 2008). The emergence of new cooperative or “mixed-type” R&D laboratories in the United States illustrates this development (Bozeman & Crow, 1990).

For some facilities, the impact on economy and society is laid down in the formal mission. For example, national reference laboratories, blood banks, and biobanks are designed to support public health and do scientific research as a supporting activity. In such cases, the impacts are embedded in the facility’s design. Larédo and Mustar (2000) have developed a schematic method – the research compass card – to map an institutions’ activity profile in five dimensions: production of new, scientifically validated knowledge; training and education; encouraging innovation; contribution to achieving public objectives; and engagement in public debates. An aggregate activity profile reflects the strategic choices made by an institution and is determined by the degree to which a laboratory is active in each of the five dimensions. Activity profiles can be seen as an alternative to the conventional distinction between fundamental and applied research.

3. Method

The following method was used to search for relevant literature to review. We first did a topical search for all publications in the Web of Science and in Google Scholar with variants of words such as ‘big science’, ‘facility’, ‘equipment’, ‘infrastructure’ or ‘laboratory’ – also in combination with other words such as ‘large’ and ‘research’ – in the title, abstract or keywords, and restricting the search to relevant research areas (i.e. economics, information science, sociology, geography, organization science, and management). The literature that was found was then used for a further search, using the reference lists of those publications as well as the publications that cite this literature. Since the results were fairly meager, we then searched for review papers and highly cited papers (as well as the recent literature citing those publications) about other large concentrations in research such as universities, large research institutes, large research programmes, and science parks. The literature about those other forms may teach us something about the societal and economic effects of large research facilities.

We were looking for empirical evidence that large research facilities (or other similar concentrations in research) produce impacts on economy and society. Tables 1 and 2 in sections 3 and 4 summarise our findings in this respect. Our focus is on three major areas of expected impact found in roadmaps for large research facilities, namely:

- attract talented researchers from abroad and help retain domestic talent for science;
- directly and indirectly promote innovation in the public and private sectors; and
- form a focal point for collaboration among a multitude of actors and produce synergy among the producers of knowledge.

The social and economic impact of networked and virtual facilities may be different from that of conventional single-sited facilities, as investments, maintenance, and use are not concentrated in one location.

4. Review of empirical evidence for societal benefits of large research facilities

We only found a small body of literature that deals directly with the economic and social impacts of large research facilities. This literature roughly consists of three streams. First, there is a number of studies on innovation and social network formation around CERN. These studies were inspired by the size, advanced technology, and dynamic nature of the centre. Piecemeal contributions notwithstanding (e.g. Cheston, 1983; Kwun, 1997; Irvine et al. 1997), there has been little or no research into the non-scientific impacts of other large research facilities. Second, there is some information in policy studies, most notably a recent study of the economic impacts of British facilities. Third, there are numerous case studies of innovative and collaborative projects within large facilities (e.g. MacEachren et al., 2006; Schissel, 2006). This section presents the summary outcomes of the first two streams. The third group of case studies is not included in this review, as these are mostly anecdotal and provide no systematic insights into the effects and opportunity costs of large research facilities or into the mechanisms that produce these effects.

4.1. The impact of CERN

The development of the Large Hadron Collider (LHC) has produced a flurry of public attention. The LHC is the largest, most complex and most expensive scientific research facility ever constructed. Its scientific utility is rarely disputed. The development of the LHC has made a contribution to a wide range of innovations. This includes, for instance, highly advanced superconducting magnets capable of producing a very strong field at extremely low temperatures; exceedingly accurate measurement equipment that can withstand very high levels of radiation; and advances in data communication, storage and analysis to deal with the annual production of about 15 petabytes of experimental data so they can be analysed by worldwide teams of collaborating scientists. CERN as a whole has been a catalyst in the development of the internet and is closely involved in the development of its next generation, Internet2 (Mohamed, 2005). To support the LHC and other experimental facilities, CERN has produced grid and distributed computing applications (e.g. Moscicki, Guatelli, Mantero, & Pia, 2003). Other large research facilities centres are faced with similar challenges and are working on comparable solutions (Hogeveen, 1995; Schissel, 2006; Schissel et al., 2004).

Since 1996, a small group of researchers has studied the manner in which a big research facility, such as CERN, encourages private sector innovation. They aim to expose the mechanisms that govern the interactions between large facilities and industry, to break open the ‘black box’ of big science (Autio & Hameri, 1995).

To study CERN, Autio, Hameri, and Nordberg (1996) developed a conceptual framework based around actor motivations. They observe that in times of cut-backs in public finances, the scientific returns of a large facility are no longer sufficient to justify the associated expenditure, but that there is not enough information on other benefits. They propose a framework in which the motivations of the three main groups of actors that collaborate in a large research facility – academia, government, and industry – are systematically compared. These motivations provide some understanding of the assumptions on the possible effects of collaborating in a a large research facility.

In subsequent publications (Autio et al., 2004; Byckling, Hameri, Pettersson, & Wenninger, 2000; Hameri, 1996, 1997; Hameri & Nordberg, 1999; Hameri & Vuola, 1996; Nordberg, Campbell, &

Verbeke, 2003; Vuola & Hameri, 2006), a model was developed in which social capital is the key factor in knowledge spillovers from big science to industry. Formal and informal relations between agents from both worlds, whose interactions are governed by their individual interests and motivations, form the main mechanism in spillovers between a science centre and a firm.

Vuola and Hameri (2006) see opportunities for innovation as a function of the interaction between parties with matching interests. Large research facilities and firms are both looking for new technologies. Large research facilities need highly advanced technologies but have limited budgets. Firms are looking for an environment in which they can develop, test, and validate prototype technologies. Collaboration is therefore mutually beneficial. A large research facility, such as CERN, is such an environment: it has the means, users, and facilities, and offers an initial market for a new technology. Vuola and Hameri conclude that informal relations between technical experts are the best basis for setting up a collaboration. Experts speak the same language and their relations form the 'meaningful social practice' that is necessary for joint innovation.

For firms, large research facilities are a learning environment that helps them deal with technological complexities and lower the uncertainty and costs of R&D (Autio et al., 2004; see also Lee & Mason, 2008; Meijer, Hekkert, & Koppenjan, 2007). Large research facilities are highly complex collections of instruments and installations, and invest heavily in the development of specifications of highly advanced technologies. They carry out large-scale construction projects according to strict plans and shared objectives, which are passed on to industrial suppliers in technical specifications as part of procurement procedures. Autio et al. see innovation and knowledge spillover between large research facilities and industry as a process of interactive learning in a mutual relationship. The ability of this relationship to absorb knowledge depends on, what Autio et al. call, the relation-specific social capital that has been developed based on the complementary resources and objectives of the two organisations. Relation-specific social capital increases the amount and diversity of knowledge that can potentially be shared, raises the percentage that is actually shared as mutual trust increases, and improves the efficiency of knowledge transfer as more knowledge is shared and organisational objectives are attuned.

