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Analyzing and organizing nanotechnology development: Application of the institutional analysis development framework to nanotechnology consortia

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ABSTRACT

Governments and companies around the globe have embraced nanotechnology as a strategically critical pan industrial technology. Many view it as one of the essential foundation technology bases of the next Schumpeterian wave. A number of commercial and government sponsored groups have developed a variety of consortia centered on the commercial promise of nanotechnology. Yet the optimal management of these consortia has proven elusive to the point that some suggest that they cannot be managed at all. If these consortia are important, and their effective management crucial, then there is cause for concern. We utilize the case study method to create a nanotechnology consortia management diagnostic model based on institutional analysis development (IAD). Nanotechnology consortia are formed for a variety of purposes and their stakeholders include governments, industries, large firms, SME, entrepreneurial enterprises, and supporting firms.

1. Introduction

Nanotechnology a term first coined by Taniguchi (1974) and suggested as commercially extremely important (Fynman, 1960; Drexler, 1986) is finally being seen by public policy makers and researchers alike as a source (Roco, 2003, 2007; Wonglimpiyara, 2005, Drexler, 2004) of the next Schumpeterian or Kondratieff wave (Schumpeter, 1912; Kondratieff, 1937a,b). Due to the emergent nature and cross industrial use of the technology they are increasingly being commercially embraced through consortia (we use this word to refer to consortia, networks or alliance). Yet knowledge consortia are notoriously difficult to manage using traditional techniques. We seek to add to the answer of this need by developing a variant of the institutional analysis development (IAD) model.

We develop our modified IAD analysis model for the effective management of nanotechnology consortia through our literature review. We first develop three sets of drivers that promote consortia formation. We then present and apply the IAD framework to nanotechnology consortia management.

Our modified IAD framework reveals that knowledge as well as technological and commercialization complexities encourage the development differing consortia forms. Three forms dominate: consortia primarily dedicated to enabling networking between members; consortia driven by the need to bridge together complex equipment for R&D activities; and consortia with the objective of enabling or supporting downstream technology development. Finally, our diagnostic model assists potential stakeholders to decide if their needs align with their embrace of a particular group.

2. A framework for organizing cooperative nanotechnology development

The National Systems of Innovation (NSI) study describes the interactions between the public and private sectors while determining the innovative performance of such organizations (Nelson, 1993). This report includes the import, modification, and diffusion of new technologies; Freeman (1987) suggests that current deficiency band provides the framework within which governments form and implement policies to influence the innovation process (Metcalfe, 1995). Innovation in nanotechnology is often at the interface between nanotechnology and disciplines, the biological, chemical, and physical sciences, are creating knowledge complexities which are encouraging the formation of knowledge-based consortia (Corley et al., 2006; Rampersad et al., 2010). Our modified IAD model directly addresses the management of these consortia.

The IAD is a model that has been used to understand the governance of common pool resources. In order to utilize IAD for nanotechnology consortia management we need to first identify where individuals interact, exchange goods and services, engage in appropriation and provision activities, and solve problems (Ostrom et al., 1994). The activities and the multiple level of rules, and cumulative effect that the action taken obtained are unique in a

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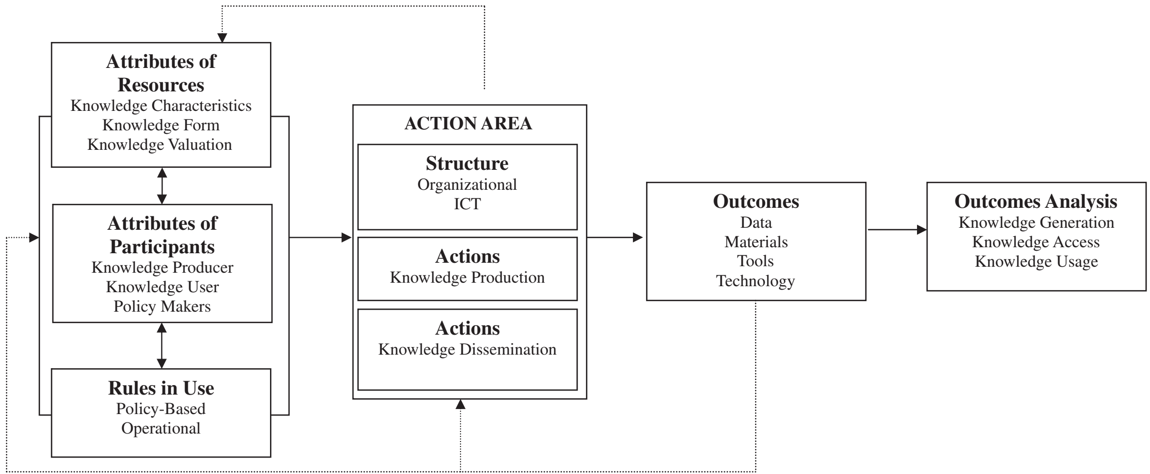

Fig. 1. Modified IAD framework for knowledge-based assets.

given consortium (Kiser and Ostrom, 1982). Fig. 1 illustrates a modified version of the IAD framework for the production of knowledge-based assets such as nanotechnology research in a variety of consortia and stakeholder typologies. We discuss the elements of the model below.

2.1. Consortia and stakeholder objectives

Stakeholders in consortia self-identify their competencies for the purpose of networking. They typically share information concerning scientific developments in the domain; funding and collaboration opportunities; encourage and support new discovery based knowledge generation; and support downstream product development. Consortia stakeholders control technological, knowledge, team member size and nature, commercialization complexities and voids. Interactions are either developed through personnel contacts or an ICT based infrastructure. These objectives are important in the case based on the complex nature of nanotechnology.

