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Developing Photonics Clusters

Commonalities, Contrasts and Contradictions

Jörg Sydow, AIM International Visiting Fellow and Free University of Berlin
Frank Lerch, Free University of Berlin
In Association with:
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Paul Hibbert, AIM Research Fellow and University of Strathclyde

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Contents

1 Introduction

Regional agglomerations or clusters of specialised firms and other organisations, in particular industries, have been around for centuries and have been a subject of research for decades (for an overview see Porter 1998a: 206-208; Enright 1998, 2003). Obviously, this is true for traditional industries such as apparel (Sabel et al. 1989; Powell 1990; Lazerson 1995), shoes (Becattini 2002), coal and steel (Grabher 1993), watch-making (Glasmeier 1994) and machine-building (Heidenreich and Krauss 1998). But even younger and still emerging high-tech clusters have already been intensively studied (e.g. Saxenian 1994 on ICT in Silicon Valley; Powell et al. 2002, Cooke 2004 and Di Tommaso et al. 2006 on biotechnology and life sciences; Braunerhjelm et al. 2000 on polymers; Martinez-Fernandez and Leevers 2004 on nanotechnology). Nevertheless, it is still quite unclear how clusters, in particular innovative high-tech clusters, develop – and are developed.

Photonics, which is the subject of this report, is a high-tech field that has recently received a lot of managerial and political attention and which is often considered the key technology for the 21st century. Although the field is new, it has already been subject to serious research (Hassink and Wood 1998; Hendry et al. 1999; Hendry et al. 2000). With this report, we aim not only to add a second (comparative) study, but also to provide insight in somewhat more depth about developmental aspects of clusters in this industry. At the same time we aim to contribute, in more general terms, to the exploration of innovative high technology clusters. While most former studies of high-tech clusters can be characterised as rather static comparisons, we pursue a more processual perspective on photonics clusters in different countries, giving the evolution of clusters and their intentional management equal attention.

Starting from Porter's understanding of industrial clusters, our notion of clusters builds on insights from a structuration network perspective (e.g. Sydow et al. 1998; Sydow and Windeler 1998, 2003; referring to Giddens 1984). This puts more emphasis not only on processes, but also on networks of relationships and their reproduction in this specific kind of social system. Further, we look more deeply into governmental issues and micro-processes of clusters that are not usually the focus of attention in studies based upon industrial economics or regional sciences perspectives. By adopting a more dynamic perspective, that has increasingly been asked for (e.g. Breschi and Malerba 2005), we address a number of managerial and policy issues in developing clusters. Most particularly, however, we highlight the commonalities and contrasts between photonics clusters developing and being developed in the United States, Great Britain and in Germany – and possible contradictions with the dominant Porterian understanding of clusters that can be inferred from our investigations.

2 Developing Clusters

The importance of regional clusters for the competitiveness of nations was explained by 'industrial district' researchers in Italy (e.g. Brusco 1982) popularised by Michael Piore and Chuck Sabel (1984) and somewhat later taken up in industrial and regional economics by Michael Porter (1990) and Paul Krugman (1991) respectively. These latter, in particular, argued that improving productivity was driven by strong domestic competition between rival firms in a particular location, thus requiring firms to become more efficient and innovative. While domestic rivalry puts competitive pressure on incumbent firms to invest in those (company) resources that most effectively enhance the particular firm's competitive advantage, geographic concentration also enables the interaction of organisations and the exchange of knowledge within a particular location and industry. These forces and regional-industrial clusters in general are said to increase productivity and the innovativeness of incumbent firms and to stimulate the formation of new businesses (Porter 2000: 21-25). In consequence, clusters are considered to promote the economic growth and competitiveness of regional and thus national economies (Andriani et al. 2005: 13-16).

2.1 Structural Properties and Processual Analyses

Much of the research on clusters has concentrated on their structural properties that are already reflected in the most prominent definitions. Porter (1998a: 197) defines clusters as "geographic concentrations of interconnected companies, specialised suppliers, service providers, firms in related industries, and associated institutions (for example, universities, standards agencies, and trade associations) in particular fields that compete but also co-operate." Rosenfeld (1996, 1997) points to the importance of social infrastructure (e.g. shared meaning systems, norms of reciprocity and sufficient levels of trust that are embedded in professional, trade and civic associations and in informal socialisation patterns (Rosenfeld 1997: 10) in order to facilitate the exchange of information and knowledge in clusters. He defines clusters as "a geographically bounded concentration of interdependent businesses with active channels for business transactions, dialogue, and communications, … that collectively shares common opportunities and threats". He highlights more processual aspects by arguing that the "flow of information, technological advances, innovations, skills, people, and capital into, out of, and within the cluster, from point to point" (Rosenfeld 1997: 8-10) are equally important for achieving agglomeration economies in a working cluster as are scale or critical mass.[1] However, in order to be an effective cluster, social interaction, trust, and a shared vision need to be present in order to generate the dynamic nature of a cluster.

Many structural properties of clusters are mentioned in these definitions as either constitutive for clusters or complementary (see Table 1), the core elements of these and other definitions, i.e. the collaborative and competitive linkages of firms and the geographic proximity of groups of interlinked companies and other organisations, remain largely unspecified, leaving the cluster concept somewhat ambiguous (Martin and Sunley 2003). On the other hand, it is this very ambiguity that provides interested agents, managers and politicians in particular, with a degree of conceptual flexibility that may be quite helpful for a variety of policy approaches (Jacobs and de Man 1996).

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[1] Other concepts for regional development like 'innovative milieu' (Malliat 1991), 'regional innovation system' (Cooke 2004) or 'learning region' (Morgan 1997) also consider this interactional or relational dimension as a constitutive feature of clusters. For a discussion of these and other cluster-related concepts see Rocha (2006).

Table 1: Structural properties of regional clusters*

Sophisticated local customers and downstream-industries
Competitive related industries
Suppliers of complementary goods and services
Capable locally-based specialised suppliers of goods and services
Accessible financial services
Innovative core companies and original equipment manufacturer (OEM)
Locally-based competitors
Sophisticated local labour market
Involvement of the local education system
Research and development and knowledge transfer infrastructure
(Trade and labour) associations
State actors and regional economic development
Critical mass of organisations
Intensive inter-organisational interaction
Shared visions and inter-organisational trust

* Based on Porter (1998a), Enright (1999), Pfaehler and Lublinski (2003).

As indicated above, while most of the previous research has investigated the competitiveness of clusters by focussing on their structural properties, we look primarily into relational processes of deliberate and emergent cluster development. We suggest that such a relational perspective requires that *networks in clusters* are considered to be at the heart of such phenomena and transcend the Porterian focus on geographic concentration and functional interconnection (see also Staber 1996; Lazerson and Lorenzoni 1999; Keeble and Wilkinson 2000; Wilson and Popp 2003). A recent study of the Motor Sport Valley cluster in England, which argued "that knowledge movement between firms is important to network development, including within regional clusters, but that this movement is tied to a partially formalised network rather than being (1) tied to the cluster as a whole, and (2) a free good for all cluster members" (Tallman and Jenkins 2002: 169), supports the utility of a *networks in clusters* perspective. Going further, a processual understanding in general and a structurationist network perspective in particular suggest that these networks (in clusters) are as much an *outcome* of action as an – enabling and constraining – *condition* of interactions.

Processual analyses of the evolution and development of clusters have often been presented in the form of stylised life-cycle models (e.g. Porter 1998a: 237-245; Andersson et al. 2004: 29-30). In the literature, such models distinguish a number of identifiable phases. In a first 'agglomeration phase' or 'embryonic stage', a cluster exhibits a number of unconnected firms and other organisations. In a second phase, sometimes called 'emerging cluster', a number of actors begins to collaborate around a central theme or activity. In the following phase of a 'developing cluster', new actors emerge or enter the cluster and new linkages between already present actors develop. The cluster becomes internally and externally visible, often through a label, name or association, and a common identity appears. Only a 'mature cluster' contains a critical mass of firms and other supporting organisations and displays a complex web of relationships between these actors within the cluster and established links to other clusters. Finally a 'transformation' of the cluster appears to be necessary in order to adapt to changes in markets, technologies and processes. However, it is very doubtful that every cluster follows these linear stages in a deterministic manner. Going further, the proposed phases might not be identifiable at all due to unclear and rather unspecified criteria.

Though these models may give managers and policy makers a general orientation, they may also be quite misleading (because of their deterministic and arbitrary nature) if applied prescriptively to the development and management of a specific cluster.

2.2 Structuration and Management of Clusters

In sharp contrast to such allegedly generalisable life-cycle and phase models we assume that each cluster develops – and is developed – in a non-linear, rather unique way of structuration processes more or less controlled by the cluster and organisational management. Though it is an important task for researchers to identify certain developmental patterns over time, these are likely to be quite idiosyncratic, i.e. cluster- and context-bound, and, eventually, even path-dependent – thus questioning the applicability of general managerial principles, not to mention so-called 'best practices'. More precisely, and in line with a structurationist network perspective that paves the middle ground between evolutionary and interventionist approaches, we expect cluster development to be influenced by (rather than independent of):

- the initial structural conditions of the cluster, its member organisations and the wider organisational field in which it is embedded;
- the reproduction and transformation of these structures by the very practices of more or less knowledgeable agents. These knowledgeable agents – as individuals as much as organisations – refer to these structures in their practices, whereby they are themselves embedded in a network of relationships. According to Giddens (1984) these structures are rules and resources;
- the impact of organisational entry, change and exit on the cluster because of this relational embeddedness, in particular if relations are more tightly rather than loosely coupled;
- the individual and organisational actors who, despite their knowledge and their ability to learn, have to reckon with unintended consequences, not least in face of unacknowledged conditions, and the ability of other agents to act differently.

Although this conceptualisation of cluster development as a more or less reflexive structuration process that is contingent upon network management – as 'reflexive social practices' (Sydow and Windeler 2003) – will be influenced by the developmental 'stage' or 'phase' of the network or cluster, we are sceptical about using life-cycle and phase models. This is because we argue that the concrete development of a cluster – or a network in the cluster – is to a large extent dependent upon the interactions of the cluster members, even though they are not able to fully control the cluster evolution by means of intervention. However, this does not mean that individual networks or clusters cannot be usefully described *ex post facto* by distinguishing certain developmental phases (see Sydow 2004 for an example).

2.3 Blurring Boundaries of Clusters

The processual, relational perspective thus challenges conventional approaches to understanding clusters through structural analyses alone. There is, however, a further challenge to such approaches. That is the growing number of situations that begin to undermine the geographic delimitation central to understanding cluster development. Whilst the geographical boundaries of traditional industries that have featured in cluster research (such as wine and shoemaking) can be reasonably clearly defined, studying high-tech clusters in general, and photonics clusters in particular, is significantly more problematic. For the boundaries of these clusters are much more blurred, especially in the case of enabling technologies such as photonics. The blurring is exacerbated in *global* cluster alliances, which are quite common in high-tech fields (see Section 3.4). Moreover, the development of such high-tech clusters seems to be much more dynamic, implying a possible shifting and re-shifting of the cluster boundaries and identities over time.

Sometimes agglomerations of specialised organisations, not least in emerging fields of new technologies, are called 'clusters' although they do not fulfil all of the conventional structural criteria mentioned – or even the most important, constitutive criteria. This would be the case, for example, if a critical mass of organisations were co-located, but did either not show the necessary degree of inter-organisational interaction or embrace enough stages of the value chain. Though other concepts (e.g. 'innovative milieu' or 'regional innovation systems' (see footnote 1)) or entirely new models may be more appropriate under these circumstances, the notion of cluster continues to be used since it seems to be attractive for managers, researchers, and politicians alike.[2] When studying developmental processes in so-called 'clusters' in the field of optical technologies/photonics in the United States, Great Britain, and Germany, we are aware of this kind of symbolic aspect.

Summing up and acknowledging the problematic state of the concept and the difficulties in applying it to high-tech fields such as photonics, we see a cluster as consisting of a critical mass of rather specialised organisations operating *and* co-operating in geographic proximity in related organisational fields. Specialisation within each field requires (vertical) collaboration along different stages of the value chain but does not exclude (horizontal) co-operation among competitors. The rather intensive economic and social interaction among these organisations – supported by and reflected in networks of inter-organisational relationships – may either emerge as in the case of so-called 'industrial districts' or result from deliberate action as, for example, incorporated in many regional developmental programmes. Mostly, it will be a combination of both, evolution *and* intervention, but in any case be based upon cluster *rules* of signification and legitimation; that is, upon shared understandings and common norms. Moreover, *resources* (of domination) are needed that agents can draw on and that are related or even pooled in the cluster, i.e. 'cluster resources'. Even if collaborative networks of rather complex and reciprocal relationships develop in a cluster, based upon such rules and resources, this does not exclude moments of competition.