Innovative outcomes in research facilities are not a given and may vary. Nordberg, Campbell, and Verbeke (2003) deduce that firms that pursue long-term strategic goals – particularly the search for complementary knowledge – benefit more from the interaction with CERN than firms that pursue short-term commercial goals. Byckling and colleagues (2000) observe that the general attitude, procedures, and decision-making process in a multinational megafacility can be both inspiring and counterproductive. Vuola and Hameri (2006) show that CERN's strict procurement rules – particularly, that the contract should always be awarded to the lowest bidder – and the political pressure associated with enormous national interests in a multinational facility, mean that the best firm that has invested years in building a solid relationship may not get the contract and that CERN may not gain access to the state-of-the-art of the required technology.

4.2. The impact of large national research facilities

Various, mainly American, examples show how knowledge spillovers from large research programmes can have a lasting impact on science, economy, and society. One such example is the Manhattan Project, created to accelerate US nuclear weapons development during the Second World

War (Gosling, 1999; Hales, 1999). Another example concerns the contributions of the Defense Advanced Research Projects Agency (DARPA) to network communications and artificial intelligence (Cohen et al., 1998; Patil et al., 1997). Both DARPA and CERN claim to have been instrumental in the development of the present-day internet.

Perhaps the most relevant study to date is a policy report written by SQW Consulting for the Department for Innovation, Universities and Skills (DIUS) in the United Kingdom. Responding to a recommendation of the National Audit Office (NAO, 2007), DIUS commissioned a study into the nature and magnitude of the economic impacts of five big science projects funded from the Large Facilities Capital Fund (SQW Consulting, 2008).

The SQW report considers the scientific value of large research facilities beyond dispute: they are considered of extreme value to the UK science system. The main non-scientific benefits of a large research facility appear to be driven by the interactions among the various actors involved in the development, construction, and use of the facility. During construction new technical solutions have to be developed; the facility's researchers and industrial suppliers exchange knowledge and technology; and visiting researchers and resident staff exchange (tacit) knowledge during experiments.

SQW identified two major advantages for British firms. First, large research facilities create a level playing field for British companies. The perception is that procurement by foreign facilities is biased towards national firms. Second, facilities create more opportunities for providing specialised, custom-made goods and services, because firms can more easily and quickly interact with the scientific staff, technical personnel, and external users of a facility. This interaction allows firms to design the technical specification of unique, specialised assignments. From the facility's perspective, there are two advantages. Local firms are better able to provide support and maintenance services and can do so at lower costs, which is especially important for components that require constant attention. And, the transport costs for facility supplies are lower, particularly for heavy or bulky components.

SQW found little evidence of a significant impact on innovation. There are various cases in which working for a research facility does not offer firms the opportunity or motivation to innovate. Firms may be asked to deliver standard commodities (e.g. noble gases) or to perform assignments according to exact specifications and using existing prototypes. The facility may wish to retain the intellectual property right to the items delivered. There are, however, also positive examples where firms "had greater scope to innovate", "pushed the limits of available technology", could "further their skills" and opened up "potential new opportunities in other fields" (SQW Consulting, 2008, p. 30).

The most substantial advantage of delivering to complex, high-tech facilities appears to be that it enhances a firm's reputation. The impact of reputation is, however, limited by the small size and high degree of specialisation of markets for large research facilities. Vuola and Hameri (2006) estimate the total size of the European market at about €500 million, divided among many small and highly specialised projects.

4.3. Conclusions

This research leads to two tentative conclusions. First, the main mechanism through which large research facilities affect economy and society is social. Large facilities are learning environments and hubs in social networks. It is through formal and informal interaction that knowledge spills over between communities and sectors. Second, facilities operate at the scientific and technological frontier and, as such, they offer opportunities for innovation. However, science rather than the private sector is the main beneficiary. For firms, working for and with a large research facility is more likely to offer gains in reputation than in innovation.

Simply supplying a large research facility with technology, goods, or services does not guarantee knowledge spillovers. Knowledge spillovers require (1) opportunity and (2) commitment. Opportunity is a function of the concentration of resources around a state-of-the-art technological core. The large research facilities market may be small and highly specialised, each individual facility does have mass. There is some evidence (from the UK) that having a large research facility in a region or country, provides a competitive advantage to local producers.

Commitment is a function of social capital. The main mechanism behind knowledge spillovers from facilities to industry and the impact of a large research facility on innovation appears to be formal and informal social interaction. The formation of heterogeneous networks and collaborations around large research facilities can be considered a precondition for the flow of innovative knowledge to economy and society.

The direct evidence is insufficient to inform decision makers and evaluators on the opportunity costs of investing in large research facilities. We have some idea of the effects generated in CERN. The evidence regarding five British facilities is biased towards economic impacts. Both strands of research focus on absolute effects rather than additional effects. The question of opportunity costs remains unanswered.

Table 1. Summary of empirical evidence for societal benefits of large research facilities

Effect	**Summary of evidence**
Attract talented researchers	No empirical evidence.
Promote innovation	Large research facilities create opportunities, for example in the construction of state-of-the-art technical equipment and through geographical proximity. Actual effects will be modest.
Focal point for collaboration	Facilities create a learning environment where scientists, users, and industry interact in development, construction, and use.

5. Review of concentrations of resources in the science system: what can we learn about the impacts of research facilities?

We may be able to compensate for the lack of empirical evidence by extending the scope of our review to studies that examine objects with properties similar to those of large research facilities.

In this section, we bring together the results of studies that focus on the individual defining characteristics of large research facilities. We examine organisational concentrations of resources (universities and large public research laboratories), spatial concentrations (high-tech science parks), and social concentrations (multi-institutional and multidisciplinary collaborations). The results can provide an indirect perspective on the societal impacts of large research facilities.

5.1. Organisational concentrations

There is an extensive literature on the contribution of university knowledge to innovation. Aggregate data suggest that this contribution is modest. The Community Innovation Survey shows that universities, higher education institutes, and public research organisations are rarely mentioned as the most valuable collaboration partner. Firms do not consider universities as their main source of technological knowledge. Studies from the 1990s show that new products and processes, that would not have been developed or whose development would have been delayed without academic research, accounted for c. 5% of the total firm turnover (Beise & Stahl, 1999; Mansfield, 1998). Of course, there are sectoral differences. The contribution of public scientific research is higher for specific industries, such as the pharmaceutical, information processing, and instruments industries (Mansfield, 1998, p. 774), chemistry, computer science, material science, metallurgy (Klevorick, Levin, Nelson, & Winter, 1995), and biotechnology (McMillan, Narin, & Deeds, 2000).

The role of universities in innovation and in their relations with firms appears to be changing as firms outsource R&D and search for new advanced technological knowledge, universities are looking for alternative funding sources, and governments actively support closer university-industry relations (Bonaccorsi, Daraio, & Geuna, 2010; Geuna & Muscio, 2009; Yusuf, 2008). The biggest contribution to knowledge transfer is, however, made by a select group of specialised (technical) universities (Kodama, Yusuf, & Nabeshima, 2008; Yusuf, 2008). The vast majority of universities have only a few strong and profitable relations with companies.