The commercial use of nanotechnology creates uniquely valuable solutions (Eijkel et al., 2007), but the required competencies to develop such solutions are often outside the scope of any single firm. Further, nanotechnology based applications are being increasingly applied to a great variety of fields (Mangematin et al., 2003; Allarakhia et al., 2010). Similarly, effective research and application nanotechnology research teams will be formed at the interface of technologies and include biological, chemical, and physical scientists to handle the multi-dimensional aspects (Ideker et al., 2001; Kitano, 2001; Kautt et al., 2007; Boardman, 2008; Boardman and Ponomarioy, 2009). Nanotechnology is not seen as an industry in itself but rather is seen as a pan or cross industrial technology competence (Walsh, 2004). Existing firms regardless of their size understand only a fraction of the industrial setting that the technology base can be applied to. Clearly, nanotechnology as part of a convergent solution often uniquely and dramatically creates value in a current industry setting or creates new ones. This aspect of nanotechnology often creates a need for consortia building since few nanotechnology knowledge generators (Linton et al., 2001) have industry quality competence in other technologies and few existing firms large or small (Kirchhoff and Walsh, 2000; Linton and Walsh, 2004) have a rich history in nanotechnology.

2.2. Attributes of resources

We utilize Hess and Ostrom's (2006) three-fold distinction for knowledge resources in our model to distinguish resources between facilities, artifacts, and ideas. Facilities store artefacts' in order to make them accessible. Artefacts are discreet, observable, nameable representations of ideas, such as articles, research notes, books, databases, maps, computer files, and web pages. Ideas are coherent thoughts, mental images, creative visions, and innovative information. Ideas are the intangible content and the nonphysical flow units contained in artefacts (Hess and Ostrom, 2006). Nanotechnology consortia necessitates a distinction between those resources that are inputs (funding, human capital, tools, equipment) and those that are outputs (information, materials, tools, products) to the consortia. Furthermore, we emphasize the specific character of nanotechnology-based knowledge by considering the form of knowledge (disembodied vs. embodied) as impacting its subsequent management. The knowledge outcomes are then managed physically or licensed to members and/or the public at large. Here, our modified IAD model effectively permits a knowledge-specific level of analysis.

2.3. Actors mapping as participants

Traditional IAD participants are categorized as those that are providers, those that are users, and those that are policy-makers (Hess and Ostrom, 2006). We modify these categories through participant motivation. We cite the motives that Foray (2004) and others identify like the need to manage complex product development issues. Motivation for participation will similarly impact the traditional IAD rules established to govern entry and exit from the consortium ensuring that the objectives regarding knowledge production and deposit levels are achieved and that knowledge appropriation does not occur prematurely (Ostrom et al., 1994). Knowledge flow is distinctly associated with driving motivation for participation in the consortium. Here, our modified IAD model provides an extension to the NSI examined models of knowledge flow by not only considering the mechanisms available, but also the link between participant type, anticipated motivation for participation and the choice and extent of knowledge dissemination (NSI, 2007).

In our model, roles may be assigned including: executive committee member with the responsibility of determining the overall goals of the consortium, seeking commitment from funding partners, and charged with participant selection and entry; scientific advisory committee member charged with the choice, the management and solicitation of projects, etc. while monitoring adherence to the rules prescribed by the consortium including appropriation of knowledge based assets (Ostrom et al., 1994; Munos, 2006).

2.4. Action area structure

Open innovation supply chain management literature assisted us in the modification of IAD action area structure for nanotechnology consortia—suggesting the use of structures to develop research or knowledge in a specific scientific or technological domain. (Hacklin et al., 2004; Grant and Baden-Fuller, 2004). Many of these nanotechnology alliances (Cassier, 2002; Walsh et al., 2002; Chesbrough et al., 2006) focus on the generation of knowledge and are not concerned with the possible application and embodiment of knowledge (Liebeskind et al., 1996; Stokes, 1997). A formal organizational structure, rules, and norms are typical of these types of network structure (Liebeskind et al., 1996). Further, members often provide resources that are complementary to and synergistic with the contributions of other members of the alliance (Child and Faulkner, 1998; Reid et al., 2001). This allows firms to benefit not only from their own knowledge, but also from the recombination of all firms knowledge (Kogut, 1998).

Many consortia, however, exist not only to create new knowledge, but also to accelerate knowledge application (Stokes, 1997). Projects and participants are often carefully chosen based on reputation and capabilities. These networks are marked by tight forms of governance and hierarchy (Reid et al., 2001). Issues relating to the ownership of intellectual property in these consortia are important (Oxley, 1999; Das and Teng, 2000, D'Silva, 2009) and access to knowledge and technology often restricted to members and licensee (Gulati and Singh, 1998; Kale et al., 2000; Allarakhia et al., 2010). Organizational structure choice is directed by governance strategy. We have modified the traditional IAD model to consider the relationship between participant type, governance strategy, participant motivation, and organizational structure.

2.5. Actions mapping as knowledge production

Modern consortia are not bounded by geographic distance (Foray, 2004). However, knowledge production and dissemination require the development of common data standards for the efficient communication and knowledge sharing mechanisms across disciplines and geographies (Hilgartner, 1996; Foray, 2004; Munos, 2006). The consortia research personnel's ability to learn from each other accelerates the creation of new products, job, and wealth (Larsson et al., 1998; Murovec and Prodan, 2009). The consortia create a collaborative learning-by-doing setting, which allows members to competitively manage both their cost and time to market during product development (Cohen and Levinthal, 1990; Murovec and Prodan, 2009).

2.6. Actions mapping as knowledge dissemination

Participants share disembodied pure knowledge including ideas, articles, papers, software, notes, results of experiments, patents as well as embodied knowledge in the form of nanomaterials, supporting tools and models that can be donated by participants. Disembodied knowledge are managed through interconnected databases. These databases may provide access to publications, patent data, nanomaterial characterization data, structural data for complex material synthesis, safety or regulatory data, and market studies. Embodied knowledge is often housed in material, tool, or model repositories.