The notion of 'networks in clusters' aims to capture this relational dimension of clusters that is, from our and others' perspective, as important as the timespace dimension of such systems, i.e. the regional agglomeration of organisations and the development of inter-organisational interaction and relationships over time (as already alluded to in the work of Rosenfeld 1996, 1997; see also, once again, footnote 1). However, it is important to recognise that we would consider a cluster to embrace the totality of such relational webs rather than only those between the formal cluster members. That is, non-members that belong to the same industry, are situated in the particular region, and interact either with each other or with formal cluster members are considered part of the cluster. Nevertheless, formal membership roles in a cluster such as those of the CEO of a 'network administrative organisation' (NAO) (Human and Provan 2000) or of the board members of a regional industry association or interest group leaders are important in the developmental process of a cluster and need to be considered.

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[2] The very recent 'High-tech Strategy' of the German Federal Ministry of Education and Research (www.bmbf.de) builds again largely on developing regional clusters, not least in high-tech industries.

3 Introducing the Field of Photonics

Before giving an overview of important photonics clusters in the world and, going further, describing the first inter-cluster alliances that have more recently emerged in this area, photonics is introduced as a technological and economic field.

3.1 What is Photonics?

Though optics or photonics (used here synonymously) have only quite recently received a lot of attention, they have a rather long history. The classic scientific text *Opticks* on the fundamental principles of reflection and refraction was published by Isaac Newton as early as 1704. The advent of modern optics, however, can be seen in the publications of Albert Einstein and Max Planck at the beginning of the twentieth century, which finally led to the development of the first laser in 1960. This has made fibre optical communications, laser surgery, and laser material processing possible. Other examples of high impact, but maybe less obvious developments in optics, include optical lithography systems, high resolution microscopes, adaptive optics for ground-based astronomy and highly efficient lighting systems (see also National Research Council 1998: 5-6).

There is no standard definition of optics or photonics. The field of photonics today is characterised by a wide variety of high technology applications and products. The term photonics is often used synonymously with the term opto-electronics (the fusion of optics and electronics) or modern optical technologies. The Canadian Advisory Council on Science and Technology (http://acst-ccst.gc.ca) defines the applications of photonics as "the acquisition, processing, communication, storage, and display of information". The Photonics Directory (www.photonics.com) defines photonics as "the technology of generating and harnessing light and other radiant energy whose quantum unit is the photon". The U.S. National Research Council (1998) defines optics as the "field of science and engineering encompassing the physical phenomena and technologies associated with the generation, transmission, manipulation, detection, and utilisation of light." The quantum unit – the photon (the fundamental particle of light) – can be utilised by optical components and instruments, lasers and other light sources, fibre optics, electro-optical instrumentation, related hardware and electronics, and sophisticated systems (SPIE 2006). A recent Department of Trade and Industry (DTI 2006) strategy paper applies a very broad definition of the photonics industry, stating that it refers to "those organisations for which the manufacture or use of photonic enabled products is a key aspect of their business", and where photonic enabled products are "products that would not be possible without their photonic content".

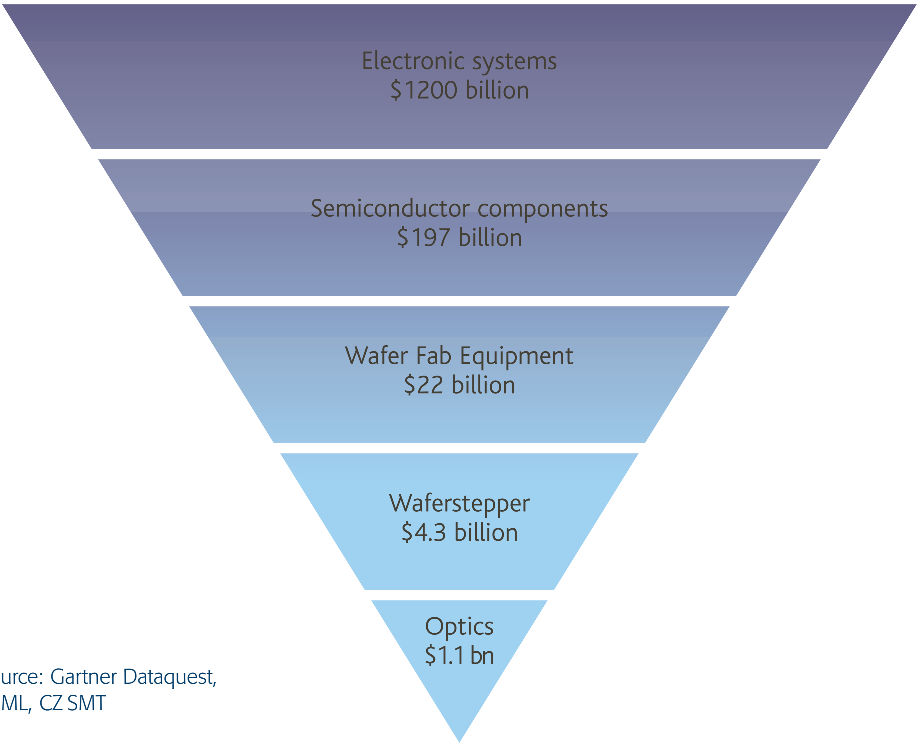
3.2 The Photonics Industry and its Impact

The variety of applications of photonics is vast and extends from optical sensing, lighting and the generation and detection of energy to communication technologies and information storing, transmitting, processing and displaying, but also to optics in manufacturing and applications in other industries such as life sciences, automotive, aerospace and many others. Well-known photonics applications include IR remote controls, CD and DVD players, digital cameras, computers, mobile phone and TV screens, fibre optics. Novel photonics technologies include LED (Light Emitting Diode) lighting and OLED (Organic Light Emitting Diode) displays, biophotonics, fempto-second technologies, uv- and x-ray technologies, diode lasers, and sensing.

As already stated, photonics is an *enabling technology* and, as implied above, has had and has a dramatic economic impact. With its extraordinarily broad spectrum of means and ways of generating, amplifying, transmitting, measuring and utilising light, photonics affects most parts of modern every day life and economic activity. This leverage effect can be impressively demonstrated in the field of manufacturing technologies, for example. Here the utilisation of reliable low-cost lasers and laser-imaging- and -sensing systems is critical in a number of contemporary manufacturing industries including laser material processing in the automobile and textile industry, chemical production, and – last but not least – semiconductor manufacturing.

Computers, the internet and mobile phones would simply not exist in the way we know them today without the availability of laser light and optics in manufacturing processes. The production of every semiconductor microprocessor or memory chip that is mass-produced in the world today relies on optical lithography. In 1998 the lithography equipment (machinery necessary to produce integrated circuits) industry had a market value of 'only' $1 billion, but ultimately enabled a $200 billion electronics business (National Research Council 1998: 3). In 2004 not only the 'food chain' of the electronic systems market dramatically increased (see Figure 1), but also the ratio between wafer stepper equipment and electronics systems increased, (to 1:280), further increasing the leverage effect of photonics as an enabling technology. In summary, photonics can be considered as a key enabling technology that is cutting across other technologies and industries and thereby establishing an essential basis for further technological advances and applications in other industries.

Figure 1: 'Food chain' of the electronic systems market (as of 2004)



Source: Gartner Dataquest,
ASML, CZ SMT

The size of the worldwide photonics industry is rather difficult to estimate, due to the blurred boundaries of the industry and its reach into other industries. However, an early assessment reports worldwide sales of photonics products of $55 billion in 1998 and predicts annual growth rates of between 10 and 20% (Arizona Optics 1999). In 1999 the German VDI, the Association of German Engineers, identified a worldwide market potential of approximately $82 billion as well as anticipated annual growth rates up to 20% (www.vdi.de). A large number of these over-positive predictions led to and were part of the so called telecoms market bubble that burst in 2000/01, affecting a large proportion of the photonics industry worldwide, especially those organisations specialising in opto-electronics for telecommunication applications. As a result, in the following years private investments and governmental funding for research were withdrawn from the industry. However the consolidation of the industry led to a more robust growth path in the following years; by 2005 the world photonics market had grown to $120 billion and is expected to double by the year 2015 (Spectaris 2006). Another rather conservative estimation for the photonics world market in 2005 totals more than €150 billion, of which about 40% relate to information and communication technologies.

Further, it is pointed out in this report that annual growth rates of the photonics industry dramatically surpass those of the general economy (e.g. laser sector +14% for the past 10 years; optics and photonics in life sciences +38%). The future prospects are also promising; as a result, the total photonics world market is expected to at least triple within the next 10 years (Photonics 21 2006). Focusing on the European photonics industry, a report compiled for the European Commission by European photonics industry leaders, science representatives and associations speaks of €60 billion worth of products, 500,000 jobs in the EU and 15,000 patents as an estimation for 2003 and predicts €250 billion worth of products, 1.5 million jobs in the EU and 45,000 patents in 2010 (Niehoff and Pearsall 2004).

While the photonics industry is in large part characterised by small and medium-sized enterprises (about two thirds are SMEs), co-operation between large and small companies as well as between firms and research organisations is very common. This is because innovations in optics or photonics are often interdisciplinary in nature and one organisation rarely has all of the resources and competences necessary in the innovation process. On a global level, it is obvious that in the photonics industry large volume production is (increasingly) located in low-cost countries, predominantly in Asia. High value-added engineering and complex systems level integration, however, seems still to be located in the so-called advanced industrial nations. Another structural property of the industry is that global niche players are very common. Even very small photonics companies with a special competence have global reach and may control a significant share of the global market for which maybe only one or two (if any at all) other companies or even research organisations compete. As a consequence it is a characteristic of this industry that there are rarely entire supply chains present within a specific region. This, however, depends largely on the specific technology and the fields of application in question. In the area of devices for telecom applications, for instance, photonics companies generally follow a global sourcing strategy, whereas in the defence and security, and even in the scientific instruments sector, national and regional suppliers are likely.

3.3 Photonics Clusters: An Overview

Even though the field of photonics can be described as a relatively young high technology industry with a global reach, a number of established traditional clusters (in the past being based on classical optics) can be identified: Jena in Germany; Rochester, New York, and Tucson, Arizona, in the U.S.; and Wuhan in China. All of these are based on a long tradition of developing optics capabilities in the region. On the other hand, fairly recently a large number of newly developing photonics clusters have been observed. This development can partly be attributed to the advancement, differentiation and specialisation in photonics technology and the perceived need to work closely together with other competent actors, but also to local and national governmental initiatives that promote regional clustering activities. Above all, traditional as well as more recent photonics clusters, like other high-tech clusters (e.g. Tallman and Jenkins 2002; Powell et al. 2002) seem to profit significantly from spatial proximity allowing for more interpersonal and inter-organisational interaction, even across different ‘societal spheres’ (Giddens 1984) such as business and science.[3]

SPIE, the International Society for Optical Engineering, identifies quite a number of optics and photonics clusters in the world (see Table 2). Even though the list is not complete, it gives an indication of the occurrence of photonics clusters. Optics and photonics clusters are, according to SPIE, “concentrations of optics-related firms and universities that maintain strong research and workforce ties, create quality jobs, share common economic needs, and work with government and stakeholders to strengthen the industry” (SPIE 2006).

Photonics can therefore be seen as an international or even global field with regional concentrations. Cutting-edge research in this high technology industry is internationally linked because knowledge and competences are often so specific and only exist in a very small number of highly specialised organisations and products. On the other hand, components are often so specific that companies only find suppliers on a global basis.

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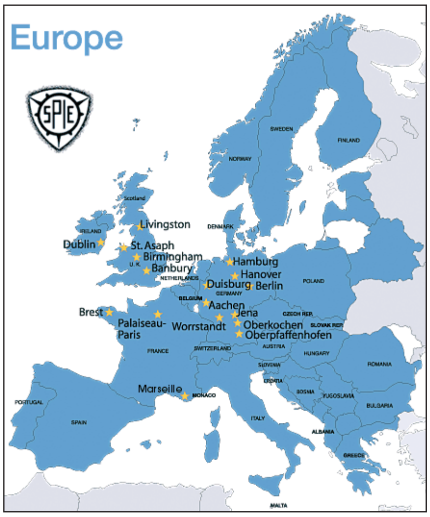
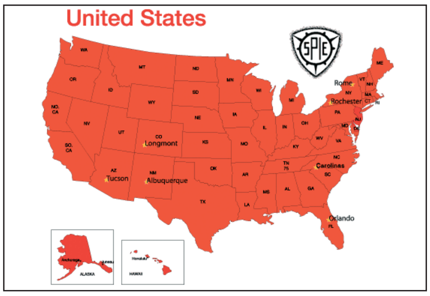
[3] See, however, Malmberg and Power (2005) for a more sceptical voice on knowledge creation and transfer in clusters.