Analyzing government R&D laboratories, Bozeman does provide some indication of the potential for knowledge transfer of large research facilities. Like government R&D laboratories large facilities are able to perform interdisciplinary research, operate expensive and unique equipment and facilities, and are designed to be used by external researchers (Bozeman, 2000). However, most relevant studies focus on laboratories and large-scale, multi-disciplinary collaborations as concentrations of human and social capital – researchers and their informal contacts and social networks – (e.g. Bozeman & Coker, 1992; Corley, Boardman, & Bozeman, 2006; Joly & Mangematin, 1996) and not on the technology embedded in the laboratory or the architecture of the facility.[2]

The mobility of researchers from academia to industry and government is one of the mechanisms through which knowledge flows between science and society (Audretsch et al., 2002). Researchers exchange science for industry, establish spin-off companies, and migrate between scientific institutions and facilities. Migrating researchers also bring along their scientific linkages to the rest of their field (Casper & Murray, 2005; Jonkers & Tijssen, 2008). University researchers use social networks as a resource to advance their careers (van Rijnsoever, Hessels, & Vandeberg, 2008). When they move from academia to business, scientists activate their accumulated knowledge and their social networks in the interests of the firm and translate this into “direct activities, valuable connections, collaborations, and employee contacts for the firm” (Murray, 2004, p. 650).

[2] Most of the work on government laboratories and R&D laboratories has been done in the United States, most notably by Bozeman. Translating the results to a European or Asian context may not be easy. Bozeman and Pandey (1994) show that there are considerable differences between government laboratories in the United States and Japan where it concerns cooperative R&D. This may have changed over time, but more recent research on the issue was not found.

Advanced research facilities are said to have a strong attraction on talented researchers, particularly from abroad (ESFRI, 2006; OECD, 2008). We found little or no evidence to support this claim. Florida (1997) found that gaining access to scientific and technical talent is the central feature of foreign-affiliated R&D laboratories in the USA. There have also been a number of studies of international mobility of scientists. Example are studies on doctoral mobility in the social sciences (Ackers, 2005, 2008; Ackers, Gill, & Guth, 2008; Guth & Gill, 2008) and on the push and pull factors of international highly-skilled labour migration (Mahroum, 2000). More general studies on researcher mobility in Germany downplay the benefits with regard to the outflow of talented researchers to industry. In a study among 569 researchers who left the Max Planck Institute, Zellner (2003) concludes that the advantages of their mobility are the result of a transfer of generic knowledge rather than specific knowledge. This suggests that large research facilities may endow their researchers with knowledge of state-of-the-art technology in a complex environment, but that, when it comes to competing on the labour market, such specific knowledge is much less important. Beise and Stahl (1999) see the mobility of highly-skilled academics to the R&D laboratories of firms as the main channel for technology transfer from the public to the private sector. They conclude that "[t]his is where big science laboratories and other non-academic public research fail. They do not spin off much human capital, for one of their justifications is that they care for long-term research requiring low staff turnover rates" (Beise & Stahl, 1999, p. 417).

5.2. Spatial concentrations

Most large research facilities are single-sited concentrations of researchers, advanced equipment, large installations and research space. There is no evidence on the localised impacts of research facilities, but the literature on science parks may provide an indirect answer. Their high-tech nature and close spatial concentration of resources might make science parks a good analogy for a large research facilities.

A review of the literature on science parks reveals that it is a collective term for a wide range of geographic concentrations of firms and knowledge institutes. The heterogeneity of science parks is apparent from the multitude of motivations for their establishment. Science parks are set up to encourage the formation and growth of R&D-intensive companies, to create an environment in which large companies can form relationships with smaller companies, to stimulate the emergence of formal and informal relations between firms, universities and small laboratories (Das & Teng, 1997; Löfsten & Lindelöf, 2005; Siegel, Westhead, & Wright, 2003), to provide an environment in which 'fast applied science' and 'slow basic science' can meet (Quintas, Wield, & Massey, 1992), to attract foreign investments and accelerate the transition to a knowledge-based economy (Koh, Koh, & Tschang, 2005), and to stimulate technological development on a regional and national level (Castells & Hall, 1994; Felsenstein, 1994; Phillimore, 1999). The motivations and structure of a science park depend on the nature of the initiator (e.g. government or university), the interests of the groups at whom the initiative is aimed (e.g. firms), and the context in which the science park is established (Shearmur & Doloreux, 2000). For example, Abramovsky and Simpson (2011) found strong evidence for the co-location of firms with universities in pharmaceutical and chemical R&D but not in other industries. It stands to reason that science parks with different organisational and legal structures, evaluation methods, and missions will also generate different effects (Bigliardi, Dormio, Nosella, &

Petroni, 2006). Because of the heterogeneity of science parks, there is no systematic framework for the analysis of their growth, performance, and impacts (Phan et al., 2005; Gurney et al., 2014).

Large research facilities share the diversity in designs, actors, and objectives as well as the absence of an analytical framework for their assessment. The science park literature does provide insights with regard to two potential impacts of large research facilities. They are expected to (1) promote innovation and they may (2) attract new, innovative firms to a city or region.

(1) Promoting innovation: Much of the literature on science parks has focused on the overarching goal of increasing innovative activity for its member firms and for the surrounding commercial and knowledge base. In most studies, the purported benefits gained from locating on or near a science park have failed to materialise or are much smaller than expected, such as with differences in R&D spending (Westhead, 1997), tenant research productivity (Siegel et al., 2003), employment growth in high-tech sectors (Shearmur & Doloreux, 2000), the creation of innovative firms (Felsenstein, 1994), and development of ties with higher education institutes (Bakouros, Mardas, & Varsakelis, 2002), despite a significant knowledge advantage of science park firms (Colombo & Delmastro, 2002). There are exceptions. Some studies do show higher productivity among on-park than among off-park firms (Squicciarini, 2008; Yang, Motohashi, & Chen, 2009) and a higher propensity among science park firms to collaborate with public research organisations (Fukugawa, 2006; Löfsten & Lindelöf, 2005). The main outright benefit companies extract from a science park location appears to be enhanced reputation rather than increased levels of innovation, a finding similar to what was found for large research facilities.

(2) Attracting new, innovative firms: Koh, Koh, and Tschang (2005) propose that the concentrated presence of high-tech firms in a region attracts secondary business opportunities in the form of "suppliers, technical expertise and potential business partners". These agglomeration effects are reinforced by firm creation and self-renewal, essential to the overall health of the science park as a whole (see also Phan et al., 2005). Yet, the agglomeration effects concern attraction among equals: a cluster of firms attracts more firms (Koh et al., 2005). The public research organisation in or near the science park does not necessarily play a significant part. A similar study by Dettwiler, Lindelöf, and Löfsten (2006) finds that the one big difference between the location choice of in-science park firms and off-science park firms is that the former highly value proximity to a university. All other motivations are more or less identical. In addition, new firms on science parks appear to be older, pre-existing firms rather than newly established firms and university spin-offs (Dettwiler et al., 2006; Westhead & Batstone, 1998). Westhead and Batstone (1998) show that even though in-science park firms value the prestige of the science park, they still cite pragmatic motivations for locating in a science park (such as agglomeration effects). The expected benefits derive from proximity to a higher education institute's facilities; prestige come further down the list. One of those benefits is access to highly skilled potential employees: newly graduated students. Students are considered an important instrument for knowledge transfer and social network formation between science, industry and government. They give university researchers access to firms, because they are both cognitively and socially related (Balconi & Laboranti, 2006). "[They] often provide enduring links as the social glue holding together many faculty scientists and the companies they work with" (Bozeman, 2000).