The pharmaceutical industry for example has shifted from monomer chemistry therapeutic development approach to solutions requiring chemistry, biology, nanotechnology, MEMS, and computational sciences (Allarakhia and Walsh, 2011). This innovation strategy has necessitated commercial strategy shifts from a solely internally driven process to alliances or one that will likely arise from the ability to connect knowledge, people, tools, and equipment from different domains (Lee et al., 2010). Further, in February of this year, the Joint Research Center (JRC) announced the creation of the first European repository of nanomaterials and it contains most types of nanomaterials that are currently used for consumer products.

Precise market knowledge is scarce and market studies vary greatly. The original National Foundation Study (NSF) market study puts the value of these markets to be in excess of $1 trillion by 2015 (Roco et al., 2000; Roco, 2007). But other academic, policy maker and consultant based studies range from $300 million to $ 3 trillion during the same or similar time periods (Rao and Walsh, 2007; Mangematin et al., forthcoming; Barton, 2007; Lux Research Inc., 2007; Roco et al., 2000; Roco, 2007; Walsh, 2004). Moreover, few firms understand the public's reaction to nanotechnology, safety concerns or the broader social issues (Roco, 2003). Chen et al. (2011) to embrace the promise of nanotechnology. The repository provides a source for harmonized risk assessment, standardized methodologies development and develop consistent results across laboratories (Science Business, 2011).

2.7. Operational rules

Internal rules or mechanisms link governance strategy to participant behavior (Ostrom et al., 1994) and can be based on competency, competition, and resource value. These rules include: formalizing the requirements to join the initiative ensuring frequent interactions; encouraging communication between participants; monitoring and punishing defection; and setting the boundary for access to resources. Rules for participation should be understood at the outset such as the resource and or competency requirements to join the consortium. Rules must be clear as well for resource provision; resource control, access, and extraction must be determined in advance and communicated to consortium members. Exit rules are extremely important as well.

How participants share information and material by rule range from sharing with members only (closed access); or without restriction to the public at large (open access). For example, rules nanotechnology intellectual property rights on upstream products and technology can have profound consequences for future use in downstream activities and rules need to be developed such as copy-left licenses and royalty free, non-exclusive licensing (Ritala and Hurmelinna-Laukkanen, 2009; Hunter and Stephens, 2010; Lemley 2005). Further, there are seven major types of property rights that are most relevant to use in regard to the digital knowledge commons. They include: access to the area; contribution of content; extraction or the right to obtain resource units; removal or the right to remove one's artifacts from the resource; management or the right to regulate internal use patterns, and resource transformation; exclusion or the right to determine who will have access, contribution, extraction, and removal rights and how those rights may be transferred; and alienation or the right to sell or lease management and exclusion rights (Hess and Ostrom, 2006). We address this issue through the modification of the IAD model for the purposes of enabling nanotechnology development through exclusion and alienation rights.

When innovation occurs at the interface of many technologies and markets as is the case with much of nanotechnology development each discipline will have its own priorities and conventions regarding knowledge dissemination and knowledge appropriation (Hilgartner, 1996). One discipline signaling new knowledge generation through the enclosure and the sale of disembodied knowledge while another by its embodiment in a product. (Hilgartner, 1996). As collaborations cross institutional and national boundaries, the complexity of parceling out of intellectual property rights will greatly increase. Finally, consortia that enable participant collaborations with the objectives of technology transfer and infrastructure development (Gross and Allen, 2003; Romig et al., 2007; Schmidt, 2007; Linton and Walsh, 2008) are useful. Here the value of modifying the IAD model to reflect this will be the common or private valuation of such resources, and the subsequent impact on intellectual property management strategy employed.

2.8. Outcomes and analysis

An analysis of outcomes is used to verify if the achievement of consortia goals. As consortia have grown in more importance scrutiny has been placed on management processes of networks (Geels, 2002; Moller and Svahn, 2009; Rampersad et al., 2010; Allarakhia et al., 2010, Kajikawa et al., 2010). These include consortia membership (Gulati et al., 2000; Ritter and Gemunden, 2003; Heikkinen et al., 2007), consortia structures and participant interactions (Powell et al., 1996; Staropoli, 1998; Etzkowitz and Leydesdorff, 2000; Gulati et al., 2000; Moller and Rajala, 2007; Medlin 2006; Plank and Newell 2007), and consortia rules and norms (Gulati et al., 1994; Gulati and Singh, 1998; Corley et al., 2006). Bargaining power of participants in networks has also been examined (Allarakhia et al., 2010; Bosse and Alvarez, 2010). Most often measured outcomes include: the generation of data, materials, tools, and/or technology; access to the knowledge assets produced; and the usage of such assets in downstream activities.

A major goal of outcome analysis is continuous improvement or the ability of participants to learn from past mistakes and success. There are a number of financial measures, metrics and global metrics that are available to managers of consortia Yet, as we found with our own research few are used. Some global networks like "Frontiers" a EU centric bio-nano-consortia of research institutions, had metrics such as enabling joint research that received funding by participants. Others have metrics such as the number of patents filed and or publications produced. Some resource centric knowledge networks that have an anchor asset as a nanotechnology intensive small tech manufacturing facility (Tierney et al., Forthcoming) utilize manufacturing metrics. Global, national, and regional imperatives often seek to link job and wealth creation metrics. The value of our modified IAD approach is the ability to measure actions outcomes and other consortia activities at a variety of knowledge-based levels in an organized reproducible manner. The limitation of the model is the amount of data and information needed to drive it.

Table 1 summarizes the components of the modified IAD framework and the impact either on the requisite infrastructure or policies required to govern the interactions that occur within the action area or consortium.