Table 2: Photonics clusters in different regions



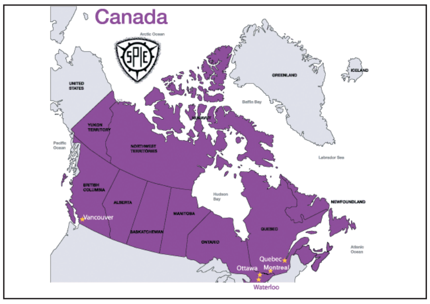
Europe

Bayern Photonics e.V.; Muenchen, Germany
Brittany Optics Coast; Brest, France
Hanse Photonik; Hamburg, Germany
Midlands Photonics Cluster; Birmingham, UK
Optics Valley France; Palaiseau – Paris, France
Optec-Berlin-Brandenburg e.V.; Berlin-Brandenburg, Germany
Optence e.V.; Darmstadt, Germany
OpTech-Net e.V.; Duisburg, Germany
OpTech-Net Deutschland e.V.; Hannover, Germany
OptoNet e.V.; Jena, Germany
Photonic Net; Hannover, Germany
Photonics BW; Oberkochen, Germany
PhotonAIX e.V.; Aachen, Germany
Scottish Opto-electronics Association; Livingston, UK
South East Photonics Network (SEPNET); Banbury, Oxon, UK
The Welsh Opto-electronics Forum; St. Asaph, UK



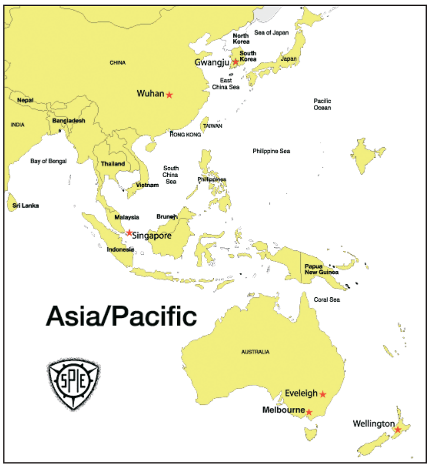
United States

Arizona Optics Industry Association; Tucson, Arizona
Carolinas MicroOptics Triangle; Western North Carolina and upstate South Carolina
Colorado Photonics Industry Association; Longmont, Colorado
Florida Photonics Cluster; Orlando, Florida
New Mexico Optics Industry Association (NMOIA); Albuquerque, New Mexico
Photonics Industry Association of New York; Rome, New York
Rochester Regional Photonics Cluster, Inc.; Rochester, New York



Canada

British Columbia Photonics Industry Association; Vancouver
Montréal Photonic Network; Montréal
Ontario Photonics Industry Cluster; Ontario
Ottawa Photonics Cluster; Ottawa
Quebec Optics and Photonics Association; Quebec



Asia Pacific

Australia Photonics CRC; Eveleigh, Australia
Korean Association for Photonics Industry Development; Gwangju-Jeonnam, Korea
New Zealand Cluster; Wellington City, New Zealand
Optics Valley of China; Wuhan, China
Singapore Photonics & Optics; Singapore
Victorian Photonics Network (VPN); Melbourne, Australia

Source: SPIE – The International Society for Optical Engineering (www.photonicsclusters.com)

However, as Table 2 indicates, advanced and high value added photonics activities appear to be present almost exclusively in the Triad Countries (Japan, North America and Western Europe) and there, more importantly, they are highly concentrated in specific regions. Prominent examples are Hamamatsu in Japan, Wuhan (Hubei province) and Changchun (Jiling province) in China, as well as South Korea and Taiwan, not to mention the regions around Jena and Berlin in Germany, around Rochester and Tucson in the United States, and ‘Silicon Glen’ in Scotland.

3.4 Photonics Cluster Alliances

In recent years some photonics clusters in the Triad have even begun to form inter-cluster alliances contributing to what is called a “transnationalisation of clusters [that] permits to preserve a local system of embedded ties, while favouring their international openness through a parallel system of arm’s lengths and embedded ties with foreign organisations belonging to other local clusters. In such a multiple embeddedness, frame innovation is favoured, home structure and culture of firms are subject to renewal, and the risks of lock-in and district sterilisation are reduced” (Zucchella 2006: 32). Furthermore, the dynamism of regional high-tech agglomerations appears to be attributable in part to their increasing interdependencies (see Saxenian and Hsu 2001 for an example in information technology). In 2005 the so called “Tri-Cluster Berlin-Tucson-Ottawa Alliance” between the photonics clusters in Berlin-Brandenburg, Tucson, Arizona, and Ottawa, Ontario, was formed. Representatives from these regions plan to: ease market access for cluster companies; increase exchange and communication amongst researchers and other cluster members more generally, including support for an international rotating summer school (of which the first was held in Berlin in Summer 2006) and the exchange of interns; promote the identification and achievement of synergies; and initiate a common website (‘Global Advantage’) for information proliferation. These cluster alliance activities are perceived as successful in the photonics community and other photonics clusters are beginning to imitate them and adopt alliances. This process can presently be observed at an early stage between the photonics clusters in Bavaria, Germany, and Québec, Canada.

Further photonics cluster alliances on a global level include the International Coalition of Opto-electronics Industry Associations (ICOIA), which was formed by 10 member associations in the U.S., Europe, the Pacific Rim and Australia: OITDA (Japan), OIDA (North America), PIDA (Taiwan), SOA (Scotland), KAPID (Korea), PAS (Singapore), OptecNet (Germany), HKOEA (Hong Kong), APF (Australia), and EPIC (EU). On a European level and primarily focused on education, the Optranet cluster collaboration should also be mentioned. This alliance started in 2003, involves five partner associations in Great Britain, Germany, Sweden, Poland and France and is supported by the European Information Society Technologies (IST) programme.

More recently, in early 2006, another cluster alliance in photonics was installed under the new Europe INNOVA initiative, which is supported by the European Commission under the 6th Framework Programme. Adopting a sectoral approach, Europe INNOVA aims to “inform, assist, mobilise and network the key stakeholders in the field of entrepreneurial innovation, including firm managers, policy makers, cluster managers, investors and relevant associations”. One of the 11 sectoral cluster networks, which are planned to provide a platform for exchange of analysis and good practice in cluster management (CORDIS News 2005), is the European Network of Optical Clusters (ENOC), which was established between photonics cluster institutions in Spain, France, Italy, Greece and the UK with the overall goal to “initiate partnerships and relationships between clusters throughout Europe” (European Commission 2006).

These photonics cluster alliances are either – as in the case of Optranet – confined to a specific domain or – as in the Berlin-Tucson-Ottawa Alliance – of a broader, multipurpose nature. These alliances either emerge from the specific needs of the participating clusters or are driven by national and, in particular, supranational government programmes. Though cluster alliances in all fields (i.e. not only in photonics) are still a rather new phenomenon, they are likely to spread. This is because they not only support the necessary embedding of regional high-tech clusters into the global economy but also conform to the prevailing Zeitgeist.

4 Case Studies of Photonics Clusters

In order to gain insights into how high-tech clusters in general and photonics clusters in particular develop and are developed, we conducted a comparative analysis of four clusters based upon semi-structured interviews with actors in the regions. Before introducing the four cases one by one and conducting a cross-cluster comparison, our method of data gathering and analysis will be presented in somewhat more detail.

4.1 Comparative Case Study Approach

The four photonics clusters studied were chosen not only because of the access we had, but also because of the significance of the respective photonics regions. The photonics clusters in Southern Arizona and Scotland are pioneers in organising their activities under the umbrella of a visible regional industry association. They were really the first in this technological field to build a cluster. Berlin-Brandenburg was chosen because of our already exceptionally good insights resulting from our involvement as researchers and, sometimes, consultants over a longer period of time.[4] Finally, the West Midlands cluster or, more formally, Photonics Cluster UK (PCUK) was chosen because it presents itself as a very aggressive and expanding new photonics umbrella organisation in the UK, particularly in England.

We have gained our insights in the Berlin-Brandenburg case on cluster development through an involvement that has now lasted for almost seven years. We conducted close to 10 personal qualitative semi-structured interviews in the summer of 2004 with the CEO of the NAO and with the spokespersons of the five technological interest groups. These interviews lasted on average 120 minutes. Additionally, we conducted 81 semi-structured telephone interviews with almost all the members of OpTecBB in 2004, in order to collect qualitative as well as quantitative relational data. In summer 2006, another round of 86 telephone interviews with the members of OpTecBB was conducted. These interviews lasted on average only 45 minutes and aimed mainly at gathering data for a quantitative (structural) network analysis (Lerch et al. 2006) but included also qualitative open questions. Further, in this case we used a broad range of qualitative methods such as participant observations of a number of strategy meetings, board meetings, roadmapping activities and other workshops, and we applied extensive document analysis of minutes, annual reports, master plans and roadmaps over the last seven years to gain detailed insight into the developing cluster in Berlin-Brandenburg.

In *Arizona* four qualitative semi-structured interviews were conducted in 2004/2005[5] with representatives of an SME, a very large company, a regional development agency and with Bob Breault, who has been the head of the Arizona Optics Industry Association for over fifteen years. Moreover a number of cluster activities were observed (board meeting, AOIA presentation) and documents analysed. Another round of seven semi-structured interviews in the Southern Arizona cluster was conducted in late 2006 and early 2007.[6]

In the *West Midlands* three PCUK members were interviewed in April 2006 (one representative of a local SME, one representative of a large internationally active company and one representative from academia). An additional two interviews were conducted with the head of the cluster organisation. Furthermore, a workshop with representatives from a cluster that will possibly collaborate with PCUK was attended.

In *Scotland* two rounds of interviews were conducted in October 2005 and in July/August 2006. Here a mix of representatives of SME, large companies, (university) research organisations, the regional development agency, a consultant and the regional industry association were interviewed. Three of the central representatives were interviewed twice in order to catch up with the more recent developments and to extend the data gathering on topics we were particularly interested in.[7]

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[4] This research is funded by the Berlin Senate of Economic Affairs with EFRD co-finance.

[5] The first round of interviews in Southern Arizona was sponsored by the German Research Foundation (DFG). The funds were granted to the first author who also thanks the Eller College of Management at the University of Arizona for its generous infrastructural support.

[6] This research was made possible by a DAAD short term PhD scholarship to the second author as well as by the generous research infrastructural support by the Eller College of Management at the University of Arizona.

[7] We thank the Advanced Institute of Management (AIM) Research for providing the funds enabling us to collect the data in the UK.

For a more detailed overview of the interviewees see Table 3. In all cases the questions focused on:

- the history of the cluster in the particular region;
- critical events in the cluster development;
- measures that foster collaboration, possible sub-structures that might have evolved or were implemented;
- the formal governance and actual leadership of the cluster.

Before the interviews were conducted, in all cases information from the internet, cluster newsletters and other documents were gathered and analysed. In all interviews, brochures and presentations were collected and included in the analysis.

Table 3: Interviews in the four clusters

Region	Time frame	Organisation	Type of interviewee
Berlin-Brandenburg (BB)	2000-2006	Max-Born-Institute for Nonlinear Optics and Short Pulse Spectroscopy	RO
		DLR (German Aerospace Centre)	RO
		Optical Institute (Technical University of Berlin)	RO
		MergeOptics GmbH	SME
		Clyxon Laser GmbH	SME
		OpTecBB e.V.	CR
Southern Arizona (SA)	2004/2005 and 2006/2007	University of Arizona, Economic Development Unit	RDA
		Southern Arizona Technology Council	RDA
		University of Arizona, Office of Economic and Policy Analysis	RO/RDA
		University of Arizona, College of Optical Sciences	RO
		Large Binocular Telescope, Steward Observatory	RO
		Optical Electronics, Inc (OEI)	SME
		Raytheon Missile Systems	LC
		AOIA	CR/SME
Scotland (SC)	2005/2006	Institute of Photonics (University of Strathclyde)	RO
		UK Astronomy Technology Centre (Royal Observatory Edinburgh)	RO
		Scottish Enterprise	RDA
		Photonix Limited	RO/SME
		Intense	SME
		Forth Dimension Displays Limited	SME
		Optimat Limited	E
		Thales Optronics	LC
		SELEX Sensors and Airborne Systems	LC
		SOA	CR/SME
West Midlands (WM)	2006	Photonics Research Group (Aston University, Birmingham)	RO
		Laser Optical Engineering Ltd	SME
		Bookham Technology plc	LC
		Photonics Cluster (UK)	CR

RO: research organisation; **SME:** small and medium- sized enterprises; **LC:** large company;
RDA: regional development agency; **E:** external expert; **CR:** cluster representative

Following Eisenhardt (1989), we first give an overall description of the four cases one by one, putting emphasis on the historic development of the cluster, the measures used to foster cluster development, and the formal governance structures. Then we conduct the cross-cluster comparative analysis. Generalising from the four focal cases is necessarily cautious given the qualitative research methodology employed, but the access and insight possible with such approaches provides some confidence that we have gleaned the rich detail required for an adequate understanding of the historical development and present management of the clusters. Furthermore, as will be shown below, the comparison of even the limited number of cases engaged within this study is sufficient to demonstrate that, even within one (high-tech) industry, clusters have developed and still are developing very differently.