We can look at a large research facility as if it were a single, large firm in a local cluster of firms, such as a science park. Agrawal and Cockburn (2003) study the co-location of relations between university research and industrial R&D. They focus particularly on the hypothesis that a single, large firm – the anchor tenant firm – facilitates the absorption of university knowledge in industry and encourages innovation in the region. Large research facilities have most of the properties of an anchor tenant firm. They are heavily engaged in research, though not always in development, and have strong absorptive capacity in their specific technological area.

Many agree that knowledge spillovers are geographically bound or 'localised' and that firms close to a university or a cluster of highly innovative firms are more likely to receive and benefit from knowledge spillovers (e.g. Adams, 2004; Mansfield, 1995; Drucker & Goldstein 2007). The literature on localised knowledge spillovers has, however, been critically reviewed by Breschi and Lissoni (2001). They reprove the lack of transparency about the mechanisms that explain knowledge transfer between science, industry, and society: "the concept of [Localized Knowledge Spillovers] is no more than a 'black box', whose contents remain ambiguous" (Breschi & Lissoni, 2001, p. 2). In this context, it is interesting to note that the studies of Autio et al. (2004) and SQW Consulting (2008) suggest that large research facilities extend benefits to small, specialised industrial suppliers, but that this effect is usually not local.

5.3. Social concentrations

Multi-institutional and multidisciplinary collaborations originate as part of the search for technical and non-technical resources in science. Local social networks and informal, face-to-face contacts are of crucial importance for innovation and knowledge transfer (Cohen, Nelson, & Walsh, 2002; Salter & Martin, 2001). Social networks give small companies access to instrumentation and equipment (Faulkner & Senker, 1995). Social networks and collaboration enable firms to mobilise scarce resources, attract university researchers, and identify commercial opportunities (Löfsten & Lindelöf, 2005). Especially in industries with a strong scientific component, the search for complementary knowledge and skills is also a key driver of collaboration (Tether & Tajar, 2008).

Similarly, access to scarce resources – such as facilities, equipment, data, and tacit knowledge – is seen as a prime motivation for collaboration between researchers (Beaver, 2001; Birnholtz, 2007; Boardman, 2008; Cheng & Bozeman, 1993; Fuchs, 1992; Hagstrom, 1965; Melin, 2000; Ponomariov & Boardman, 2008; Thorsteinsdottir, 2000; Whitley, 1984). Chompalov, Shrum, and Genuth refer to the "technological imperative" when they observe that most multi-institutional collaborations are highly dependent on instruments and use technical equipment and procedures for observation, experimentation, and data analysis; the social organisation and management of multi-institutional projects is related to their dependence on technology and on data collection facilities; and collaboration is often only intended to construct equipment (Chompalov, Genuth, & Shrum, 2002; Chompalov & Shrum, 1999; Genuth, Chompalov, & Shrum, 2000; Shrum, 2000; Shrum, Chompalov, & Genuth, 2001). The Pace Report observes that firms see the development of new instrumentation as the main output of science, after the production of specialised knowledge (Arundel, Van de Paal, & Soete, 1995).

Multi-institutional collaboration does not necessarily produce tangible (societal or scientific) benefits. Social capital is accumulated over a longer period of time and gradually creates a complex network of knowledge capital in which individual researchers, knowledge institutions, firms, and other actors are closely interrelated, providing each other significant benefits (Bozeman, 2000). What's more, multi-institutional collaboration makes the coordination of research more difficult, but work on equipment and infrastructure is not hampered by institutional or disciplinary boundaries: the coordination costs of collaborations aimed at the development of instrumentation are comparatively low (Cummings & Kiesler, 2005, 2007).

5.4. Conclusions

What can other concentrations of scientific resources tell us about potential effects of large research facilities? We should be careful in transferring evidence on universities and government laboratories to the context of large research facilities. At best, the literature provides analogies. Large research facilities cannot be compared with universities. With the exception of a few very large facilities like CERN, universities are much larger and more diverse, spanning a wide range of disciplines divided among largely unconnected faculties and research groups. They are not defined by technology nor are they technologically homogeneous. The societal impact of universities may be large but is also rather diverse (De Jong, Van Arensbergen, Van der Meulen, & Van den Besselaar, 2011). The evidence on general university-industry knowledge transfer does not apply directly to large facilities. The same limitations apply when comparing public (R&D) laboratories or science parks with facilities.

The conclusions we can draw based on the literature relate mostly to innovation, knowledge transfer, and the regional economy. To the extent that a large facility is able to achieve such benefits, the effects will be felt in specific industries, linked to certain scientific disciplines, and in specific regions. The impacts are expected to be more modest than those associated with universities, public research laboratories, and science parks. In terms of resources, large research facilities generally are an order of magnitude smaller in terms of budget and they are less diverse.

The "technological imperative" of scientific collaboration offers perhaps the strongest indication of potential societal impact. Large research facilities facilitate multidisciplinary research, offer access to unique, expensive equipment as well as the tacit knowledge around it, and are open to external users. Potential is no guarantee that innovation and knowledge transfer will occur. Knowledge may not flow and, even when it does, firms may not transform this into innovation, at least not in terms of conventional innovation indicators.

Large research facilities are unlikely to replicate the impacts of a university or achieve the agglomeration effects of an entire science park. A large research facility may be a catalyst for collaboration and knowledge transfer and, if it is large enough – dominant perhaps – it may act as an anchor tenant. This role would be reinforced by a large facility's particular nature: state-of-the-art technology, open to external users, and a meeting place for many, heterogeneous actors. And yet, the literature provides no empirical evidence to show that the potential impacts actually occur around large research facilities.

Table 2. Summary of insights deduced from literature on similar concentrations of resources

Attract talented researchers	There is a general lack of empirical evidence on researcher mobility. What there is, relates mostly to universities as suppliers of talent. There is some evidence to suggest that innovative firms locate near universities to access the supply of talented young graduates.

Promote innovation	Effects on innovation will depend heavily on the nature and size of facilities. Large research facilities are as diverse as universities and science parks. In most cases, contributions to innovation will be modest and not localised.
Focal point for collaboration	Technology is a strong driver of interdisciplinary and inter-institutional collaboration in science. Collaborations with a strong technical component have lower coordination costs and are more likely to attract the interest of firms.