3. Methodology

We initially used secondary literature including documents and/or databases to select nanotechnology consortia (Eisenhardt, 1989; Yin, 2009). The nanotechnology consortia selected are not only globally dispersed enabling for an analysis of the developments in this domain across markets, but represent an adequate selection of consortia with at least one of the suggested complexities driving formation. We triangulated literature sources which included peer-reviewed journal articles by consortia members or third-party researchers, press-releases, consortia websites, publications, and/or presentations (Eisenhardt and Graebner, 2007),

The results were also substantiated with a survey instrument sent to the directors of the consortia (Fowler, 2009). These directors were asked to verify the focus of consortia, the types of participants including private sector participants, governance strategies, and the existence of rules regarding intellectual property management. While we initially sought to analyze the impact of driving factor on formation of the consortium, the second level of analysis sought to determine the similarities and differences in governance strategies employed by the consortia. Based on this cross-case analysis, several governance issues were isolated and used to develop the proposed framework including organizational structure, participant type, roles assignment, project selection, project management, knowledge production and dissemination, use of supporting technology, as well as resource control, access, and use.

The consortia analyzed include the Accelrys Nanotechnology Consortium, BioNanoNet, EuroIndiaNet, ICPC NanoNet, the Global Nanotechnology Network (GNN), the MEMS Consortium, NanoNed, and the National Nanotechnology Infrastructure Network (NNIN). Driven by at least one primary complexity—technological, knowledge, or commercialization, the consortia provide an interesting assessment of models of innovation currently being used to promote the nanotechnology arena (see the appendix for details about each consortium).

Table 1
A framework for organizing cooperative nanotechnology development.

Governance issue	Description	Impact
Objectives	Networking, information/resource provision, discovery research, technology support, product development	Organizational structure and ICT requirements.
Participants/roles assignment	Participant type: public or private sector	Entry requirement: need for upfront requirements; entry based on scientific credentials and other selection parameters; exit rules.
	Roles: executive committee, scientific advisory committee, boundary spanner, project manager, contributor, monitor	Selection of participants for designated roles.
Organizational structure/ technology infrastructure	Open network vs. development network ICT Infrastructure; discovery or development tools	IP concerns and need for IP management. Need to source or internally develop infrastructure and/or tools.
Knowledge production/project selection/project management	Individual research vs. teams; virtual network; conferences, workshops; training exchange programs Proposal solicitation; team formation Monitoring; tool provision; resource management	ICT/resource requirements. Criteria used to select proposals and form teams. Criteria used to evaluate progress; sourcing of tools used for discovery or development.
Knowledge dissemination	Disembodied knowledge vs. embodied knowledge	Need to manage various knowledge assets including data, articles, patents, materials, models, tools.
Resource control, access, extractions	Rules govern resources; dissemination policies	Policies governing access (open vs. closed access); IP management (copy-left for data, non-exclusive licensing for materials, models, products); agreement and adherence to rules governing resources.

4. Application of the modified IAD framework to nanotechnology consortia

Is the IAD model appropriate? Can we map these consortia to our model? Can this model assist in the proactive management and evolution of consortia? Using the data attained and generated in our case studies we now begin the task of mapping the modified IAD framework to the selected nanotechnology consortia. We show that the use of our model and analysis would have improved these cases results.

4.1. Objectives

The case analysis revealed that nanotechnology consortia seek to address key complexities associated with the domain (Table 2). EuroIndiaNet, ICPC NanoNet, and GNN specifically address knowledge complexities—bridging together information based resources and enabling human capital development. The NNIN, the MEMS Consortium, and even NanoNed address technological complexities—bridging together laboratories, equipment and large-scale infrastructure needed for downstream activities. Finally, the Accelrys Consortium, BioNanoNet, NanoNed, and the MEMS Consortium address commercialization complexities—directly in supporting product development and venture development.

4.2. Attributes of resources

Facilities, artefacts, and ideas are either contributed to or generated by consortia members. These resources consisting of information, facilities, equipment and tools, as well as expertise, are used to generate partnerships, technology, or develop human capital. In the majority of cases, facilities contributed and accessible by members or partner organizations include research labs housing sophisticated equipment and tools for nanotechnology development. In the case of BioNanoNet, NanoNed, and NNIN, the associated research labs are geographically dispersed and linked via consortia portals. Artefacts' (or embodied knowledge) include research papers contributed to article repositories, databases generated to provide information on organizations, researchers, educational programs, funding and collaboration opportunities, and analytical tools contributed and then augmented by members. In all cases, disembodied knowledge or ideas are generated and shared through associated portals or at workshops, education, and training events. In this case, we contend that the objective set at the outset of consortium formation determined the resource commitments and generation (Table 3). These consortia fit the boundaries of our model concerning resource attributes.

4.3. Participant type

The Accelrys Nanotechnology Consortium, having its origins in the private sector, sought to collaborate with academic organizations. The success of the Accelrys Nanotechnology Consortium is not only measured by its 20 plus members, but by the amount of new software solutions it has developed to meet customers' needs (Accelrys Nanotechnology Consortium Brochure, 2010). The Singapore MEMS Consortium also brings together private sector members, (supported by the Institute of Microelectronics (IME)—the research arm of Singapore's Agency for Science, Technology, and Research (A*STAR) and the Singapore Economic Development Board (EDB) (IME, 2010)). In addition to membership fees, MEMS Consortium members must have operations in Singapore.

NanoNed partners are devoted to developing cooperations in nanotechnology in various application areas. Due to the considerable size of the NanoNed program it has been divided into overarching themes called flagships. These programs are led by senior researchers or professors who are called flagship captains. In addition, NanoLab NL provides a coherent and accessible infrastructure for nanotechnology based research and innovation. Companies and researchers are permitted access to the NanoLab expertise and facilities. Equally, companies and researchers can participate in the NanoNed endeavor through user committees tied to each flagship—permitting knowledge dissemination (NanoNed Brochure, 2010). The task of the users' committee is to provide adequate supervision of each flagship and to ensure that researchers do not lose sight of the application aspect whilst carrying out research. It provides information, and also functions

Table 2
Consortium driving complexity (ies) and objectives.