4.2 Introducing the Cluster Cases

4.2.1 Berlin-Brandenburg: The Old and Young, Now Densely Connected Cluster

The region of *Berlin-Brandenburg* has a very long tradition in optical sciences and in the manufacture of optical instruments and related products. In 1801 and about 80 kilometres west of the city centre of Berlin, the Optische Industrie Anstalt zu Rathenow was founded and primarily produced glasses for spectacles, lenses and cameras. In Berlin a number of smaller companies produced microscopes and other optical instruments during the 19th century before Zeiss of Jena, Thuringia, became the dominant player towards the end of the century. Companies like Auer, Pintsch, Siemens, AEG and later OSRAM produced light bulbs in large volumes for national and international markets at the turn and beginning of the 20th century and Berlin was called the 'City of Light'. Around that time Planck and Einstein worked on photonic-related issues at the then Berlin University and the newly-established non-university research facilities in Berlin (e.g. the Kaiser-Wilhelm-Gesellschaft, which is now the Max-Planck-Society).

During World War II most of the industrial base of Berlin was destroyed. What was left was either relocated to other, especially western parts of Germany (e.g. Siemens, OSRAM, Kodak, and Philips) or shipped to the Soviet Union as reparation. During the division of Berlin the two parts of the city developed independent capabilities in photonics. In the western part the development of telecommunications, lighting and laser technology was pursued, and the Optical Institute at the Technical University, Fraunhofer Heinrich-Hertz-Institute, and BESSY, a particle accelerator, were (re)established. The PTB, the national institute of physics and technology, was partially reopened and instituted in West Berlin. In the eastern part of the city the Academy of Sciences and the Humboldt University, the former Berlin University, were particularly active in photonics-related areas and a large combine that produced television screens was located here.

The post-reunification era in Berlin saw a dramatic downsizing of eastern institutions. The Academy of Sciences and its Central Institute of Optics and Spectroscopy in Berlin-Adlershof were closed resulting not only in a huge number of job losses, but also in quite a number of spin-off companies and newly-founded research institutes in Berlin-Adlershof. Adlershof today can be seen as *the* high-tech centre of photonics, biotechnology, nanotechnology and media in the Berlin-Brandenburg region. The natural sciences of the Humboldt University and BESSY as well as labs of PTB and Hahn-Meitner-Institute were also relocated to or newly established in Adlershof towards the end of the 1990s. About half of OpTecBB's more than 90 member organisations are located in Adlershof.

In 2000 OpTecBB e.V. was founded in Berlin-Brandenburg as a regional industry association to take part in the German national (OptecNet) competition for federal grants for the cluster building processes in the field of photonics. In 2001, OpTecBB was one of the seven winning regions in Germany and an NAO was set up in Berlin-Adlershof with another office in Rathenow. The office in Adlershof is staffed with a CEO, a secretary and an additional employee who is responsible for IT and other administration work. As early as 2001 in Berlin-Brandenburg, four technological interestgroups were organised that represented a critical mass of competences in the region (photonics in telecommunication; uv- and x-ray technologies; biomedical applications; photonics application in space and transport). An additional interest group was set up to cover activities in education and qualification in photonics.

Each of the four interest groups has one spokesperson from academia and a deputy from business (or vice versa) in order to reflect the intention to collaborate across distinct societal spheres. Additionally, OpTecBB e.V. is governed by a board whose work is supported by the NAO. The first chairman of the board was a professor at the Free University of Berlin who was simultaneously a director at the Max-Born-Institute in Berlin-Adlershof and was a former secretary of state in Berlin. In 2004, with the intention of deliberately balancing the representation from the two distinct societal spheres, a representative from a medium-sized company was elected as his successor. The board meets about every two months and sets the strategy for OpTecBB. According to German e.V.-law the official members of the association relieve and re-elect (or newly elect) board members in annual meetings. These annual meetings are a forum for member participation in the strategy process.

One of the most important measures to foster the cluster building process in Berlin-Brandenburg appears to be the annual two-day strategy workshops called ‘Networking Days’ in November or December that take place in addition to the annual members’ meeting required by law which is largely concerned with reporting (financial and activity) and formal organisation. Another important measure is the event ‘Members Introduce Themselves’, which takes place around four times per year and in which the inviting member presents the profile of its organisation to the visitors, organises a tour through their facilities and closes with an informal get-together (see also Appendix).

Because of Berlin-Brandenburg’s substantial research potential in different locations in Berlin and in Potsdam, Brandenburg, there is a wide range of colloquia and presentations in photonics related issues which are not administered or co-ordinated by a central body like OpTecBB. Another measure to foster collaboration is the meeting of members within the technological interest groups and the collaborative (mainly project-based) work in these groups (especially in the groups working on photonics for telecommunication and on x-ray-technologies).

OpTecBB also has a very comprehensive website www.optecbb.de with a presentation of upcoming activities, profiles of the competences in the region and, within OpTecBB’s internal member base, a very extensive news archive and a competence database of the members. Furthermore, OpTecBB is quite active in public relations activities and issues news releases on photonics in the region, and collects and displays news about its member organisations. About twice a year OpTecBB issues a newsletter on different topics. Moreover, the second largest photonics exhibition in Germany (Laser-Optik-Berlin) is organised in Berlin-Adlershof every two years (by the Technologiestiftung, a state agency of Berlin). The Technologiestiftung, OpTecBB and the technological interest groups within OpTecBB actively support members to participate collectively in international exhibitions. OpTecBB also organises presentations about the photonics region Berlin-Brandenburg at international trade shows. In Berlin the association moderated a process to draft a strategic technology concept ‘The Future of/through Optical Technologies’ which was aimed at and has since been accepted by politicians and economic development representatives in Berlin. This concept is likely to ensure that OpTecBB’s public funding will reach well beyond the present funding of the Optec-Net competition.

In its early years of cluster development OpTecBB brokered several state-funded co-operative R&D projects which, together with the region’s long and well-known history in the field of optics and photonics, provided a fertile ground for implementing the cluster development policy within the Optec-Net competition. Today OpTecBB has more of a consulting role, with the state-owned Investitionsbank Berlin and Brandenburg (IBB and ILB, the primary investment banks and financiers of high-tech firms in the states of Berlin and Brandenburg) and the Technologiestiftung of the states of Berlin and Brandenburg.

Furthermore in 2006 and early 2007 OpTecBB has begun to restructure the internal and external governance of the cluster. An important aim of the restructuring is to represent more of the member organisations in adequate technologically focused interest groups, which reflect the full technological photonics potential of the region; another to support the organisation of projects within and across these interest groups in a broad array of applications – thereby creating a dynamic matrix structure.

4.2.2 Southern Arizona: The Veteran but Still Vital Photonics Cluster

In the state of Arizona photonics began to play an important role somewhat later than in Berlin-Brandenburg, in the 1940s, when astronomical observatories were located in *Southern Arizona* because of the mountains and the favourable dry climate in the area. The University of Arizona introduced study programmes in optical sciences and attracted additional scientists. In 1964 a new Optical Science Center was founded at the University of Arizona in order to provide an alternative centre for optics skills and research to the then other principal photonics centre in the USA, Rochester, New York. This centre soon became one of the world's largest and most comprehensive academic institutions focusing on optics and realising synergies between the observatories and academia in the 1950s and 1960s, thus laying the foundations for Arizona's optics cluster (Collaborative Economics 2001).

In the late 1980s and early 1990s Arizona's economy transformed from a mainly defence (e.g. Raytheon Missile Systems) and aerospace (e.g. Hughes) dominated region to a more commercially oriented field. Today companies like Intel and Motorola are located in Southern Arizona, primarily in and around Phoenix, using photonic processes to produce integrated circuits. Many optics companies, however, were founded by scientists of the University of Arizona's Optical Science Center, primarily in Tucson in the early 1990s, so that today the photonics cluster in Arizona is characterised by a very large number of small, innovative and highly sophisticated companies spun-off primarily from the university and located in and around Tucson.

In response to the real-estate collapse in Southern Arizona in the late 1980s, the universities, politicians and economic development agencies in Arizona joined forces to formulate a state-wide economic development strategy. This strategic planning process, which was concluded in 1992, adopted a cluster-based strategy which was probably the first cluster-oriented development strategy in photonics in the world (Waits 2000). During its implementation, the programme was administered by the Arizona Department of Commerce on behalf of the public-private partnerships representing each cluster (apart from the photonics cluster there are now six other clusters). The genesis for the cluster strategy and organisation in Southern Arizona were industry studies conducted in the mid 1980s by the University of Arizona. Around that time the Governor of Arizona asked Bob Shannan, the then Dean of the Optical Sciences Center, and Jim Wyant, Professor at the Optical Sciences Center and board member of several companies and currently dean of the College of Optical Sciences at the University of Arizona, to start an optics cluster in Tucson. These two individuals were appointed by the governor to be the co-chairs of this cluster and served for about one year before handing over to Bob Breault. A representative from IBM together with Bob Breault and the representatives from the University of Arizona, provided staffing for the optics cluster that was subsequently established in Tucson in 1992 (Esher 2004) in the form of an industry association. A year earlier the Tucson area had become very visible as Arizona's 'Optics Valley' through a cover story of Business Week. Bob Breault, one of the founders and protagonists of the Arizona Optics Industry Association (AOIA), has promoted the idea of (photonics) clusters ever since in Arizona and in many other regions of the world.

The AOIA as an optics industry association, founded in 1992 and chartered to represent the entire optics/photonics community of Arizona, has governed the cluster to the present day. The AOIA in the past was basically managed and administered by Bob Breault, owner of an optics software and optics engineering consulting firm in Tucson. Now there is a board of eleven individuals (three from academia) with four co-chairs. The AOIA board holds meetings every month in which the basic strategies are drafted and decided upon. In very recent years the other co-chairs of the board, from a small and a large company in the city, have been taking a more active role. So there is a development from a one-man-show to a real board system. There is, however, no NAO and the co-ordination of activities is mostly done in the spare time of the active board members; it is classical volunteers' work. Even though there are considerable overlaps between the optics cluster and the other technologically oriented clusters in the Tucson and wider Southern Arizona area, there are no technological interest groups or regular sub-community workshops or colloquia.

AOIA's co-ordinative activities are paid for by AOIA members' fees and by private sponsoring. State funds are only eligible on a project basis (e.g. for the redesign of the website). The state provides some support via the Southern Arizona Technology Council (SATC) that organises cross-cluster activities in the seven technology clusters in Southern Arizona. The SATC is more like an umbrella organisation for all the technological clusters in the Tucson area (such as aerospace, optics, plastics and composite materials, biotechnology) and is governed by the chair persons of each cluster. SATC, and not the industry organisations, receives money from the City of Tucson, Pima County, and the State of Arizona for projects like workforce development, website building and maintenance, and so on. Individual cluster organisations have to apply to SATC for funding. Recently, under the so called 21st Century Fund, AOIA and its members are applying for project funding and are even planning to pay for and staff an NAO in Southern Arizona. The membership structure however is divided into fee-paying members of the AOIA and the other members of the cluster, which do not necessarily have to be optics companies (but in general these organisations have some kind of stake in optics).

