The societal footprint of big science

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The societal footprint of big science
A literature review in support of evidence-based decision making

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Abstract
Large-scale 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-scale 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-scale research facilities produce economic and social impacts. The literature provides no direct, empirical evidence to show that such impacts actually occur around large-scale research facilities. There is insufficient evidence to support the claim that they attract and retain talent and promote innovation. More evidence exists that large infrastructures forge new networks and communities. Empirical research on large-scale research facilities and their effects on science, economy and society is sorely needed.

Keywords: big science; large-scale research facilities; evaluation; knowledge spillovers; innovation; social interaction; research collaboration

1. Introduction
Big science requires big budgets. Large-scale research facilities are among the most expensive items of scientific expenditure. 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 financing is a national matter, national roadmaps each plan 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. The societal benefits of scientific research are more uncertain, take longer to materialise, and are more difficult to substantiate (Martin & Tang, 2007). This is why any decision to invest in the knowledge infrastructure should be based on sound evidence and a careful consideration of options.The need for a careful 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). Even so, there is a surprising lack of evidence on the nature and extent of the impacts of large-scale research facilities on the economy and society and on the mechanisms that generate such effects.

What we do know is biased towards the demands of 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). There is a clear need for studies that focus on the effects of scientific infrastructures as such (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.

In this paper we review the extant literature to determine the net benefits to society of organising research on a large scale, in distributed collaboration or on a specific geographic location. The central question is whether or not and, if so, through which mechanisms research facilities produce economic and social impacts.

The rationale behind investments in big science is clear: large, state-of-the-art research facilities help raise the potential for scientific advances, improve the competitiveness of national science systems, and encourage economic innovation. We will focus specifically on three assumptions that are used to justify investment decisions, to evaluate investment proposals ex ante, and to test research facility performance ex post. Large-scale research facilities:

1. attract talented researchers from abroad and help retain domestic talent for science;
2. directly and indirectly promote innovation;
3. are a focal point for collaboration among a multitude of actors.

In section 2 we give a brief definition of a research facility and discuss its dual nature of complex capital good and social construct. In section 3, we show that many large facilities have an explicit societal aim. In these cases societal impact is endogenous to science. The focus of this review, however, is on the large set of research facilities that have a predominantly scientific function.In section 4 we review direct evidence for the economic and social impacts of such research facilities. Section 5 looks at organisational and geographic concentrations of resources comparable to large-scale research facilities and approaches the problem from an indirect angle. Finally, in section 6 we draw conclusions with respect to the three key assumptions, discuss the increasing distributed and virtual nature of research facilities, and formulate a research agenda.

2. What are large-scale research facilities?

It is important to understand the dual nature of a research facility. A large-scale research facility is a complex capital good with an advanced technological core that is state-of-the-art at the time of construction. It is also a social construct incorporating the objectives and expectations of a diverse range of actors. Effects on economy and society depend on both identities.

Research facilities are, first of all, one of the resources used by scientists, a tool for science. Scientific researchers mobilise resources to produce knowledge. They hire other researchers; they design and construct laboratories, databanks, and other research facilities; they build social networks; and they accumulate and apply knowledge and experience. The production factors used in scientific knowledge production are dynamically interrelated with each other and with their institutional, technological, spatial, and socio-economic environment (Bonaccorsi, 2008; Carayol & Matt, 2004).

The development and use of capital goods in knowledge production depends on other resources. 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. A research facility is in constant dynamic interaction with its environment. Large-scale facilities are more than just expensive. They require such vast resources that they can generally only be realised by means of multi-institutional and often multidisciplinary collaboration as well as substantial public support, frequently from several funding sources. This implies that large-scale facilities involve a wide array of scientific and non-scientific actors with their different objectives and expectations. It takes effort to reconcile the motivations and interests of a multitude of actors, and the outcome depends as much on this social process as on the initial technical design. When research groups collaborate in a research facility, the final design will be the outcome of negotiation and may satisfice rather than satisfy each group.

3. Economic and social impacts of 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). Large research facilities are commonly classified in the domain of basic science.These boundaries are, however, becoming more diffuse. Gibbons et al. (1994) witness the rise of Mode-2 as a new system of knowledge production. 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 nature and expertise of the parties involved (Hessels & van Lente, 2008). 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 emergence of new cooperative or “mixed-type” R&D laboratories in the United States illustrates this development (Bozeman & Crow, 1990). It follows that generating societal impacts is becoming endogenous to science. As we will argue, this is also true for large-scale facilities.

Large-scale research facilities require significant amounts of funding during their entire lifespan. 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 social construction of large-scale research facilities can internalise the realisation of societal impacts.