Consortium	Primary driving complexity (ies)	Objective
Accelrys Nanotechnology Consortium	Commercialization	Technology development
BioNanoNet	Commercialization	Product development support
EuroIndiaNet	Knowledge	Stakeholder linkage
Global Nanotechnology Network	Knowledge	Stakeholder linkage, training
ICPC NanoNet	Knowledge	Stakeholder linkage
MEMS Consortium	Technological and commercialization	Technology development
NanoNed	Technological and commercialization	Product development support
NNIN	Technological	Product development support

Table 3
Consortium resource commitments.

Consortium	Shared Resources
Accelrys Nanotechnology Consortium	Analytical tools
BioNanoNet	Funding, information, facilities
EuroIndiaNet	Information, facilities
Global Nanotechnology Network	Information, facilities
ICPC NanoNet	Information
MEMS consortium	Funding, equipment, human capital
NanoNed	Funding, infrastructure, equipment, human capital
NNIN	Infrastructure, equipment, human capital

as a discussion partner (NanoNed Brochure, 2010). In parallel, the BioNanoNet comprises of 30 partners from universities, non-profit research institutions, and industry. The network has identified and is focusing on six research areas—termed lighthouses, that are generally regarded as being of key future economic importance for Austria (BioNanoNet, 2010). Worth noting is that BioNanoNet initiates and subsequently coordinates national and international research projects at different stages of the pharmaceutical value chain with the sole goal of retaining the entire value creation process in Austria (BioNanoNet, 2010). This appears to be a central principle of the Singapore MEMS consortium with not only the need for members to have operations within Singapore, but also free access to intellectual property ensured for those organizations seeking to exploit the technology within Singapore (IME, 2010). The flexibility of our modified IAD model allows us to manage these differing participant types.

4.3.1. Collective policies

Continuing the participant type analysis and taking advantage of the multiple levels of analysis possible with the IAD model, the role of government became apparent in the creation of several consortia. EuroIndiaNet was created under EU's 6th Framework Program to promote stronger innovation through cross-border collaborations between EU and Indian scientists, private sector firms, research organizations, and policy makers (EuroIndiaNet Brochure, 2009). As an extension, ICPC NanoNet is funded by the EU under the 7th Framework Program (FP7) bringing together academic, private sector, and non-profit research organization partners from the EU, China, India, Russia, and Africa. Activities funded from FP7 must have a European added value. The European added value is apparent in the transnationality of many actions including research projects carried out by consortia which include participants from different European (and other) countries; fellowships in FP7 also require mobility over national borders (ICPC NanoNet, 2010). On a global scale, the GNN was launched by international partners in 2001 and has been developed through a series of international workshops involving researchers, educators, and policy makers from academia, non-profit research organizations, government, and industry (GNN, 2010). Equivalently, government catalyzation is apparent in the National Nanotechnology Infrastructure Network and Singapore MEMS Consortium. The NNIN is an integrated partnership of 14 academic (user) facilities, supported by the US National Science Foundation (NSF), to provide unparalleled access to nanotechnology based research infrastructure (NNIN Brochure, 2010). The Singapore MEMS Consortium is supported by government-based agencies to promote the sector in Singapore (MEMS, 2010).

4.4. Organizational structure

From our analysis, we were able to categorize consortia as those dedicated to encouraging networking and knowledge dissemination, those that were driven by the need to provide access to large scale assets including equipment and laboratory space, and those supporting technology development (Table 4) As advocated by our modified IAD model, several rules-in-use were in place to manage participant entry into the consortia. Finally, we were able to determine the ICT infrastructure needed to enable participant interaction and ultimately knowledge flow. We are able to assist in their management through our modified IAD model.

The EuroIndiaNet, ICPC NanoNet, and GNIN for example, primarily use information and communication technology to bridge together partner organizations and researchers in the nanotechnology arena—focusing on the upstream stages of discovery research by encouraging networking and knowledge dissemination. Beyond the initial EuroIndiaNet partners, it was proposed that other institutions could be identified and contacted to join the platform. Platform partnership members would decide on membership by vote. The possibility of using payment for membership as a source of funding the platform was also discussed (EuroIndiaNet Deliverable 11, 2006). Likewise, the original partners of ICPC NanoNet were established in the application created under FP7. In this sense, both EuroIndiaNet and ICPC NanoNet are closed access networks at the partnership level. ICPC NanoNet partners are organized into work packages and are responsible for various initiatives such as managing the nanotechnology publication archive, publishing the annual report, organizing other dissemination activities, or managing the overall project. The director of ICPC NanoNet confirmed however, that participants with the objectives of networking, participating in workshops, training and educational events, could join the virtual network provided by ICPC NanoNet by completing a simple registration process. GNIN similarly enables for membership via a registration process through the network's virtual portal.

BioNanoNet functions essentially as an R&D support network—enabling stakeholders from the pharmaceutical industry to quickly and efficiently find reliable R&D partners with the required expertise from amongst the network. NanoNed and NNIN function as closed access networks at the partnership level—having determined the partners and user facilities during formation of the networks. Common to BioNanoNet, NanoNed, and NNIN are their efforts to address the technological complexities associated with nanotechnology. Each consortium links geographically dispersed "centers of excellence" to provide open access, both on site and remotely, to human capital and equipment to external nanotechnology stakeholders (BioNanoNet, 2010; NanoNed Brochure, 2010; NNIN Brochure, 2010). Here, we see the usage of varied organizational structures at the partnership level and user level. Simple contact, queues based on user type, or project applications are used by stakeholders to begin the process of accessing the BioNanoNet, NanoNed or NNIN resources respectively. The Accelrys Nanotechnology Consortium and the Singapore MEMS Consortium both operate as closed networks requiring membership fees to be paid to join the initiative. Both consortia are focused on the downstream aspects of nanotechnology where intellectual property

Table 4
Nanotechnology consortium organizational structures and participants.