In summary, the Arizona cluster is basically run through the initiative of small companies. Raytheon, as the largest company in the cluster, has only recently started to actively support the cluster development. But first and foremost, Raytheon is likely to be trying to utilise the competencies in the cluster for its own business rather than operating collaboratively within the network. Nevertheless, they reached out to all members with their Small Business Innovative Research (SBIR) letters of support.[8] Raytheon also has an agreement with the University of Arizona for sponsored research: "And they do quite a bit with the university. And there is a master license agreement that they negotiated on intellectual property" (Expert SA-LC). Beyond the involvement of the Optical Science Center, the role of the universities is a bit unclear. The Economic Development unit at the University of Arizona tries to organise some support but more on a cross- or meta-cluster level in the state of Arizona (aiming at the development of high-tech clusters in general). However, as far as the governance of the cluster is concerned, there appears to be 'a kind of disconnection' (Expert SA-RO) between industry and the university research side. Whereas the AOIA as an industry association is organising the cluster, the Optical Sciences Center or now the College of Optical Sciences appears to care predominantly for research and even though companies and university researchers are interacting intensely, a unified concerted cluster development appears to be absent in Southern Arizona. "Our [the Optical Sciences Center] actual involvement [in cluster activities] is not real large. […] I am really not involved much with the cluster at all. I haven't gone to a cluster meeting in a couple of years. […] We might be separated from the association but I don't think we are separated from the members of the association. I think that a lot of the members are involved with us all the time" (Expert SA-RO).

Specialisation as well as integration is observable. In the Arizona photonics cluster three sub-fields of application can be identified. There are activities in biotechnology-optics/photonics applications, in defence/imagery (especially Raytheon Missile Systems), and in software/IT applications. There are 24 specialties (Expert SA- CR/SME) present in the cluster, like meteorology, scattered light or software, aerospace, telecommunications or medical applications to name just a few.[9] Nevertheless, the perception is shared within the cluster that optics is not recognised as a viable technological field on the state level ('in Phoenix'). Only in connection with other preferably high-tech clusters is attention paid and funds provided to the optics community.

Perhaps either in response to, or implicated in, this lack of recognition, the AOIA board members actively take on a broker role in the cluster development process, but sometimes in relatively less visible ways. Companies are 'silently' brought together to identify possible projects and work on common grounds, often independent of the Economic Development Unit at the University of Arizona, the regional agency or even the State agency. "It is almost an undercover type of communication that you have to have" (Expert SA-SME).

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[8] SBIRs are a Federal set aside program for small and medium-sized enterprises.

[9] Astronomy is seen as a field of application of optics in Arizona, but not as an important field within the cluster and the AOIA, at least it is not really mentioned in the interviews (similar to the role of the Astrophysical Institute in Potsdam (AIP) in the Berlin-Brandenburg case and the Royal Observatory in Edinburgh in the Scottish case).

However, some rather more prominent communication means are also employed. For example, commissioned by the AOIA, Breault Research Organisation and Optics Reports Inc. publish a web-based newsletter 'Optics Report' primarily aimed at informing financial organisations about current trends in optics, latest technology developments, markets and management and possible investment opportunities.

Further, the AOIA sends out informative emails and has a limited web presence. Breault Research Organisation has also printed brochures with optics company profiles to be handed out at trade shows. The AOIA is also promoting the 'Optics Valley' at trade shows and negotiates discounts on booth prices for the members. Furthermore AOIA is a partner in the tri-cluster-alliance between the photonics regions of Ottawa in Canada, Berlin-Brandenburg in Germany and Southern Arizona (see again Section 3.4).

Formal means of promotion and interaction are also complemented by less formal approaches. The AOIA organises four to six 'Business Lunches' per year. At these luncheons, where up to 80 people will show up, with up to four people coming from one organisation, members of the AOIA are preferentially accepted on the guest list. So a sense of exclusivity is created in order to urge potential members to join the association and to pay the fees. This procedure also allows non-members such as suppliers to the industry or vendors or service firms to network with the optics community. In addition, in February 2005 another measure to foster inter-cluster collaboration was initiated by Suzanne Gerdes, an AOIA Co-Chair: the 'Mixer' events. These are cross-cluster meetings sponsored by SATC (cross-cluster umbrella organisation) and are similar to the initiative 'Members Introduce Themselves' in Berlin-Brandenburg, where an organisation presents itself to the audience and the audience is shown around the facilities of that organisation. But also other companies from different clusters and venture capitalists (that have an interest in investing in photonics firms) can introduce themselves in 5-10 minute presentations (see also Appendix). There appears to be no common theme for each 'Mixer' event.

The College of Optical Sciences also hosts a number of activities to foster collaboration in the cluster, but as indicated above, the College as well as the hosted activities are rather disconnected from the AOIA. A broad range of such activities take place at, or in association with, the University of Arizona: talks are frequently held in different optics related areas; industry practitioners give lectures in optics and photonics; an industry affiliate's programme is organised at the College of Optical Sciences; young people at high school level are recruited for degree studies in optical sciences; a collaboration with Pima Community College was set up in the late 1990s to teach optical technicians; and annual graduates alumni meetings are held.

A final collaborative development of note is that the AOIA has been involved as a lobby group to work on a co-ordinated curriculum for the optical technician program at the Pima Community College in Tucson and, in close collaboration with Raytheon Missile Systems, has set up a quick response team that enables small and medium-sized optics firms in the region to respond quickly to requests from this firm.

4.2.3 Scotland: Developing the Photonics Glen

Scotland also has a long tradition in optical science and research, and in the transfer of research results from Scottish universities into Scottish industry. Scotland's photonics industry is largely based in defence and electronics related areas. Pilkington Optronics (now Thales Optronics), founded in 1888 as Barr and Stroud, produced optical systems for naval and other military applications. "The laser was invented in 1960, then the two or three defence companies at that time, Ferranti, Barr and Stroud, and Hughes were using lasers for military range finding from the 60s and the universities have, since that period, increased their interest in laser technology. So you have most of the laser [types] covered in Scotland in research, […] newer ones, semi-conductor lasers etc have come on. So Strathclyde and Heriot-Watt and St. Andrews are three universities that do a lot of research into the lasers" (Expert SC-CRI). Similarly, today companies like GEC Marconi, formed from the Scotland based defence operations of Ferranti and Marconi Space and Defence, (now Selex) and Thales (former Pilkington) manufacture a diverse range of products based on photonics applications for international defence markets.

A large number of global players in the field of electronics and related photonics companies were located in Scotland after 1945, including amongst others those focussed on semiconductors (Motorola, National Semiconductor), electronics (NEC, Fuji Electric), computers and office machinery (IBM, Compaq, Digital, Sun Microsystems, OKI Electric, Apricot Computers), communication technology (Hewlett-Packard, Philips, Cubix), and consumer electronics industries (JVC, Matsushita, Mitsubishi Electric). In the early second half of the 20th century Scotland actually became a manufacturing base for low-cost electronics products for European markets. In addition to these OEMs, a considerable number of specialised suppliers settled in the 'Silicon Glen' between Glasgow and Edinburgh that, originally, was consciously modelled according to California's 'Silicon Valley'. However, it was noted as early as the 1980s that the large multinational electronics firms were unable to find local suppliers in Scotland and to build a strong local Scottish value chain. Components were, and still are, sourced overseas (Sutherland 1995: 71). The present focus of Scottish opto-electronic companies and university research institutes on photonic applications in telecommunication, display technologies, optical sensing and new lasers can be attributed to the presence of these large electronics and defence companies.

The strong focus on telecommunication and defence related applications remained only until the bubble of the telecoms market burst in 2001; since then the cluster has become more diversified. The diversification has included biophotonics and displays/imaging, for example. Over the last two years a change in the level of involvement of the larger companies in the activities of the cluster has been recognised. For instance, defence companies have started to use more of the regional research base as well as the capabilities and capacities of SME especially through the Electro Magnetic Remote Sensing Defence Technology Centre (Expert SC-LCa; Expert SC-LCb). Other large firms such as Polaroid have established a research laboratory at their Scottish site, and so are reaching out more into the cluster. Also there is more cross-cluster, interdisciplinary activity organised by the Scottish Opto-electronics Association (SOA) under the Scottish Technology Forum.

The SOA was established within Scottish Enterprise in 1994 by former industry representatives who were working there at that time, to represent the opto-electronics community in Scotland. Then in 1997 the SOA was spun out of Scottish Enterprise to become an independent industry body. From then on, a cluster policy was pushed forward by Scottish Enterprise. In a first wave, food and drink, textiles, and micro-electronics clusters were formed in Scotland and, in a second wave about a year later, opto-electronics was added. In 1999/2000 the SOA, which now combines industry and academia, and continues to be supported by the Scottish Executive and Scottish Enterprise, organised a strategy process identifying areas of interest within opto-electronics, gaps in the infrastructure, and the strengths and weaknesses of the cluster. This led to a benchmarking and ongoing strategy process as well as to an action plan. Following the 2000 strategy process, the SOA has produced four technology roadmaps identifying opportunities for Scottish photonics companies. Between July 2004 and October 2005 a joint project between the SOA and Scottish Enterprise, 'The University to SME Technology Transfer Programme in Opto-electronics & Microelectronics (TTOM)' has been awarded £182,135 to "help Scotland's micro and opto-electronics companies develop the commercial potential of leading edge research." Under the SEEKIT Programme universities, research institutes and other public sector bodies were supported to develop "infrastructure needed to facilitate co-operation in research and development (R&D) and productive knowledge transfer between the Scottish public sector science base and Scottish SMEs" (Scottish Executive 2005). The TTOM project involved a number of network meetings and focused workshops with representatives from academia and companies and a number of feasibility studies between researchers and the matched companies were funded with up to £5000 each, which were oriented towards these identified opportunities. Recently, under the UK-wide Knowledge Transfer Network (KTN) administered by the DTI, the Photonics KTN was established in July 2006 with lead partner the UKCPO. Under this still-developing group, the SOA will now be hosting a number of UK-wide roadmap meetings (Expert SC-CRII). This outward orientation of the SOA can be seen as a direct result of the UK and the EU strategically moving at the same time to promote photonics (as evidenced by calls for proposals relating to both the DTI's national photonics strategy and the EU's 7th Research Framework Programme).

The SOA is now governed by a council of eight persons which directs its activities. Two members retire by rotation each year and new members are elected at the annual general meeting held in June. In 2005 the council was chaired by a representative from a venture capital firm and also included one university representative, two representatives from infrastructure institutions, and four representatives from small companies. There is an NAO with an executive and a secretary in charge not only of implementing the council's strategy, but also coming up with its own initiatives. The SOA is presently funded by member contributions, and operates a number of projects relevant to its members funded by Scotland, the UK and Europe.

Collaborative developments have been noted in the academic section of the cluster as well as more generally across the photonics field. Between 1990 and 1999 four Scottish universities pooled their resources and capabilities in the Scottish Collaborative Initiative in Opto-electronic Sciences (SCIOS) in a research programme in order to develop new technologies and devices for optical information processing. In May 2005 six universities with physics departments in Scotland agreed to form a new alliance named the Scottish University Physics Alliance (SUPA) in order to strengthen the position of physics higher education institutions' research and teaching in Scotland in competition with universities like Oxford and Cambridge. The development of photonics as a large and important part of research and education in physics in Scotland is one of the stated key themes in SUPA activities (Gillespie et al. 2005: 14) that aim to develop the science sphere of the photonics cluster in Scotland.

Academic developments have also been integrated into the broader patterns of development; the SOA has also been involved in developing specific opto-electronics master degrees at universities inside and outside the region (e.g. the display masters degree, a pan UK degree taught at Oxford, Cambridge, Dundee, Edinburgh etc.). The integration also extends to lower levels, as the association also advises skills councils on technician training and has been involved in school education as part of a Scottish Enterprise initiative called the 'High Technology Talent Strategy' to promote curricula in science, technology, engineering, and mathematics.

Within the SOA there are no official substructures implemented concerning specific technological applications. However, over the last five years there have been co-ordinated road mapping activities between Scottish Enterprise and the SOA to identify specific technological knowledge potential (e.g. optical sensing and lasers). Among these activities, conferences on a specific technological topic were organised in Scotland. The SOA, furthermore, organises technology oriented meetings (e.g. on flexible displays) on a regular basis. Members interested in these fields and from related areas (e.g. capital, lawyers, marketing) attend these workshops. At other meetings the SOA informs members about the different grants that are available for the opto-electronics community. These meetings on different topics are organised at a frequency of about once a month. The SOA also organises business missions to other countries and hosts other international photonics associations.

4.2.4 Photonics Cluster (UK): Out of the West Midlands for England

The West Midlands of England (the area around the city of Birmingham) can be characterised as having a strong and traditional mechanical and heavy industry manufacturing background. Photonics in the West Midland region has been of importance, especially at Aston University where a large group of researchers at the Photonics Research Group, founded in 1991, have been involved in the development of experimentation and modelling in high-speed fibre optic systems and components, sensors research, and biophotonics. Similarly the commercial infrastructure for entrepreneurial technology companies has also been in place for some time. In terms of specialist facilities, the Aston Science Park was established in 1983 with a strong regional developmental focus. In terms of large organisations active in the area, QinetiQ, formerly DERA, Europe's largest science and technology organisation in this field, has been involved in semiconductor research since the 1990s and is known for pioneering work in technologies such as liquid crystals and infrared detector materials.