6. Virtual research facilities

Our current, limited understanding of the economic and social impacts of large research facilities may eventually be overtaken by the rise of distributed and virtual facilities. Especially since the late 1990s, developments in ICT have resulted in entirely new kinds of facilities with new functionalities (e.g. grid infrastructures, digital databanks, remote access, virtual collaboratories). One effect is that large research facilities are becoming relevant in more disciplines, such as the biological sciences and the social sciences. Another, potentially more powerful, consequence is the rise of distributed and virtual facilities as a substitute for conventional single-sited facilities.

The impacts of a distributed or virtual research facility may be different from those of a single-sited, geographically localised facility. Virtual facilities are not subject to the same capacity limitations as conventional facilities and can prevent duplication of expensive investments (Kim et al., 2007). Distributed facilities are scalable, grow incrementally, and may facilitate participation of smaller institutions in collaborative projects. To the extent that large research facilities have a localised impact, this will most likely be much reduced in distributed and virtual facilities. Then again, to the extent that they have effects through large-scale collaboration, their effects may increase. Such new arrangements of technologies and resources will dramatically alter the nature and impact of large research facilities on their environment. The scientific, technological and social evolution of big science remains dynamic.

Even more fundamental, these new virtual facilities may be revelant for much wider audiences. Especially the large data centres, for example in the social sciences or in biodiversity and taxonomy research may attract users from many sectors, including citizens. Examples are GBIF (www.gbif.org), ViBRANT (vbrant.eu) and many more, especially in the taxonomy and biodiversity realm. The claim is that these facilities may also inform policy makers, citizens, municipalities, and other actors outside academia.

The societal and economic benefit of these facilities may have to be measured in a different way than for the conventional single-sited large facilities, focusing for example on who the users are and what they do with the information retrieved. How much do we currently know about the impacts of virtual facilities? Again, there is not much literature available. Duin et al. (2012) have, for example, made a start with the building of tools to identify users. Yet, there is no systematic knowledge about users and use or about the benefits that non-scholarly users gain from a virtual facility.

7. Conclusions

A review of the literature leaves the central problem unsolved. We did find that societal impacts are endogenous to many facilities: in the Netherlands almost 60% of large facilities has a formal mission that is non-scientific. Yet, there remains a lack of empirical evidence on the societal impacts of primarily scientific large research facilities. What little there is does provide a better understanding of the effects that may occur and the mechanisms that drive them. But the evidence is skewed and cannot be extrapolated to the entire architectural and disciplinary diversity of large research facilities.

When we translate the results of our review to the three key assumptions that are used in decision making and evaluation, we must conclude that there is insufficient empirical evidence to support the claims that large research facilities attract and retain talent and promote innovation. Evidence on the facility as a social construct is considerably stronger.

It is plausible that large research facilities *attract talented researchers from abroad and help retain domestic talent for science*, but there is no evidence to support this claim. What's more, one article observes that staff turnover at large research facilities facilities is low, suggesting that once a facility is operational there is little room for a marginal impact on the national stock of scientific talent.

It is quite likely that they *directly and indirectly promote innovation in the public and private sectors*, but the effects will be modest. The evidence regarding universities, public research laboratories, and science parks is contradictory and where impacts are identified, the effects are modest. Research facilities are generally an order of magnitude smaller.

There is consistent and convincing evidence that large research facilities *generate impacts as a focal point for collaboration among a multitude of actors and produce synergy among the producers of knowledge*. Technology – a defining feature of research facilities – plays a crucial role, as the object of transfer and as a driver of collaboration and social network creation. When we extrapolate from the extant knowledge on large-scale, heterogeneous research collaborations, large research facilities in the public domain have a number of characteristics that reinforce the synergetic effects of social networks and collaboration. They involve large numbers of actors; they connect a large variety of actors and are a hub in social networks; and they are accessible to external users from knowledge institutes and firms, domestic and abroad (cf. Chinoy, Moskowitz, Wilmore, & Souba, 2005). There is, however, little empirical evidence.

More research is needed to collect empirical evidence on the effects of research facilities on innovation, researcher mobility, and collaboration. European Commission (commissioned) reports note that "social and economic benefits are difficult to quantify and opportunities arising from knowledge transfer and spinout companies are inherently unforeseeable"[3] and that economic or industrial impact is apparent in isolated cases and impact on wider society is not measurable (EC, 2009). Research is also needed on the effect of ICT on large research facilities. ICT may change the societal impact of investments in large facilities, while large virtual facilities – such as ecological and social science data facilities – may attract a wide range of non-scholarly users. Here as well, systematic insight has yet to be produced.

If the societal footprint of large research facilities is to be a serious element of science policy and decision making, we need both a good evaluation framework and the evidence to support it. The scientific and technological merit of proposals for the construction of large facilities must be the primary touchstone. Building political support and gathering the required financial resources calls for

---

[3] 5th European Research Infrastructures Workshop on Exchange of Experiences between Preparatory Phase Projects: How to best demonstrate the impact of Research Infrastructures (Brussels, 15 June 2011).

motivations that appeal to a wider audience, especially when funding is scarce. The opportunity costs of large research facilities should be made explicit.

Acknowledgements

The authors thank three anonymous reviewers for their thoughtful comments. PvdB acknowledges the support of the EC-funded ViBRANT project (contract no. RI-261532).

References

Abramovsky, L., & Simpson, H. (2011). Geographic proximity and firm-university innovation linkages: evidence from Great Britain. Journal of Economic Geography, 11(6), 949-977.

Ackers, L. (2005). Moving people and knowledge: Scientific mobility in the European Union. *International Migration*, 43(5), 99-131.

Ackers, L. (2008). Internationalisation, Mobility and Metrics: A New Form of Indirect Discrimination? *Minerva*, 46(4), 411-435.

Ackers, L., Gill, B., & Guth, J. (2008). Doctoral Mobility in the Social Sciences. Report to the NORFACE ERA-NET. Helsinki: University of Liverpool.

Adams, J. D. (2004). Industrial R&D Laboratories: Windows on Black Boxes? *The Journal of Technology Transfer*, 30(1-2), 129-137.

Agrawal, A., & Cockburn, I. (2003). The anchor tenant hypothesis: exploring the role of large, local, R&D-intensive firms in regional innovation systems. *International Journal of Industrial Organization*, 21(9), 1227-1253.

Archibugi, D., & Coco, A. (2004). International partnerships for knowledge in business and academia: A comparison between Europe and the USA. *Technovation*, 24(7), 517-528.

Arranz, N., & de Arroyabe, J. C. F. (2008). The choice of partners in R&D cooperation: An empirical analysis of Spanish firms. *Technovation*, 28(1-2), 88-100.

Arundel, A., Van de Paal, G., & Soete, L. (1995). Innovation Strategies of Europe's Largest Firms: Results of the PACE Survey for Information Sources, Public Research, Protection of Innovations, and Government Programmes. Final Report, PACE Report. University of Limburg, Maastricht: MERIT.

Audretsch, D. B., Bozeman, B., Combs, K. L., Feldman, M., Link, A. N., Siegel, D. S., et al. (2002). The Economics of Science and Technology. *The Journal of Technology Transfer*, 27, 155-203.