Consortium	Organizational structure	Participant type	Entry rules
Accelrys Nanotechnology Consortium	Closed	A, P	Monetary commitment
BioNanoNet	Partner-linked	A, N, P	Expert review and membership fee; project based
EuroIndiaNet	Virtual	A, N, G, P	Vote by partnership
Global Nanotechnology Network	Virtual	A, N, G, P	Open application
ICPC NanoNet	Virtual	A, N, G, P	Closed at partnership level; application for portal access
MEMS Consortium	Closed	N, G, P	Monetary commitment
NanoNed	Partner-linked	A, N, P	Closed at partnership level; user committees for knowledge dissemination
NNIN	Partner-linked	A,G	Project based

A=academic; N=non-profit research organization; G=government agency or laboratory; P=private sector organization.

concerns are paramount and typical of such development networks.

4.5. Knowledge production and dissemination

In most cases, the consortia use training events and workshops to generate knowledge. For example, our analysis revealed that members and associated researchers needed to have opportunities to meet and discuss in person their priorities with respect to research and suitable research methodologies. Beyond these events and workshops, some consortia members deemed it necessary to foster the exchange of personnel between organizations for extended periods of time in order to meet the goal of human capital development (EuroIndiaNet Brochure, 2009; GNN, 2010). The flow of knowledge via movement of human capital is equivalently discussed in the NIS model. Where we contend that our modified IAD approach differs, is the impact of knowledge structure—disembodied or embodied—on choice of knowledge dissemination mechanism. As discussed earlier, databases, material, model, or tool repositories, even laboratories physically housing equipment, are varied options to permit knowledge dissemination and access.

From our analysis, consortia primarily use databases, tool repositories, or laboratory space housing equipment to permit knowledge dissemination or learning-by-doing opportunities respectively (Table 5). Specifically, to permit knowledge dissemination, consortia (specifically those consortia not engaged in selected stakeholder projects) utilize either closed or open portals and databases. Portals encourage member discussions and hence virtual collaborations; databases permit the sharing of resources such as research papers and articles, consortia-based reports, presentations, and contact information for key experts, the location of facilities or list of available tools, and the location of educational programs (EuroIndiaNet Brochure, 2009; GNN, 2010; ICPC NanoNet, 2010; NanoNed Brochure, 2010; NNIN Brochure, 2010). For consortia engaged in stakeholder-based projects, learning-by-doing provides a unique opportunity for knowledge transfer between network partners and participants (BioNanoNet, 2010; MEMS, 2010; NanoNed Brochure, 2010; NNIN Brochure, 2010). In addition, given the complexities associated with nanotechnologies, stakeholders can enjoy access to technology (including tool access) early in the discovery and development process through membership in such knowledge networks.

4.6. Governance

Many of the consortia analyzed had instituted rules to manage participants and projects (Table 6). Advisory or experts boards for example are often charged with the responsibility of screening and selecting participants as well as guiding the research program and/or choosing projects (including stakeholder projects) for the initiative (EuroIndiaNet Brochure, 2009; GNN, 2010; NanoNed Brochure, 2010; NNIN Brochure, 2010). In the case of the Accelrys Nanotechnology Consortium, the members are charged with steering the future direction of software technology development for Accelrys (Accelrys Nanotechnology Consortium Brochure, 2010). Unique to NanoNed is the existence of not only the board—with the mandate to create policy and make decisions about the organization of the program, to grant individual projects, and to organize overall activities for NanoNed, but also the industrial advisory board—used to advise the board on important technological and societal trends in the nanotechnology domain (NanoNed Brochure, 2010). For the MEMS Consortia, all members serve as steering committee members with the Singapore Institute of Microelectronics (IME) acting as project manager (IME, 2010). Finally, the BioNanoNet partners' role is to provide information on and contact experts who are willing to join projects coordinated by BioNanoNet members; alternatively, BioNanoNet partners may join stakeholder initiated and coordinated projects (BioNanoNet, 2010). The flexibility inherent in our modified IAD model allows for its effective use in the governance issues of these differing consortia.

4.6.1. Intellectual property management

The need to manage intellectual property (IP) is of significance in the Accelrys Nanotechnology Consortium, the MEMS Consortium,

Table 5
Understanding knowledge production and knowledge dissemination within consortia.

Consortium	Knowledge production	Knowledge dissemination
Accelrys Nanotechnology Consortium	Training, workshops	Members' only portal
BioNanoNet	Training, workshops, via client projects	Virtual portal, publications
EuroIndiaNet	Virtual, training, workshops	Database, virtual portal, publications
Global Nanotechnology Network	Virtual, training, workshops	Database, publications
ICPC NanoNet	Virtual, training	Database, publications
MEMS consortium	Workshops	Publications
NanoNed	Via flagship projects	Members' only portal, database, publications
NNIN	Via client projects	Virtual portal, database

Table 6
Governance strategies and outcomes.

Consortium	Governance	Outcomes
Accelrys Nanotechnology Consortium	Membership fees; closed access to tools; IP owned and managed by Accelrys	Technology development
BioNanoNet	Membership fees; project reviews; IP stays at the client site	Partnerships/technology development
EuroIndiaNet	Open access to resources	Training/partnership development
Global Nanotechnology Network	Open access to resources	Training/partnership development
ICPC NanoNet	Open access to resources	Information sharing/partnership development
MEMS consortium	Membership fees; contractual agreement; closed access to technology; IP managed by consortium; no fees for licensing and usage within Singapore	Technology development
NanoNed	Categories of users of NanoLab; IPR filed and managed for members	Technology support/development
NNIN	Project based application	Technology support/development