However, photonics activities in England were historically concentrated in regions like Oxford, Cambridge, London and Southampton and regional photonics networks have previously existed outside the Midlands, most prominently the South East Photonics Network (SEPNET).[10]

In November 2000 the Midlands Photonic Cluster, based at Aston Science Park in Birmingham, was formed, supported by funds from the DTI and Advantage West Midlands (the regional development agency). In 2002 the Midlands Photonic Cluster and the UK Laser and Electro-Optics Association (UKLEO) merged and formed Photonics Cluster UK (PCUK) to establish an organisation for companies and academia within the opto-electronics and photonics sector with a more than regional reach. Through the merger, the member base grew to 50 organisations.

Photonics Cluster (UK) is a brand name. The legal entity behind it is Birmingham Technology Limited, the organisation that owns and manages Aston Science Park. This regional link is also expressed in the composition of the board that contains representatives from Birmingham City Council, Advantage West Midlands, Aston University and also a commercial bank, Lloyds TSB (because of a donation made at the start of the park). The chief executive of Birmingham Technology Limited is also the chief executive of Hertfordshire business incubation centre which is located in Stevenage. PCUK basically has a secretariat that is staffed by these entities. Glen Barrowman, its director, has been visible in the community, representing PCUK since his involvement in the Midlands Photonics Cluster in 2000.

The West Midlands cluster, in addition to an administrative group, also has specialist, shareable facilities. In 2003 the Photonics Application Centre was established as a central cluster facility in Birmingham. The Centre, which is a joint venture initiative between PCUK and equipment suppliers, provides the growing photonics community with equipment that can be rented for a daily rate or on a project basis, and the users are supported by the Centre's technical staff. PCUK, at that time, employed four full-time staff, including two business development personnel, in order to directly promote and market the Application Centre. The Application Centre is now promoted by attending trade shows, visiting identified target sector companies, the PCUK newsletter and presentations about PCUK held at various national and international events. It is planned that the "Centre will be fully integrated into the cluster activities and will support technology transfer, collaborative market led innovation projects, encouraging and supporting technology companies in their necessity to develop into diversification, technology exploitation and alternative market development projects" (PCUK 2003). Interactive exhibitions and end-user open days are organised as well. In addition, industry training courses in areas like LED Laser Safety, Colour Measurement, Integrated Sphere Analysis, and Co-ordinated Measurement Techniques are organised by PCUK.

Nominally PCUK's cluster activities have been expanding in scale as well as scope. In 2004 the still Midlands-based PCUK expanded to the South of England and opened a base at Hertfordshire Business Incubation Centre in Stevenage in order to develop the member base there (PCUK 2004). A year later, in October 2005, it was announced that PCUK will further increase its member base by organising Northeast Photonics Cluster UK event activities supported by the County Durham Development Company, Cenamps and One Northeast (the regional economic development agency) (PCUK 2005b). PCUK's very expansive strategy is further expressed in the extension of East of England activities through linkages with the East of England Enterprise Hub and the integration of Photonics Cluster (UK) within West Midlands ICT Hub activities (PCUK 2006).

Expansion has also been supported through collaboration with other organisations. PCUK has organised industry-focussed events together with both member organisations and other organisations like the Association of Industrial Laser Users (AILU), National Metals Technology Centre (NAMTEC), Aerospace Alliances, and CERAM (a materials research organisation) and entered a strategic partnership with the National Physical Laboratory in order to engage with National Measurement System initiatives.

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[10] This was initiated and managed by Oxford Innovation, a spin-off company from The Oxford Trust, an independent charitable foundation for the advancement of technology transfer in the region. SEPNET existed until the telecoms crash.

This multi-directional expansionist approach seems to have been successful. In early 2004 the member base of PCUK had reached 100. By June 2006 this number had almost doubled. In order to develop and involve this rapidly growing member base the idea of special interest groups (SIGs) was introduced in the course of 2004. As part of this strategy a number of special workshops were organised by PCUK, beginning with a two-day seminar programme and exhibition on Light Emitting Diodes (LED) in July 2004 and the subsequent formation of an LED SIG during a second special LED symposium in April 2005. This first SIG, for example, will have a voluntary steering committee of 8 individuals or organisations that represent the industry, and the strategies developed at the steering committee will be implemented by the secretariat at the PCUK for the benefit of the LED industry (PCUK 2005a). At about the same time, networking activities in the biophotonics community resulted in the formation of a biophotonics and healthcare SIG that was formed out of a DTI supported industry workshop in October 2004. The SIGs will work in different industry areas including optical communications, displays and imaging, security and defence, micro and nano technology, and medical and biophotonics. In 2005 PCUK also launched a technology seminar programme; PCUK has been active in a wide range of technology events including 30 in 2005/06 alone (PCUK 2006).

Communication, information sharing and interactive events have also been important in England. In their newsletters, the Midlands Photonics Cluster (MPC) – until 2002 – and then subsequently PCUK have provided information about project funding opportunities on a national and European level, as well as including space for member organisation, industry and product news, details of past and upcoming events and information about the MPC facilities/Photonics Application Centre. In 2004 the PCUK-produced newsletter began to incorporate proportions of the Photonics Focus newsletter – the DTI information outlet for the industry. PCUK has been involved in a close collaboration with the DTI on its Photonics Strategy Workshops in the areas of Optical Communications and Next Generation Networks, BioPhotonics, and Solid State Lighting and Photovoltaics and on a European Level in the composition of the Photonics 21 strategy paper.

PCUK is also active in national and international trade initiatives, thereby communicating beyond its membership and not just within it. It is taking part in the major photonics exhibition, has entered into collaboration with UK Trade Fair Support in helping members gain assistance to exhibit at global opto-electronics exhibitions, and organises trade missions for its members to the US and the Pacific Rim. In the UK the cluster has become an integral part of the annually held Photonex conference and trade show, where PCUK organises members' breakfasts and networking lunches and presents the clusters' activities for the coming year.

4.3 Comparative Analysis of the Clusters: Commonalities and Contrasts

Given the explorative nature of this report, the quality of data we were able to collect in the course of this research and its focus on the development or 'structuration' of the clusters, the cross-cluster comparison that follows will focus on the commonalities and contrasts in (1) the structural properties that characterise the 'knots' and the 'relations' in the clusters, (2) the formal and informal cluster rules of signification and sense-making as well as of legitimation, (3) the resources that are available for cluster development, and (4) the 'phase' that most adequately describes the present stage of the development. Table 4 gives a summary of the commonalities of and contrasts between the four clusters.

Table 4: Commonalities and contrasts

Dimension	BB	SA	SC	WM
(1) Structural Properties				
Geographic scale	concentrated	concentrated	dispersed	dispersed
Economic size (firms/employees)*	260 / 7,400	250 / 25,000	90 / 4,000	60 / n.a.**
Main domain	science	industry	science	industry
Value chain	incomplete	incomplete	incomplete	incomplete
Level of interaction	high	high, but centralised	high	low
Involvement in cluster leadership	relatively high	low	low	low
(2) 'Cluster Rules'				
Collective identity	pronounced	present	present	not present
Perceived legitimacy	high	high	high	low
(3) 'Cluster Resources'				
Financial resources	significant	hardly any	some	significant
(4) Phase of Development				
Cluster age in years	5	15	15	5
Phase	developing	developing	developing	emerging

* The numbers refer to different years
** n.a.: not available

4.3.1 Structural Properties

Even though all four clusters belong to the most important concentrations of the photonics industry in the world, they nevertheless differ in geographic scale as well as economic size. The Berlin-Brandenburg cluster is *de facto* concentrated within the metropolitan region of Berlin, despite its nominally wider reach. A similar situation can be found in the U.S. case, with the Southern Arizona photonics industry located mainly in and around Tucson, where 80% of the photonics companies and 66% of the employees can be found (Catts 2002; Esher 2004). A more recent study of the cluster finds that 68% of the respondents come from Pima County (Tucson) and 28% are from Maricopa County (Phoenix). This follows the same pattern as ten years ago when the last thorough regional photonics industry study was conducted (Expert SA-RO/RDA). In Scotland, by contrast, the photonics industry is basically located not only in Glasgow and Edinburgh, but also between these two cities in the so-called 'Silicon Glen'. In even sharper contrast, PCUK – though it originated in the West Midlands – now, after rapid growth, extends to most parts of England. In the latter case in particular the regional boundedness of clusters, which is one of the constitutive properties of the concept, can be questioned.

The 'Knots'

In the Berlin-Brandenburg case a high proportion of (photonics related) research organisations can be observed. A survey conducted by OpTecBB in 2002 identified about 260 companies and about 40 photonics research organisations. In 2005 more than 90 photonics organisations in the region were paying fees to OpTecBB. The companies generated a total turnover of about €1.8 billion and employed 7,400 people in the region (Hornauer 2002). There are four universities and three technical colleges with Physics departments and especially photonics research groups. Additionally, there are more than 20 non-university research organisations that have some activities in photonics, ranging from basic research (e.g. BESSY and the Max-Born-Institute) to more applied photonics research (e.g. Ferdinand Braun Institute or Fraunhofer Heinrich-Hertz-Institute). In the Berlin case about 90% of the companies are small companies (up to 49 employees). Only a small proportion of the companies can be characterised as medium-sized (4%; 50 – 249 employees) with the remaining 5% being large companies of 250 and more employees. These large companies account for the largest proportion of the turnover and employees, but are not really active, at least in the process of developing the cluster. The latter diagnosis is typical in all four clusters studied. The following quotation from a cluster representative is illustrative:

> *"What we've found and it might be a type thing, but we've found that the large corporates have been difficult to convert. They're still involved because you cannot operate without having them, so in some cases they benefit from our activities, but they don't actually subscribe to our activities" (WM-CRII).*

In the Southern Arizona photonics cluster, according to the director of the industry relations program at the University of Arizona Office of Economic Development, state-wide employment in optics companies grew 81% in five years, from 3,818 in 1995 to 6,907 in 2000. Pima County accounted for 4,573 (66%) of the state wide optics jobs in Arizona. There are about 200 optics-related firms in the state of Arizona, of which about 160 are located in and around Tucson (90% in the private sector). 73 of these companies are paying fees to the AOIA and about 40 are core to the cluster (Expert SA-RDA). The photonics industry in Arizona accounts for estimated annual revenues of about $650 million in 2000 ($100 million in 1989 and $300 million in 1994). These numbers exclude large companies like Raytheon Missile System, Intel and Motorola that are counted within/attributed to other clusters (aerospace and ICT) (cf. Fischer 2001; Catts 2002). Preliminary results from a study of the photonics and nanotechnology cluster in Arizona conducted in 2006 by the University of Arizona indicate an even larger size of the cluster. According to this analysis there are now 25,000 people employed (2500 employees in 1996) in about 250 photonics organisations in this regional cluster. The revenue generated by these organisations has grown to $2 billion in 2006 ($184 million in 1996). 56% of the 84 respondents in the study export to Asia (77%), Europe (77%), and Canada (57%) (Expert SA-RO/RDA). In comparison to the Berlin-Brandenburg and the Scottish cases, Arizona has a relatively high proportion of medium-sized companies (17.6%). Public research in photonics in Arizona is basically carried out at the Arizona State University in Phoenix and the University of Arizona in Tucson. Non-university public research organisations in Southern Arizona, Scotland and the West Midlands is not as common as in Berlin-Brandenburg. For example, in Scotland research is concentrated in thirteen universities with 25 university departments (Expert SC-CR-I) engaged in opto-electronics research, in total involving more than 450 researchers. It is notable that Scotland accounts for 34% of UK Government spending in opto-electronics research (with only 10% of the UK's population). This exceptionally well-developed academic competence base is frequently utilised by photonics companies in Scotland:

> *"Where we benefit from the local environment, and we have benefited very well, is in some of the diagnostic tools and things like that available in the universities. Because, as you will be aware, there are a lot of universities doing electro-optic type work. In fact, pretty much all the universities in this area are doing it. That's been really good for very specialist diagnosis where we just don't have the expertise, the knowledge, tools or analysis – we've done quite a lot of that over the years" (Expert SC-SMEb).*

In 2004 around 90 companies employed more than 4,000 people in Scotland and reached an annual turnover of £800 million, of which 65% were exported (Scottish Enterprise 2005, 2006).