Audretsch, D. B., Lehmann, E. E., & Warning, S. (2005). University spillovers and new firm location. *Research Policy*, 34(7), 1113-1122.

Autio, E., & Hameri, A.-P. (1995). The structure and dynamics of technological systems: a conceptual model. *Technology in Society*, 17(4), 365-384.

Autio, E., Hameri, A.-P., & Nordberg, M. (1996). A framework of motivations for industry-big science collaboration: A case study. *Journal of Engineering and Technology Management*, 13(3-4), 301-314.

Autio, E., Hameri, A.-P., & Vuola, O. (2004). A framework of industrial knowledge spillovers in big-science centers. *Research Policy*, 33(1), 107-126.

Bakouros, Y. L., Mardas, D. C., & Varsakelis, N. C. (2002). Science park, a high tech fantasy?: an analysis of the science parks of Greece. *Technovation*, 22(2), 123-128.

Balconi, M., & Laboranti, A. (2006). University-industry interactions in applied research: The case of microelectronics. *Research Policy*, 35(10), 1616-1630.

Beaver, D. D. (2001). Reflections on scientific collaboration (and its study): Past, present and future. *Scientometrics*, 52(3), 365-377.

Beise, M., & Stahl, H. (1999). Public research and industrial innovations in Germany. *Research Policy*, 28(4), 397-422.

Bigliardi, B., Dormio, A. I., Nosella, A., & Petroni, G. (2006). Assessing science parks' performances: directions from selected Italian case studies. *Technovation*, 26(4), 489-505.

Birnholtz, J. P. (2007). When do researchers collaborate? Toward a model of collaboration propensity. *Journal of the American Society for Information Science and Technology*, 58(14), 2226-2239.

Boardman, P. C. (2008). Beyond the stars: The impact of affiliation with university biotechnology centers on the industrial involvement of university scientists. *Technovation*, 28(5), 291-297.

Bonaccorsi, A. (2008). Search regimes and the industrial dynamics of science. *Minerva*, 46(3), 285-315.

Bonaccorsi, A., Daraio, C., & Geuna, A. (2010). Universities in the New Knowledge Landscape: Tensions, Challenges, Change-An Introduction. *Minerva*, 48(1), 1-4.
Bozeman, B. (2000). Technology transfer and public policy: a review of research and theory. *Research Policy*, 29(4-5), 627-655.
Bozeman, B., & Coker, K. (1992). Assessing the effectiveness of technology transfer from US government R&D laboratories: the impact of market orientation. *Technovation*, 12(4), 239-255.
Bozeman, B., & Crow, M. (1990). The environments of U.S. R&D laboratories: political and market influences. *Policy Sciences*, 23, 25-56.
Bozeman, B., & Pandey, S. (1994). Cooperative R&D in government laboratories: comparing the US and Japan. *Technovation*, 14(3), 145-159.
Breschi, S., & Lissoni, F. (2001). Knowledge Spillovers and Local Innovation Systems: A Critical Survey. *Industrial & Corporate Change*, 10(4), 975-1005.
Byckling, E., Hameri, A.-P., Pettersson, T., & Wenninger, H. (2000). Spin-offs from CERN and the case of TuoviWDM. *Technovation*, 20(2), 71-80.
Carayol, N., & Matt, M. (2004). The exploitation of complementarities in scientific production process at the laboratory level. *Technovation*, 24(6), 455-465.
Casper, S., & Murray, F. (2005). Careers and clusters: analyzing the career network dynamic of biotechnology clusters. *Journal of Engineering and Technology Management*, 22(1-2), 51-74.
Castells, M., & Hall, P. (1994). *Technopoles of the World: The Making of 21st Century Industrial Complexes*. London: Routledge.
Cheng, J. L. C., & Bozeman, B. (1993). Resource dependence and interorganizational linkage among R&D labs: The impact of research orientations. *The Journal of High Technology Management Research*, 4(2), 255-270.
Cheston, T. S. (Ed.). (1983). *Space Social Science*: Georgetown University / NASA.
Chinoy, M. R., Moskowitz, J., Wilmore, D. W., & Souba, W. W. (2005). Basic science faculty in surgical departments: Advantages, disadvantages and opportunities. *Journal of Surgical Research*, 123(1), 153-157.
Chompalov, I., Genuth, J., & Shrum, W. (2002). The organization of scientific collaborations. *Research Policy*, 31(5), 749-767.
Chompalov, I., & Shrum, W. (1999). Institutional Collaboration in Science: A Typology of Technological Practice. *Science, Technology and Human Values*, 24(3), 338-372.
Cohen, P. R., Schrag, R., Jones, E., Pease, A., Lin, A., Starr, B., et al. (1998). The DARPA High-Performance Knowledge Bases Project. *AI Magazine*, Winter 1998.
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), 1-23.
Colombo, M. G., & Delmastro, M. (2002). How effective are technology incubators?: Evidence from Italy. *Research Policy*, 31(7), 1103-1122.
Corley, E. A., Boardman, P. C., & Bozeman, B. (2006). Design and the management of multi-institutional research collaborations: Theoretical implications from two case studies. *Research Policy*, 35(7), 975-993.
Cummings, J. N., & Kiesler, S. (2005). Collaborative research across disciplinary and organizational boundaries. *Social Studies of Science*, 35(5), 703-722.
Cummings, J. N., & Kiesler, S. (2007). Coordination costs and project outcomes in multi-university collaborations. *Research Policy*, 36(10), 1620-1634.
Das, T. K., & Teng, B. S. (1997). Time and Entrepreneurial Risk Behavior. *Entrepreneurship Theory and Practice*, 22(2), 69-71.
Dasgupta, P., & David, P. A. (1994). Toward a new economics of science. *Research Policy*, 23(5), 487-521.
De Jong, S., Van Arensbergen, P., Van der Meulen, B., & Van den Besselaar, P. (2011). Evaluation in practice oriented disciplines. *Research Evaluation* (submitted).
Dettwiler, P., Lindelöf, P., & Löfsten, H. (2006). Utility of location: A comparative survey between small new technology-based firms located on and off Science Parks--Implications for facilities management. *Technovation*, 26(4), 506-517.
Djokovic, D., & Souitaris, V. (2008). Spinouts from academic institutions: a literature review with suggestions for further research. *The Journal of Technology Transfer*, 33(3), 225-247.
Drucker, J., & Goldstein, H. (2007). Assessing the regional economic development impacts of universities: A review of current approaches. International Regional Science Review, 30(1), 20-46.
Duin, D., King, D., & van den Besselaar, P. (2012). Identifying Audiences of E-Infrastructures - Tools for Measuring Impact. *Plos One*, 7(12).
ESFRI. (2006). European Roadmap for Research Infrastructures. Report 2006. Luxembourg: European Strategy Forum on Research Infrastructures.