NanoNed, BioNanoNet, and the NNIN. As discussed earlier, the technology developed within the Accelrys Nanotechnology Consortium is owned and controlled by Accelrys, with early and exclusive access (available prior to commercial availability) provided to members as part of their membership fees. Members are granted lifetime rights to all consortium deliverables (Accelrys Nanotechnology Consortium Brochure, 2010). The MEMS Consortium uses a contractual agreement to bind member activity with respect to IP exploitation. The IP is owned and managed by IME and provided to members free of charge for manufacturing in Singapore. There is however a fee (to be negotiated) if IP is to be used for manufacturing outside Singapore (MEMS, 2010). In contrast, intellectual property rights for NanoNed members are established in the name of the consortium partners whose employees made the discovery. If the results are generated by two or more consortium members and are indistinguishable, then the members concerned are joint owners of the results. If a company from outside the NanoNed consortium (often a member of the users' committee) is interested in obtaining a license then this can, in principle, be granted in exchange for the current market fee (NanoNed Brochure, 2010). Finally, BioNanoNet clients and users of the NNIN facilities, interact with experienced consortium members and staff respectively for assistance and access to resources, while retaining full control over the associated intellectual property. For BioNanoNet, the IP remains with the client; therefore, BioNanoNet itself does not gain the IP but supports client members to acquire IP in their projects. In the case of NNIN, the universities comprising the network providing access to the facilities make no claim on user intellectual property as the relationship involves only the purchase of equipment services rather than a research agreement (NNIN Brochure, 2010) (Table 6). Given the levels of analysis possible in the IAD model, noteworthy is the usage of both collective policies and operational rules to regulate appropriation strategies. For instance, at a collective policies level, grant agencies or other such catalyzing agencies may advocate appropriate exclusion and alienation rights. At an operational (day to day) rules level, participants may be required to disclose new knowledge based assets generated via consortium based interactions.

4.7. Outcomes

There are several measures that can be used to assess the performance of each consortium. Such measures are likely common to the NIS model in terms of assessing knowledge flow. In the case of consortia dedicated to aggregating resources, offering training courses, and exchange opportunities, measures of success can include the number of resources collected and/or hosted on the associated portals, the number of courses offered as well the number of attendees, and finally, the number of exchange opportunities afforded to members. ICPC NanoNet currently has over 7000 items its publication archive, over 800 researchers and 1000 organizations in its database, has held several webinars and conferences. Similarly GNN has held several global workshops. As an outcome of the 2009 workshops held in Rio, is the development of a plan to establish the Pan-American Nanotechnology Network (PNN), as part of the larger GNN (2010).

For consortia assigned the task of completing member or other stakeholder projects, performance assessment measures can include the number of projects completed, the intellectual property assigned, papers published, or the products under development as a result of consortium activities. BioNanoNet has successfully supported several project proposals and coordinated joint research projects such as NanoTrust, Nano-Health, and Euro-NanoTox (BioNanoNet, 2010). NanoNed has educated 300 PhD. student for nanotechnologies, enabled the establishment of 7 start-up companies, acquired approximately 60–70 patents, published numerous scientific papers, has actively participated in public debates on nanotechnologies, and has supported the writing of a Nanotechnology Action Plan of the Dutch Government. The NNIN actually produces statistics to monitor the number of users of the facilities at each of the 14 sites on a monthly and year basis including a categorization by user type (NNIN Brochure, 2010). In terms of product development, the MEMS Consortium has conducted initial feasibility development and testing for various technology modules and Accelrys Nanotechnology Consortium has successfully developed leading-edge technologies for studying large-scale, complex systems and validated streamlined protocols for complex tasks. The recent phase sought to deliver flexible software solutions that address the advanced materials and nanotechnology-based industries' need for a more design-oriented approach to nanotechnology—namely, Computer Aided Nanodesign (CAN) (Accelrys Nanotechnology Consortium Brochure, 2010). Most consortia are like those we review here, however, tend to lack an analysis at the outset and often seek to develop them as the network grows. Our modified IAD model allows for the interaction between outcomes—both positive and negative including the development of physical infrastructure, the crafting of legal rights, and development of social capital—that ultimately determine sustainable knowledge dissemination and access (Hess and Ostrom, 2006).

5. Findings, discussion and conclusion

We discuss that nanotechnology based consortia are exceptionally important to future regional wealth and job creation. Past experience has demonstrated that large-scale collaborations permit the participants to cost-effectively and quickly access the discovery based research and technological tools to move into product development (Allarakhia et al., 2010). We further contend that the effective management of consortia is difficult and have added to the literature through the development of our modified IAD model which addresses this issue. The saliency of the IAD model arises from the multiple levels of analysis, the association between participant types and resource attributes as impacting resource governance strategies. We also show that consortia participation has moved from pre-competitive research to, in the case of nanotechnology, converging technology based product development. Consortia have to address new product development challenges and following these developments should prove worthwhile (a limitation in our analysis given the current focus of the selected consortia).

We provide some evidence from the NanoNed and the NNIN of this move toward larger scale and infrastructure based collaborations. As partners jointly collaborate to develop nano- (and micro-scale) products, management of intellectual property generated by consortia members as well the outcomes from consortia become critical. For example, in a previous study of biotechnology based consortia, issues such as intellectual property management have been addressed through creative solutions including open access and open licensing (Allarakhia et al., 2010).

We revealed that several different models of governance are utilized by the selected nanotechnology consortia (see Table 6). These consortia used both open and closed access models. Interestingly in some cases, consortia members' generated new knowledge, in other cases consortia partners support other stakeholders in their nanotechnology development activities. Our analysis reveals the importance of determining the role that the stakeholder assumes in catalyzing the consortium. A role that is uniquely captured in our modified IAD approach. For example the influence on the governance strategy adopted and expected outcomes in the case of the Accelrys Nanotechnology Consortium. Similarly, one can argue that consortia catalyzed by government based agencies appear to have the goal of enabling networking and supporting the development of the domain itself either through training endeavors such as those provided by EuroIndiaNet, ICPC NanoNet and the GNN, or the provision of supportive services as in the case of the NNIN and NanoNed.