Many research facilities exist for scientific purposes only, and economic and social impacts are generated more or less by accident. But for other facilities, the impact on economy and society is laid down in their 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.
We have applied the ‘research compass card’ (Larédo & Mustar, 2000) to an inventory of large-scale research facilities in the Netherlands that was made in 2008 (Horlings & Versleijen, 2008). A research compass card maps an institutions’ activity profile in five dimensions (Figure 1): 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 it is determined by the degree to which a laboratory is active in each of the five dimensions. Activity profiles can serve as an alternative to the conventional distinction between fundamental and applied research.

Figure 1 schematically shows where the activities of Dutch large-scale research facilities are focused in terms of the five dimensions. The 66 facilities were divided into four groups, depending on their mission and the parties with whom they collaborate. Scientific research is the primary objective of 29 facilities that are used for research as well as (higher) education. The seventeen facilities of the five large, applied-science technological institutes are located between science and innovation. Fifteen facilities combine a primary societal goal – e.g. public health protection – with a secondary scientific goal or have a mixed societal-scientific mission. Five facilities form the ICT backbone of Dutch science that is public and shared.
Of the 66 large-scale research facilities in the Netherlands, 37 facilities (almost 60%) are explicitly and primarily intended for the production of economic and social benefits. Such facilities have been designed to carry out a public task, such as the protection against infectious diseases or the conservation of cultural heritage. Their costs are not paid for from research funding and are justified using arguments that are relevant to their primary task;

their scientific mission is secondary. While this lends further support to the integration of science, economy and society, it shows that societal impacts can be inherent to the design of research facilities. This creates opportunities for joint investments in research facilities by public and private actors. The challenge is to identify the societal footprint of facilities with a primary scientific mission.

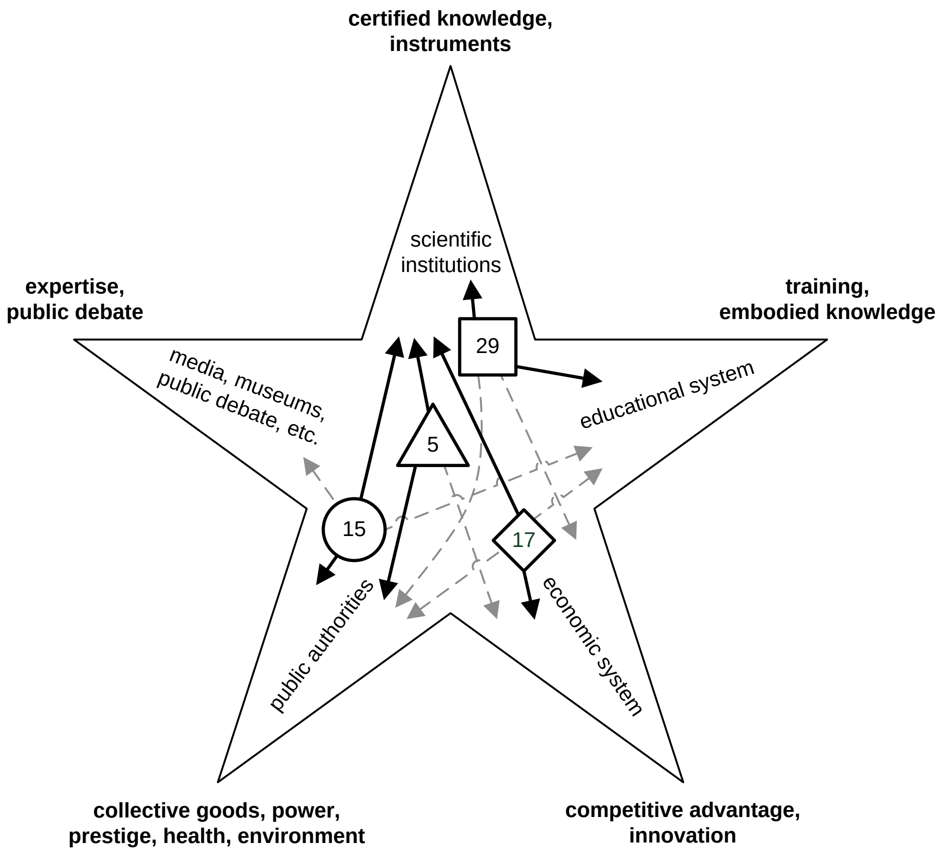

Figure 1. Primary and secondary activities of large-scale research facilities in the Netherlands

Note: Thick, black lines indicate primary activities; dashed, grey lines indicate secondary activities.
Source: Horlings and Versleijen (2008). Based on Larédo and Mustar (2000).