ESFRI. (2008). European Strategy Forum on Research Infrastructures Roadmap 2008. Luxembourg: Office for Official Publications of the European Communities.
ESFRI. (2010). Strategy Report on Research Infrastructures. Roadmap 2010. Luxembourg: Office for Official Publications of the European Communities.
European Commission (2009). Community Support for Research Infrastructures in the Sixth Framework Programme: Evaluation of pertinence and impact, Luxembourg.
Faulkner, W., & Senker, J. (1995). *Knowledge Frontiers: Public Secto+r Research and Industrial Innovation in Biotechnology, Engineering Ceramics, and Parallel Computing*. Oxford: Clarendon Press.
Felsenstein, D. (1994). University-related science parks -- 'seedbeds' or 'enclaves' of innovation? *Technovation*, 14(2), 93-110.
Florida, R. (1997). The globalization of R&D: Results of a survey of foreign-affiliated R&D laboratories in the USA. Research Policy, 26(1), 85-103.
Fuchs, S. (1992). *The professional quest for truth: A social theory of science and knowledge*. Albany, NY: State University of New York Press.
Fukugawa, N. (2006). Science parks in Japan and their value-added contributions to new technology-based firms. *International Journal of Industrial Organization*, 24(2), 381-400.
Galison, P., & Hevly, B. (Eds.). (1992). *Big Science: The Growth of Large-Scale Research*. Palo Alto: Stanford University Press.
Genuth, J., Chompalov, I., & Shrum, W. (2000). How experiments begin: The formation of scientific collaborations. *Minerva*, 38(3), 311-348.
Geuna, A., & Muscio, A. (2009). The Governance of University Knowledge Transfer: A Critical Review of the Literature. *Minerva*, 47(1), 93-114.
Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., & Trow, M. (1994). *The new production of knowledge. The dynamics of science and research in contemporary societies*. London/Thousand Oaks/New Delhi: SAGE Publications.
Gosling, F. G. (1999). *The Manhattan Project: Making the Atomic Bomb*. Washington DC: US Department of Energy.
Gurney, T., Horlings, E., van den Besselaar, P., Sumikura, K., Schoen, A., Laurens, P., & Pardo, D. (2014). Analysing knowledge capture mechanisms: Methods and a stylised bioventure case. Journal of Informetrics, 8(1), 259-272.
Guth, J., & Gill, B. (2008). Motivations in east-west doctoral mobility: Revisiting the question of brain drain. *Journal of Ethnic and Migration Studies*, 34(5), 825-841.
Hagstrom, W. (1965). *The scientific community*. New York: Basic Books.
Hales, P. B. (1999). *Atomic Spaces: Living on the Manhattan Project*. Champaign, IL: University of Illinois Press.
Hameri, A.-P. (1996). Technology transfer between basic research and industry. *Technovation*, 16(2), 51-57.
Hameri, A.-P. (1997). Innovating from big science research. *The Journal of Technology Transfer*, 22(3), 27-35.
Hameri, A.-P., & Nordberg, M. (1999). Tendering and contracting of new, emerging technologies. *Technovation*, 19(8), 457-465.
Hameri, A.-P., & Vuola, O. (1996). Using basic research as a catalyst to exploit new technology-based innovations -- a case study. *Technovation*, 16(10), 531-539.
Henderson, J. V. (2007). Understanding knowledge spillovers. *Regional Science and Urban Economics*, 37(4), 497-508.
Hessels, L. K., & van Lente, H. (2008). Re-thinking new knowledge production: A literature review and a research agenda. *Research Policy*, 37(4), 740-760.
Hoffmann-Riem, H., Biber-Klemm, S., Grossenbacher-Mansuy, W., Joye, D., Pohl, C., Wiesmann, U., & Zemp, E. (Eds.). (2008). Handbook of transdisciplinary research. Dordrecht: Springer.
Hogeveen, S. J. (1995). The Astronomical Information Infrastructure from the end-user perspective. *Vistas in Astronomy*, 39(1), 13-20.
Hallonsten, O. (2014). How expensive is Big Science? Consequences of using simple publication counts in performance assessment of large scientific facilities. *Scientometrics*, 1-14.
Irvine, J., Martin, B. R., Griffiths, D., & Gathier, R. (Eds.). (1997). Equipping Science for the 21st Century. Cheltenham/Lyme: Edward Elgar.
Joly, P. B., & Mangematin, V. (1996). Profile of public laboratories, industrial partnerships and organisation of R & D: the dynamics of industrial relationships in a large research organisation. *Research Policy*, 25(6), 901-922.
Jonkers, K., & Tijssen, R. (2008). Chinese researchers returning home: Impacts of international mobility on research collaboration and scientific productivity. *Scientometrics*, 77(2), 309-333.

Kim, J.-h., Ahn, J. W., Kim, C., Kim, Y., Cho, K. W., Kwon, J. H., et al. (2007). Construction of numerical wind tunnel on the e-science infrastructure. In *Parallel Computational Fluid Dynamics* 2006 (pp. 99-106). Amsterdam: Elsevier Science B.V.

Klevorick, A. K., Levin, R. C., Nelson, R. R., & Winter, S. G. (1995). On the sources and significance of interindustry differences in technological opportunities. *Research Policy*, 24(2), 185-205.

Kodama, F., Yusuf, S., & Nabeshima, K. (2008). Introduction to special section on university-industry linkages: The significance of tacit knowledge and the role of intermediaries. *Research Policy*, 37(8), 1165-1166.

Koh, F. C. C., Koh, W. T. H., & Tschang, F. T. (2005). An analytical framework for science parks and technology districts with an application to Singapore. *Journal of Business Venturing*, 20(2), 217-239.

Kwun, S.-I. (1997). Physics, Big Science, and Modern Industrialization in Korea, STEPI-GMU/CSTP Occasional paper 97-06: Center for Science, Trade, and Technology Policy of George Mason University / Science and Technology Policy Institute of Korea.

Larédo, P., & Mustar, P. (2000). Laboratory activity profiles: An exploratory approach. *Scientometrics*, 47(3).

Lee, I. H., & Mason, R. (2008). Uncertainty, co-ordination and path dependence. *Journal of Economic Theory*, 138(1), 262-287.

Link, A. N., & Scott, J. T. (2003). U.S. science parks: the diffusion of an innovation and its effects on the academic missions of universities. *International Journal of Industrial Organization*, 21(9), 1323-1356.

Löfsten, H., & Lindelöf, P. (2005). R&D networks and product innovation patterns--academic and non-academic new technology-based firms on Science Parks. *Technovation*, 25(9), 1025-1037.

MacEachren, A. M., Pike, W., Yu, C., Brewer, I., Gahegan, M., Weaver, S. D., et al. (2006). Building a geocollaboratory: Supporting Human-Environment Regional Observatory (HERO) collaborative science activities. *Computers, Environment and Urban Systems*, 30(2), 201-225.

Mahroum, S. (2000). Highly skilled globetrotters: mapping the international migration of human capital. *R & D Management*, 30(1), 23-31.

Mansfield, E. (1995). Academic Research Underlying Industrial Innovations - Sources, Characteristics and Financing. *Review of Economics and Statistics*, 77(1), 55-62.