There are a number of existing basic nanotechnology patents (D'Silva 2009; Lemley 2005). The often complex ownership of these patents is creating hurdles for downstream product development. Many of these foundational patents have pan industrial implications. The bargaining problems and holdouts could impact several firms and industries. The use of nanotechnology patent pools, open source licensing for such building blocks, non-exclusive licensing, and cross-licensing are all suggested solutions (Lemley, 2005; D'Silva, 2009). While we provide an initial discussion, we need further effort on how consortia will uniquely manage and craft patenting rules. Consortia are beginning to address this need and the IAD model offers an effective analytical solution for understanding the common vs. private management of knowledge based assets—extending the discussion beyond the mechanisms used for and measures of knowledge flow in the NIS model. A variety of mechanisms are indeed in use including: the use of membership fees to ensure exclusive access to technology; regulations stipulating the geographic limitations for exploitation of the resulting technology in exchange for free access; differential licensing fees for access by researchers external to the consortium; and finally, simply supporting associated researchers to acquire and control their own intellectual property. Our efforts suggest the effectiveness of these types of actions and we assert that consortia should give further thought to ensuring broad access to resulting intellectual property as a rule or a norm.

The new potential Schumpeterian economic waves might be named the era of convergence. This emphasis on convergence is expected to open new opportunities across several sectors. Understanding the opportunities available in combining developments from different fields should enable innovators to outpace their competitors pursuing developments in isolation. Clearly there is role for national policies to enable the bridging of disciplines and advocating the management of knowledge based resources. Specifically, learning must take place, knowledge must be disseminated, and IP or technology must be accessible to innovators to reap the benefits of collaboration at the firm and even national levels, equally advocated by the NIS model. Given the anticipated scale of collaboration, the attributes of any collaboration as discussed in this paper must be known in advance. National and firm level policies—key elements in the IAD model, can support transparency in these collaborations.

In summary, we provide a beginning look at how consortia stakeholders are organizing themselves in the nanotechnology arena by modifying and applying our own version of a nanotechnology based specific consortia IAD. We have shown how our model added value to the three types of nanotechnology consortia reviewed. We have a future goal of transferring the lessons learned in this paper to other emerging sectors. The goal of future research in this area should be a better understanding of emerging technology consortia. We see future research focusing on an understanding of the shifting nature from pre-competitive discovery to fully embracing complex product development. We provide a basis for new consortia to learn from the successes and failures of those we chronicle in order to generate cost and time effective new technological solutions.

Appendix

Accelrys Nanotechnology Consortium: the Accelrys Nanotechnology Consortium gives members from academia and industry the opportunity to work in collaboration to steer Accelrys' development of leading-edge modeling and simulation software technology. This Accelrys initiated consortium aims to directly address members' needs to rationally design nanomaterials and nanodevices for applications ranging from the design of catalysts, coatings and adhesives, to new materials for electronics applications, and provides early and exclusive access to jointly developed leading-edge technology (Accelrys Nanotechnology Consortium Brochure, 2010).

BioNanoNet: BioNanoNet is an Austrian Network that connects companies, universities, and non-profit research organizations. BioNanoNet has created a broad technology platform with the objective of enabling innovative interdisciplinary research focused on the development of nanomedicines and nanotoxicology. In addition, the network develops and coordinates national and international research projects in close cooperation with its members. Hence, this network serves as a research based consortium—collaboratively and internally conducting research and as a partner based consortium—collaboratively enabling external stakeholders to conduct research (BioNanoNet, 2010).

EuroIndiaNet: EuroIndiaNet brought together a consortium of institutions from the EU and India to provide a medium for discussions on various issues related to nanotechnology. The project established an EU-India cross-border strategy implementation plan with the aim of initiating other nanotechnology research collaborations between the EU and India (Ramachandran, 2006). While the EuroIndiaNet commenced in 2006 and was concluded in 2007, its successor is the International Cooperation Partner Countries (ICPC) NanoNet project.

ICPC NanoNet: the project brings also together partners from the EU, China, India, and Russia to provide wider access to published nanoscience and nanotechnology research and opportunities for collaboration between scientists in the EU and International Cooperation Partner Countries (ICPC NanoNet, 2010).

The Global Nanotechnology Network (GNN): in parallel, the GNN consists of diverse nanotechnology stakeholders from industry, academia, and government and is dedicated to promoting beneficial collaborations in nano-research, education, and networking through the sharing of resources, the development of education events and workshops, as well the use of databases to link stakeholders respectively (GNN, 2010).

Singapore MEMS Consortium: Singapore's microelectromechanical systems (MEMS) consortium is a group of 9 global companies and is supported by local research and government to facilitate and grow Singapore's expertise in this arena. Resembling the Accelrys consortium, MEMS has the objective of enabling downstream efforts; in addition, the MEMS consortium supports the mandate of the EuroIndiaNet, ICPCNanoNet, and the GNN in terms of encouraging networking and human capital development (IME, 2010).

NanoNed: NanoNed is a Dutch initiative by 8 centers of excellence and Philips, and covers investments in experimental facilities, scientific research, and knowledge dissemination. Under the NanoNed umbrella are the NanoNed NL program—to build up, maintain and provide a coherent and accessible infrastructure for nanotechnological research; the technology assessments program—to assess the ethical, legal, and social aspects of nanotechnology based projects; and the valorization program—to support intellectual property management and venture creation based on nanotechnology (NanoNed Brochure, 2010).

National Nanotechnology Infrastructure Network (NNIN): sharing the NanoNed NL model is the National Nanotechnology Infrastructure Network (NNIN). The mission of National Nanotechnology Infrastructure Network (NNIN) is to support advancements in nanotechnology by providing efficient access to nanotechnology infrastructure. The NNIN provides access to shared open, geographically diverse laboratories—each with specific areas of technical excellence—and provides fabrication, synthesis, characterization, and integration resources to build nanotechnology (NNIN Brochure, 2010).

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