4. Direct evidence for societal benefits of research facilities

The small body of literature that deals directly with the economic, social, and other impacts of large-scale research facilities roughly consists of three streams. First, there is number of studies on innovation and social network formation around CERN. These studies were inspired by the phenomenal 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 ‘ordinary’ big science. There is some information in policy studies, most notably a recent study of the economic impacts of British facilities. Finally, there are numerous case studies of innovative and collaborative projects within big science centres (e.g. MacEachren et al., 2006; Schissel, 2006). This section presents the summary outcomes of the first two streams.

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 big science 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 science centre, such as CERN, encourages private sector innovation. They aim to expose the mechanisms that govern the interactions between big science 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 big science centre 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 big science facility – academia, government, and industry – are systematically compared. These motivations provide some understanding of the assumptions on the possible effects of collaborating in a big science centre.

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. Big science centres and firms are both looking for new technologies. Large-scale 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 big science centre, 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, big science centres 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). Big science centres 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 big science centres 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 et al. (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 ordinary national 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 scientific value of big science facilities is beyond dispute: they are considered of extreme value to the UK science system. The main non-scientific benefits of a large-scale 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, big science 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 big science markets. 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

These modest strands of research lead to two tentative conclusions. First, the main mechanism through which research facilities affect economy and society is social. Large-scale 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 big science centre is a pure business opportunity and is more likely to offer gains in reputation than in innovation.

Table 1. Summary of direct evidence

Effect	Summary of evidence
Attract talented researchers	No empirical evidence.
Promote innovation	Large-scale 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.

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 big science market may be small and highly specialised, each individual facility does have mass. There is some evidence (from the UK) that having a large-scale 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-scale research facility on innovation appears to be formal and informal social interaction. The formation of heterogeneous networks and collaborations around large-scale 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-scale research facilities. We have some idea of the effects generated in CERN, but CERN is not an ordinary facility. The evidence regarding five ‘ordinary’ 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.

5. 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 direct evidence by extending the scope of our review to studies that examine objects with properties similar to those of large-scale research facilities. We can compare facilities with universities, science parks, public R&D laboratories, and multi-institutional or multidisciplinary research programmes.

In this section, we bring together the results of scientific studies into the individual defining characteristics of large-scale 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-scale 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).[1]

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 public R&D organizations, Bozeman does provide some indication of the potential for knowledge transfer of large-scale research facilities. Like federal R&D laboratories they 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

[1] 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).

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).

Advanced research facilities are said to have a strong attraction on talented researchers, particularly from abroad (ESFRI, 2006; OECD, 2008). We found no evidence to support this claim. There have 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-scale 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-scale research facilities are single-sited concentrations of researchers, advanced equipment, large installations and research space. There is no direct evidence on the localised impacts of research facilities, but the literature on science parks may provide an

[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.

indirect answer. Their high-tech nature and close spatial concentration of resources might make science parks a good analogy for a large-scale 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).

Large-scale 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-scale 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-scale 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-scale 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-scale 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-scale 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 scale research facilities? We should be careful in transferring evidence on universities and government laboratories to the context of large-scale research facilities. At best, the literature provides analogies. Large-scale research facilities cannot be compared with universities. 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-scale facilities. The same limitations apply when comparing public (R&D) laboratories or science parks with facilities.

The conclusions relate mostly to innovation, knowledge transfer, and the regional economy. To the extent that a large-scale 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 will be more modest than those associated with universities, public research laboratories, and science parks. In terms of resources, large-scale research facilities are an order of magnitude smaller and they are less diverse.

The “technological imperative” of scientific collaboration offers perhaps the strongest indication of potential societal impact. Large-scale 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-scale research facilities are unlikely to replicate the impacts of a university or achieve the agglomeration effects of an entire science park. A large-scale 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-scale 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-scale research facilities.

Table 2. Summary of indirect evidence

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-scale 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. 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 60% of large-scale facilities has a non-scientific primary mission. Yet, there remains a lack of empirical evidence on the societal impacts of primarily scientific large-scale 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-scale 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 evidence to support the claims that large-scale 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-scale 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 big science 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 moderate. Research facilities are generally an order of magnitude smaller.

There is consistent and convincing evidence that 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-scale 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 direct empirical evidence.
More research is needed, specifically to collect empirical evidence on the effects of research facilities on innovation, researcher mobility, and collaboration. If the societal footprint of big science 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-scale facilities must be the primary touchstone. Building political support and gathering the required financial resources calls for motivations that appeal to a wider audience, especially when funding is scarce. The opportunity costs of large-scale research facilities should be made explicit.

Our current, limited understanding of the economic and social impacts of large-scale 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 infrastructures as a substitute for conventional single-sited infrastructures.

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-scale 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 big science on their environment. The scientific, technological and social evolution of big science remains dynamic.

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