An early estimation of the Midlands Photonics Cluster (MPC) dating back to 2002 (Weir 2003) identifies over 60 photonics companies within a 50-mile radius around Birmingham and companies which have already had previous interactions with the MPC, generating a turnover of £500 million. Over 90% of sales were exported from the region and over 50% were exported from the UK. There was, according to the study, little supply chain collaboration and little rationale for a Midlands photonics location. However, because of its expansive course and its limited boundedness to a specific region, the economic size of PCUK is somewhat difficult to assess. Also, so far there are no official statistics evaluating the photonics industry in England and the UK available. As of summer 2006, there were 185 member organisations of PCUK – almost exclusively from England.

In any case, there are no complete value chains present in any of the photonics clusters studied. This is due to the global nature of this industry:

> *"… all aspects, if I choose just any specific parts of this company there is not a regional demand for any aspect of the work. [Its] global. Absolutely" (Expert WM-LC).*

Furthermore, the necessary high specialisation requires the international sourcing of parts, components and systems that go into astronomical instruments, for example:

> *"But to be honest most of the work goes into industry because it's very specialised and has not been done in Scotland. In fact very little of it ends up in the UK. Most of the partners are in Europe or in the U.S" (Expert SC-ROb).*

Nevertheless, as at least some of the cases show, there is enough reason for intensive interpersonal and inter-organisational interaction.

The 'Relations'

The structural properties of clusters, like those of any kind of inter-organisational network, should not only be described in terms of size and kind of membership organisations, but also with regard to the structure and quality of inter-organisational relationships. Dimensions used most often to assess these are the strength or coupling of such ties (e.g. Granovetter 1985; Uzzi 1996) and the level of trust that is often associated with strong or tightly coupled relations (e.g. Gulati 1995), but also the openness or closeness of a network measured in terms of the extent of network member diversity, willingness to accept new members, and external linkages to organisations outside the cluster, especially under conditions of high environmental uncertainty (cf. Eisingerich et al. 2006).

In the Berlin-Brandenburg cluster, a lot of informal interaction has developed over a rather short period of time due to the favourable historic antecedents of the cluster and the particular quality of the implemented formal cluster-building approach that took a developmental perspective and, especially, created social space for personal interaction. Though these relations are rather strong and have so far been used to generate quite a number of important collaborative R&D projects, they have not led to an equal amount of commercial relationships that go beyond joint R&D (cf. Lerch et al. 2006). In the Southern Arizona case the situation is similar, though here the level of personal interaction/personal relationships has developed over a significantly longer period of time and, in the main, centres around one individual, Bob Breault. A sharp contrast, however, is the relatively large proportion of Southern Arizona photonics companies exchanging goods and services within the cluster. 84% of the companies in the photonics cluster buy from and/or sell to other photonics companies in the cluster and about 39% of the revenues of the photonics companies are generated locally (Catts 2002).

The Scotland cluster, due to its similar age, is also characterised by a quite high level of interpersonal interaction and many of these relationships have developed into joint R&D projects – or, as one would expect in such an R&D intensive field, such joint projects have also been the source of developing a network of interpersonal relationships. However, these relationships seem to have developed in a much less centralised manner. Moreover, commercial relationships are also rare here, despite more than 15 years of cluster history. This is reflected in a number of statements about the global nature of sourcing and selling in this high-tech field, not only in Scotland:

> *"It's one of the things that surprise people about the opto-electronics community that they don't buy from local companies. When I ran [another] Photonics [company] for five years we didn't have any British customers and British suppliers. I suppose we must have had some buyers of something but basically our attitude to develop the company was: we would buy components from Korea, Australia or whoever was cheapest and whoever was best. Our customers that we sold our products to were global. So we didn't have any allegiance to Scotland. We didn't have any given that we were part of the Scottish opto-electronics cluster that we should be trading with Scottish companies" (Expert SC-RO/SME).*

> *"Most of our, 91% of our customer base is outside the UK. Very, very little of our customer base is in Scotland. Almost 0%. […] The supply side is also, we do use some local suppliers but only because it's something we could get wherever we were. We would use a local supplier for convenience. But we could be anywhere" (Expert SC-SMEb).*

As far as the case of PCUK is concerned, the network of interpersonal relationships seems to be (still) less dense and joint R&D activities across the cluster are the exception rather than the rule. Members of the 'cluster' got to know each other mainly during the course of conferences, workshops, and exhibitions that are dispersed all over England. In consequence and in comparison with the three other clusters, this one is still comparatively 'open', at least with respect to the number of potential cluster members and to the extent of cluster membership diversity and the willingness to accept new members. However, the PCUK management seems to have recognised the problem of still too little interpersonal and inter-organisational interaction and seems to strive for somewhat more 'closure' when it outlines its future plan for developing:

> *"…we quite deliberately made our membership fees very low so we would get a lot of companies joining us quickly. […] Now that we have actually got that, I think we're at the stage where we should evolve our structure. […] we have actually got these special interest groups. Six or seven. […] That has been formed. But I think it's a smallish step now for us to actually develop groups for each of these different sections. What that will do is actually then devolve power and guidance and suggestions really down into the membership" (Expert WM-CRII).*

Despite the significantly less cluster openness to be found in the three other cases, these are far from being 'too closed' and therefore not likely to run into ossification, groupthink or even a cognitive or normative lock-in in the foreseeable future (Grabher 1993).

4.3.2 'Cluster Rules'

Hence, it comes as no surprise that the cluster members' understanding of the purpose and the means and norms of the cluster building process, and even their feeling of belonging to a cluster with a 'regional industrial identity' (Romanelli and Khessina 2005) seems to be least developed and pronounced in the West Midlands case. With regard to the issue of legitimation, it is certainly safe to say that the PCUK – as a cluster – has still to earn its internal and external legitimacy (cf. Human and Provan 2000), especially as a cluster that embraces most parts of England.

The members of the Berlin-Brandenburg cluster seem to be best informed about the purpose of clustering and about the actual path the cluster-building initiative has taken, not least because many of them have been involved in the process right from the beginning in 2001. It is for this very reason that the internal legitimacy also seems to score the highest of all clusters studied – with of course positive implications for its external recognition, despite its relatively short existence. In the Berlin-Brandenburg case, the boundary of the cluster also seems to be clearer than in the other three cases, which further contributes to the binding character of the most important schemes and norms the agents refer to in their system practices. This is despite the fact that the actual photonics cluster in the region consists not only of the formal members of OpTecBB, but is surrounded by a web of relatively loosely coupled photonics firms that have not (yet) joined the association and hardly refer to the cluster rules.

With respect to the cluster rules of signification and legitimation, including the issue of identity, the Scottish and the Arizonian cluster seem to lie somewhere between these two somewhat extreme cases. Since the actors in the Scottish photonics cluster are regionally concentrated in the area between Glasgow and Edinburgh, building a regional industrial identity is much more easily done than in the PCUK case. Additionally, a slight Scottish nationalism may support this process of delimitation. However, the identity and sensemaking issue is somewhat ambiguous in Scotland, since most of the (globally leading) companies often do not really see a rationale for locating their business in Scotland or for being part of the cluster or the cluster-building process:

> *"… it is purely our responsibility for making the company a success. We are not expecting a safety net, we are not expecting anyone to do our job for us. We are not expecting anyone to fund us, we are expecting to make the product, also design, develop, make and sell the product and be successful through that. […] The people like the SOA do not really help with that. We are just using the fact that generally there is a positive environment. If you look at the engineering, we do, with one exception where we use a specialist sub-contractor down in England, we do most of it in house. […] We could almost be anywhere in the world."* *(Expert SC-SMEb).*

In the Southern Arizona case the central agent, Bob Breault, is a very important source of the cluster's internal and external legitimacy. He still appears to be the visionary sensemaker and identity-builder for the cluster. His long-term involvement in developing the Southern Arizona Cluster and his reputation in the worldwide cluster community emanates and contributes to the internal as well as to the external legitimacy of the cluster. Companies in Southern Arizona and other photonics organisations see themselves as part of the cluster in Arizona. Even a common (though a very broadly defined) goal of the cluster has crystallised: "To grow optics in Tucson" (Expert SA-RO). So a cluster identity and rules of signification that have formed over the last 15 years can well be identified. However, the somewhat casual, down-to-earth approach of developing the cluster with little resources may significantly decrease the deliverable benefits of this cluster for its members and thereby somewhat question its internal legitimacy. Therefore, institutionalising the leadership of the cluster does not only imply the broadening of the group of members that is actively involved in the cluster building process, but also developing the 'cluster rules' further. For instance, setting up SIGs with clearly defined tasks seems to be quite beneficial in this context as in others. Nevertheless, both clusters, the Scottish as well as the Arizonian, derive their internal and external legitimacy mainly from the prominence of the cluster in the world and its visibility over a period of 15 years.

4.3.3 'Cluster Resources'

The most important resources for the development of photonics clusters are those that the cluster members bring with them when joining and building the cluster, i.e. financial and human resources, technological and marketing capabilities, as well as their business relations and knowledge on how to use them for collaboration in the course of cluster development. These in the main organisational resources become, at least to some extent, available for the cluster – as more or less common goods – the more a common understanding and shared norms – i.e. 'cluster rules' – are present, the more the actors are therefore willing to participate in the cluster-building process, and the less direct competition between cluster members thwarts it. The purpose of 'cluster resources' in a much narrower sense, e.g. of the budget for setting up cluster meetings or consulting cluster members, is by and large to facilitate the mobilisation of these organisational resources.

In the Berlin-Brandenburg case, the Federal Government has supported the development of the cluster between 2001 and 2006 financially and politically. This support has now been extended until 2008. The financial resources were used to set up the NAO that is staffed with four (two full-time personnel and two half-time) people supporting the board of OpTecBB in a variety of ways. Among other things, the money pays to keep up the internal database, to publish press releases and the bi-annual newsletter, and to organise the annual 'Networking Days' and annual members meeting. This budget had to be – and has been – matched by an equal amount of financial resources raised from membership fees and state funding.

In the West Midland case, the MPC secured DTI Innovative Clusters funds in 2001 to stimulate photonics related projects between academia and industry. At the same time MPC and the newly created PCUK received quite significant financial backing from the Midlands regional development agency. Hence, as in the Berlin-Brandenburg case, the development of this cluster benefits significantly from public sector support. At present PCUK is partly financed by the European Regional Development Fund. The 'secretariat' represents the largest 'NAO' staff of the four focal clusters with six full-time employees, four of which are members of the Birmingham Technology Limited business development team based at Aston Science Park. However, besides running the cluster activities this group also operates the cluster's Application Centre. So PCUK has financial and political support in regional as well as at the UK national level and, in addition, has a large number of fee-paying members (although the fees are comparatively low). However, the involvement of the cluster's companies in developing the cluster at the moment appears to be limited. Only in very few areas (i.e. LED) are networks developing within the cluster and thereby also indirectly fostering cluster development.

In Scotland the SOA, in its early years between 1994 and 1997, was incorporated and directly financially supported by Scottish Enterprise. Today there is no basic public financial endowment for the maintenance of the cluster infrastructure. Rather, the SOA is now concerned with securing funding on a less long-term basis in order to manage single projects and arrange particular exhibitions, for example. Also in Scotland, the member base of the cluster pays fees to the SOA. However, the funding is not sufficient to have a larger cluster management team, as in the Berlin-Brandenburg or the PCUK cases. The SOA is basically managed by the board and the chief executive and his secretary, though it is open to participation by cluster members.

In Arizona the resource endowment on local, state and federal levels has basically been non-existent, although all these public bodies press for some kind of cluster policy. Instead, the cluster management relies on volunteers' work which, from time to time, is supported by project-related public funds.

As argued above, the direct resource endowments vary significantly, being quite high in the West Midlands and Berlin-Brandenburg cases, significantly lower in the Scottish case, and close to non-existent in the Southern Arizona case. In these latter two cases, the lack of resources has to be compensated for by personal engagement and commitment, not least by the cluster leaders. This, however, makes developing the cluster and, in particular, the institutionalisation of the cluster development process more difficult.

Thus, as stated earlier, in all four cases the main and most important resources for development are brought to the clusters by the organisations that have joined the 'regional innovation system' (Cooke et al. 2004). These resources are leveraged to a larger or lesser extent by the direct resource endowments of the cluster management, depending however on the cluster rules. For instance, the central actors in the Berlin-Brandenburg case share a common view of how to further develop the cluster. This makes it more likely that the cluster resources will continue to be used in an effective way.