Mansfield, E. (1998). Academic research and industrial innovation: An update of empirical findings. *Research Policy*, 26(7-8), 773-776.

Martin, B. R., & Tang, P. (2007). The benefits from publicly funded research, SPRU Electronic Working Paper Series, Paper no. 161. University of Sussex, Brighton, UK: SPRU.

McMillan, G. S., Narin, F., & Deeds, D. L. (2000). An analysis of the critical role of public science in innovation: the case of biotechnology. *Research Policy*, 29(1), 1-8.

Meijer, I. S. M., Hekkert, M. P., & Koppenjan, J. F. M. (2007). The influence of perceived uncertainty on entrepreneurial action in emerging renewable energy technology; biomass gasification projects in the Netherlands. *Energy Policy*, 35(11), 5836-5854.

Meijer, I., Molas-Gallart, J., & Mattsson, P. (2012). Networked research infrastructures and their governance: The case of biobanking. *Science and Public Policy*, 39(4), 491-499.

Melin, G. (2000). Pragmatism and self-organization: Research collaboration on the individual level. *Research Policy*, 29(1), 31-40.

Mohamed, A. (2005). Cern lays foundations for next-generation internet with intercontinental 10 Gig Wan. *ComputerWeekly.com* (29 November 2005).

Moscicki, J. T., Guatelli, S., Mantero, A., & Pia, M. G. (2003). Distributed geant4 simulation in medical and space science applications using DIANE framework and the GRID. *Nuclear Physics B - Proceedings Supplements*, 125, 327-331.

Murray, F. (2004). The role of academic inventors in entrepreneurial firms: sharing the laboratory life. *Research Policy*, 33(4), 643-659.

NAO. (2007). Big Science: Public investment in large scientific facilities, Report by the Comptroller and Auditor General: National Audit Office.

Nelson, R. R. (1959). The simple economics of basic scientific research. *The Journal of Political Economy*, 67(3), 297-306.

Nordberg, M., Campbell, A., & Verbeke, A. (2003). Using customer relationships to acquire technological innovation: A value-chain analysis of supplier contracts with scientific research institutions. *Journal of Business Research*, 56(9), 711-719.

OECD. (2008). *The Global Competition for Talent Mobility of the Highly Skilled*. Paris: OECD.

Patil, R. S., Fikes, R. E., Patel-Schneider, P. F., Mckay, D., Finin, T., Gruber, T., et al. (1997). *The DARPA knowledge sharing effort: progress report*. San Francisco, CA: Morgan Kaufmann Publishers Inc.

Pavitt, K. (1991). What makes basic research economically useful? *Research Policy*, 20(2), 109-119.

Phan, P. H., Siegel, D. S., & Wright, M. (2005). Science parks and incubators: observations, synthesis and future research. *Journal of Business Venturing*, 20(2), 165-182.

Phillimore, J. (1999). Beyond the linear view of innovation in science park evaluation An analysis of Western Australian Technology Park. *Technovation*, 19(11), 673-680.
Phillimore, J., Joseph, R., & Larisa, V. S. (2003). Science Parks: A Triumph of Hype over Experience? In *The International Handbook on Innovation* (pp. 750-757). Oxford: Pergamon.
Ponomariov, B., & Boardman, P. C. (2008). The effect of informal industry contacts on the time university scientists allocate to collaborative research with industry. *The Journal of Technology Transfer*, 33(3), 301-313.
Quintas, P., Wield, D., & Massey, D. (1992). Academic-industry links and innovation: questioning the science park model. *Technovation*, 12(3), 161-175.
Salter, A. J., & Martin, B. R. (2001). The economic benefits of publicly funded basic research: a critical review. *Research Policy*, 30(3), 509-532.
Schissel, D. P. (2006). The collaborative tokamak control room. *Fusion Engineering and Design*, 81(15-17), 2031-2037.
Schissel, D. P., Burruss, J. R., Finkelstein, A., Flanagan, S. M., Foster, I. T., Fredian, T. W., et al. (2004). Building the US National Fusion Grid: results from the National Fusion Collaboratory Project. *Fusion Engineering and Design*, 71(1-4), 245-250.
Shearmur, R., & Doloreux, D. (2000). Science parks: actors or reactors? Canadian science parks in their urban context. *Environment and Planning A*, 32(6), 1065-1082.
Shrum, W. (2000). Science and story in development: The emergence of non-governmental organizations in agricultural research. *Social Studies of Science*, 30(1), 95-124.
Shrum, W., Chompalov, I., & Genuth, J. (2001). Trust, conflict and performance in scientific collaborations. *Social Studies of Science*, 31(5), 681-730.
Siegel, D. S., Westhead, P., & Wright, M. (2003). Assessing the impact of university science parks on research productivity: exploratory firm-level evidence from the United Kingdom. *International Journal of Industrial Organization*, 21(9), 1357-1369.
Squicciarini, M. (2008). Science Parks' tenants versus out-of-Park firms: who innovates more? A duration model. *The Journal of Technology Transfer*, 33(1), 45-71.
SQW Consulting. (2008). Review of economic impacts relating to the location of large-scale science facilities in the UK: Final report.
Stokes, D. E. (1997). *Pasteur's Quadrant: Basic Science and Technological Innovation*. Washington, D.C.: Brookings Institution Press.
Tether, B. S., & Tajar, A. (2008). Beyond industry-university links: Sourcing knowledge for innovation from consultants, private research organisations and the public science-base. *Research Policy*, 37(6-7), 1079-1095.
Thorsteinsdottir, O. (2000). External research collaboration in two small science systems. *Scientometrics*, 49, 145-160.
Valentine, A. J. (2010). Comment on 'Big science, little science'. Embo Reports, 11(3), 152-152.
van Rijnsoever, F. J., Hessels, L. K., & Vandeberg, R. L. J. (2008). A resource-based view on the interactions of university researchers. *Research Policy*, 37(8), 1255-1266.
Vuola, O., & Hameri, A.-P. (2006). Mutually benefiting joint innovation process between industry and big-science. *Technovation*, 26(1), 3-12.
Weinberg, A. M. (1961). Impact of Large-Scale Science on the United States. *Science*, 134(3473), 161-164.
Westhead, P. (1997). R&D 'inputs' and 'outputs' of technology-based firms located on and off Science Parks. *R&D Management*, 27(1), 45-62.
Westhead, P., & Batstone, S. (1998). Independent technology-based firms: The perceived benefits of a science park location. *Urban Studies*, 35(12), 2197-2219.
Whitley, R. (1984). *The intellectual and social organization of the sciences*. Oxford: Oxford University Press.
Yang, C.-H., Motohashi, K., & Chen, J.-R. (2009). Are new technology-based firms located on science parks really more innovative?: Evidence from Taiwan. *Research Policy*, 38(1), 77-85.
Yusuf, S. (2008). Intermediating knowledge exchange between universities and businesses. *Research Policy*, 37(8), 1167-1174.
Zellner, C. (2003). The economic effects of basic research: evidence for embodied knowledge transfer via scientists' migration. *Research Policy*, 32(10), 1881-1895.