4.3.4 Phases of Cluster Development

All four photonics clusters studied have continually grown, though at a different rate. While in Scotland and Southern Arizona almost steady growth has been observed for 15 years, the development of the clusters in Berlin-Brandenburg and in the West Midlands has been much more recent (5 years). The rather continuous growth, at least of the two former clusters, was of course interrupted by the telecom crisis in 2000/01. While in Southern Arizona this crisis only led to a reduced growth rate, the Scottish cluster was affected more severely, which was reflected not only in reduced cluster membership, but also significant job losses. As a consequence, the cluster is now much more diversified in terms of technologies and products than it used to be:

> *"There have been technological shifts, away from opto-electronics for communications markets. Telecom was an important research area in the telecom business here. Glasgow University was a dominant opto-electronics player. It does not have as much of an electronics focus now […]. We think there is a lot of things happening in micro electronics that the photonics, the optics people are missing and by putting them together, in our view, that's where the big stuff is coming now. It's not just in photonics, but it is in photonics with chemistry, photonics with life sciences. So it is getting more diverse" (SC-RO/SME).*

Despite this rather sustained and significant growth, none of the clusters studied has so far reached or is close to reaching a stage of maturity. Referring to the stage or phase model presented and discussed earlier (see Section 2), all four clusters could still be characterised as 'developing', and perhaps PCUK may still be in an 'emerging' stage as far as it extends beyond the West Midlands (see, once again, Table 4). However, some caution is in order, since the three 'developing' clusters are quite different and the transition from 'emergent' to 'developing' is anything but clear. In any case, this is an *ex post facto* classification that does not imply any assumptions about the future development of the clusters.

The future development of the four clusters, including possibly reaching a stage of maturity some time in the future will, due to the path-dependent nature of cluster development (e.g. Grabher 1993; Meyer-Stamer 1998; Fuchs and Shapira 2005), be heavily influenced – though not determined – by their past development, including the traditions they have built on, the decisions that were taken sometimes years ago, the critical incidents (like the telecom crisis) that were overcome, and so forth. Hence, it comes as no surprise, particularly from a structuration perspective, that clusters develop rather idiosyncratically. In order to give only one example, the very fact that the Berlin-Brandenburg cluster has its roots in the very diverse technology policies of two formerly separate nation-states (West Berlin and East Berlin being a part of the FRG and the GDR, respectively), still impacts upon the more recent forms of collaboration. This becomes particularly obvious in the only recently (partly a result of the cluster development process) reformed x-ray- and telecom-application-network. This particularly built on former relations originating many years before the formal cluster development process was started. Nevertheless, the future development of the clusters also depends upon the present and future actions, neither exclusively nor excluding those of the cluster management.

5 Conclusions and Contradictions

This paper reports a comparative case study of four major photonics clusters in the United States, Great Britain and Germany, focussing on how they have evolved emergently and have been deliberately developed. Photonics is still quite a young, high-tech and science-based industry. Structural commonalities of clusters in such industries are likely to include: embryonic and dynamic stage of development; blurred cluster boundaries because of the enabling character of many of these technologies; a characterisation of the cluster as more or less dispersed in terms of networks with research organisation and small and medium-sized enterprises; and an international dimension in sourcing and marketing as 'local knots in global networks' (Amin and Thrift 1994). With respect to the developmental process the main commonalities of these clusters concern:

- the importance of the significance of the science base as a critical initial condition for their development
- the relevance of central actors, though none of the four clusters should be seen as a network led strategically by some kind of 'hub firm' (Jarillo 1988)
- the involvement of mainly small and medium-sized enterprises and research organisations, including leading research universities, in the process (while there has been and continues to be a lack of engagement of larger firms)
- the heavy involvement of main actors from two distinct societal spheres that are quite difficult to bridge, i.e. the economic and science spheres
- the usage of a rather broad range of measures to foster collaboration in the cluster, i.e. the building of networks in clusters (though these are used to a different extent by the four clusters, not least due to different resource endowments) and the developing of 'cluster rules' and 'cluster resources' (see Appendix for details)
- the focus on developing local R&D collaborations and networks while not neglecting the global marketing and supply relationships that reach beyond the clusters
- the intensification of inter-cluster interaction with the result of increasingly blurred cluster boundaries
- the observation that all four clusters should (still) be considered as 'developing' and may not have reached the level of positive feedback associated with a path-dependent, self-sustaining development.

Despite these obvious commonalities that, to some extent at least, seem to be typical of high-tech fields like photonics, these four cases develop quite differently. While Berlin-Brandenburg is a young, but traditional, cluster that now is densely connected, Southern Arizona is an older but still vital photonics cluster. In Scotland, the rather traditional Silicon Glen has developed over a similarly long period of time, while Photonics Cluster (UK) has only quite recently started to expand out of the West Midlands to include members from all over England. The cases also contrast with respect to:

- some important structural properties of the clusters, such as the actual size and spatial distribution of the clusters, including the initial structural conditions before the cluster development process started
- the actual presence of interpersonal and inter-organisational networks in the clusters
- the implicit and explicit 'cluster rules' that have emerged and been deliberately constructed/developed over time and now, whether formal or informal, orient the interactions in the clusters to a more or less significant extent
- the (typically scarce) 'cluster resources' that are available to the main actors for developing the cluster – and how they make use of them
- the particular number and kind of measures used to actively develop the cluster – from convening workshops over setting up SIGs and sharing cluster infrastructure to organising roadmap planning sessions
- the involvement of the state and its regional agencies and, in this context, the formal governance and actual leadership of the cluster.

So far none of the four has exploited the cluster concept to its full potential, despite the fact that two have already developed a common understanding and collective identity. This common understanding reaches well beyond the main purpose of the cluster, to encompass such questions as how to interact with each other, solve conflicts, or address new cluster members. Surprisingly, the Berlin-Brandenburg cluster is one of these two, although it belongs to the two definitively younger ones – reinforcing our earlier reservations about generic life-cycle models. Despite this advancement of two clusters, our analysis suggests that in all four cases the 'cluster rules' – the formal and informal understandings and norms – have not (yet) been produced and reproduced to an extent that promotes cluster interaction as much as policymakers or others with a regional economic interest would wish.

With respect to 'cluster resources' it is clear that a sufficient endowment of a cluster with financial, human and social resources eases cluster development significantly. However, it is not the resource endowment *per se* that is decisive, but rather, how agents draw upon these structures and use them to foster interpersonal and inter-organisational interaction, to make ongoing interactions more effective, or to direct and redirect resources flows. The cases studied – in particular the Berlin-Brandenburg case – show that even within a relatively short time frame significant results can be achieved if sufficient resources for network and cluster development are available – and if they are used in an appropriate manner. The question of sustainable assurance of sufficient cluster resources, however, is, in all four cases, an important task faced by managers and political actors alike.

Our research identifies some conceptual contradictions with Porter's rather static understanding of clusters. First, we believe that the argument for the existence of complete value chains necessarily being present in clusters is overemphasised in the Porterian cluster concept. Especially in high-tech and therefore dispersed industries such as biotechnology or photonics, value chains are usually global and only parts of the chain are likely to be agglomerated in a specific, well-defined region. Second, co-operation, though mentioned in Porter's cluster concept, needs significantly more emphasis, since its relevance goes well beyond functional interconnections. Otherwise, instead of providing an innovative milieu, a cluster would simply be an agglomeration. Third, the content of these dominantly co-operative interactions, the actual social practices of co-operation as well as the dynamic processes of structuration of the relationships need much more conceptual attention. All these are not reflected in the classical economic understanding of the cluster.

6 Future Research on Photonics Clusters

This research will be continued, looking into the micro processes of developing clusters in somewhat more detail, with particular regard to leadership and learning. In that context, *cluster leadership* is understood as action that 'makes things happen' (Huxham and Vangen 2005) in a cluster as a particular social system, often through the actions of others. As any action, leadership in general and cluster leadership in particular necessarily relies on structures, i.e. rules as well as resources. Like relationships these structures are produced and reproduced by the very action that 'makes things happen'. Because of the networked character of (real) clusters, 'relational leadership' in the sense of both relation-based and relation-focused mobilisation of action is of particular importance for developing the cluster in general and the networks in the cluster in particular. The study of actually practiced leadership in clusters, no matter whether initiated from 'above' as in many governmental programmes or from 'below' within or without the frame set by such programmes, necessarily supplements the investigation of leadership roles as they are seen, expected and reconstructed by the individual and corporate agents leading the cluster and those being led.

Cluster leadership in the sense of leading a cluster or, more broadly, leadership in clusters, may or may not foster 'local process learning' (Hibbert and Huxham 2005). *Local process learning* is a deeply contextualised, largely informal process related to the need to capture the learning about a particular collaborative context parallel to processes of engagement. It relates to the challenge of understanding enough about the *particular* people, processes and purposes of the collaboration, in order to support its development. The local process learning challenge will be new and subtly different in each collaboration; a general level of understanding of this challenge will therefore be helpful in underpinning managerial judgment and informing action within collaborations as they are experienced. It also adds an important nuance to research that aims to establish the competencies needed for collaborating (Williams 2002; Draulans et al. 2003); the constant potential for change as particular situations develop implies a continual need to learn, adjust and apply such understandings. It is likely that expectations of base motives, fear of relative powerlessness, or uncertainty about who partners *really* are (Durnell-Cramton 2002), are likely to become potential obstructions to local process learning in networks and clusters.

In the face of the results of this study, especially those concerning the structural properties of the systems studied, the question arises as to whether the cluster concept really captures the reality of high-tech 'clusters' in general and of photonics 'clusters' in particular. For despite its popularity even in these fields (e.g. Saxenian 1994; Powell et al. 2002; Cooke 2004; Di Tommaso et al. 2006), most interactions in these extremely science-based systems seem to be limited to the field of R&D, i.e. it takes place between research institutes, internal and external to universities, and firms, in particular small and medium-sized enterprises. Though this type of interaction may without any doubt be a potential source of future cluster development, it does not constitute a cluster by itself. Such an R&D-focused agglomeration may be more adequately named a Collectivity of Research and Entrepreneurship – or CoRE for short – but contradicts the idea of Porter (1998a, b) and others that a complete value chain is present in a cluster.

A CoRE[11] is made up of related practices of a number of research and entrepreneurial organisations in a region that interact intensively, aiming at technological innovation and that are supported in this process by regional institutions. Trade associations, state agencies, network brokers and network administrative organisations are among them. Despite the dominantly regional character of the interaction, the mostly project-based relationships of CoRE members typically stretch well beyond the limits of a particular region, especially since these very members have limited linkages to other stages of the value chain in the locality (see also Keeble and Wilkinson 2000: 12-13).

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[11] When talking of a CoRE we prefer the notion of a collectivity to that of a community of practices because the latter does not only inadequately address issues of innovation, power and manageability but also – like the original notion of *'Gemeinschaft'* (Tönnies 1935) puts too much emphasis on shared norms and values on the one hand and strong, affect-laden relations on the other. The notion of collectivity enables us to focus on specialisation-driven collaboration rather than ideational communality (cf. Lindkvist 2005).

This seems to be rather typical of science- in contrast to engineering-based industries, the former requiring the creation of new knowledge by close and systemic industry-university co-operation in the context of, for example, science parks or incubator centres (Asheim and Gertler 2005). However, it may be more common in some science-based industries than in others (e.g. biotech versus photonics). As such, a CoRE is a subsystem level construct that may well exhibit its own identity and that is potentially important in stimulating the emergence of a more encompassing high-tech cluster or innovation system.

Despite all the commonalities identified in the four photonics clusters the developmental paths of the clusters seem to be quite different. This implies that any measures undertaken in the development of the clusters will be situated in – and have to take into account – a specific context. Therefore our conclusions challenge Porter's (1998a, b) idea of identifying fully generalisable 'best' or even good practices for developing clusters.

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8 Appendix

Measures Practiced to Foster Developing Clusters

Cluster Measures	Berlin-Brandenburg	Southern Arizona	Scotland	West Midlands
Annual cluster strategy workshops	•			
Cluster meetings	•		•	
Members introduce themselves	•			
Speed dating			•	•
Optics colloquia	•	•	•	•
Focused cluster workshops	•	•	•	•
Special Interest Groups (SIG)	•			•
(Co-) organising national fairs	•		•	•
Web page	•	•	•	•
Newsletter	•	•		•
Online member competence database	•		•	
Member technology catalogue	•	•		
Collaborative regional technology concept/ road mapping	•		•	
Active network brokerage				
Co-ordination of collaborative projects	•			
Legal support				
Finance services				
Start-up support				
Brokering technical facilities				
Mentoring of new cluster members				
Presentation of photonics to the general public or schools	•	•	•	•
Collaborative masters degrees	•		•	
Provision of technical facilities				•
Seeding Company University Tech Transfer			•	
Promotion of cluster locally, nationally & internationally	•	•	•	•

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