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Innovation and sustainability in print-on-paper: a comparison of nanoparticle and deinking niches as emergent sociotechnical networks

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Abstract

Nanoparticle innovation with application to 'print-on-paper' is analysed as an emergent network using social network mapping methods. Its relationship with the innovation network concerned with deinkability for enhanced fibre recycling is explored. Three types of nano-innovations are identified: ink, fibre and coatings applications embedded in heterogeneous networks of nanoparticles and deinkability. It is shown that, in spite of expectations for the potential contribution of nanoparticle technology to deinkability, the networks are poorly linked. The primary role of the nanoparticle innovations identified is for commercial printability rather than sustainable deinkability. These findings suggest that broad claims for the contribution of nanotechnology to sustainability are not necessarily translated into specific innovation priorities in business practice. If such potential is to be realised then these currently separate networks need to be linked much more effectively. Key gatekeepers are identified who could potentially contribute to the achievement of this.

Keywords: Nanotechnology; Innovation; Sustainability; Paper recycling industry

1. Nanoparticles, sustainability and sociotechnical networks

The paper explores the dynamics of interaction between innovations in a novel generic technology and those in a more established sustainability oriented technology. These are analysed as different niches within a sociotechnical system in order to assess their potential in a prospective sustainability transition. Nanoparticle innovations in print-on-paper are investigated in terms of their relationship with deinking innovations for the sustainable recycling of digitally printed paper. Expectations have been promoted that nanotechnology offers the prospect of radical innovation in control over the adhesion of ink to paper which could contribute significantly to such a pursuit of sustainability. Yet it has also been observed that the pursuit of improved printability may be in conflict with better deinkability. This study addresses the dynamics of innovation in nanotechnology and sustainability through an empirical analysis of emergent sociotechnical networks [1]. The results show that nanotechnology and sustainability can now be appraised in a less abstract and more situated fashion.

Nanotechnology is often framed as a new generic technology with sustainability potential [2] underpinning 'a new generation of innovative technologies that fulfil ecological criteria' [3]. Such arguments are drawn on, along with competitiveness in the promotion of nanotechnology in Europe and the UK [4,5]. Nevertheless nanotechnology is also open to diverse interpretations over its feasibility, contribution to sustainability, and its potential risks. A recent study suggested that nanotechnology was in a stage of embryonic innovation and 'path creation' which meant that it was difficult as yet to judge its contribution to sustainability [6]. Expectations of the contribution to sustainability of nanotechnology innovations are therefore, very difficult to judge in general and need to be assessed in relation to particular technological paths.

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This study explores it in the situated context of nanoparticle innovations in print-on-paper.

In spite of concerns regarding resources and biodiversity, global paper production and consumption have continued to increase. Printing and writing paper constitute 31% of world paper production [7]. For the growing cut sheet office paper sector the proportion of recovered fibre remains small [8]. A particular focus of importance is to address the rapidly growing problem of deinking and recycling digitally printed paper texts − mainly from inkjet and laser printing. Innovations in deinkability of print-on-paper for recycling and recovery draw on a range of new and old technologies in the pursuit of this goal. Nanoparticle innovations applied to paper coatings and printing inks offer the prospect of greater control over the adhesion and sorption of print-on-paper which could potentially facilitate deinking and recycling.

Innovation can be analysed as a process of construction of a heterogeneous sociotechnical network by enrolment of diverse actors through boundary spanning and communicative interaction. The significance of an innovation arises from the stabilisation and durability of this network [9]. Freeman [10] stresses that technological innovations must be supported by a corresponding evolution of social arrangements and institutional support, and Hellstrom [11] argues similarly for ecoinnovation. The idea of a network is not simply a distinct mode of governance or policy instrument but is a fundamental conceptualisation of the process of innovation itself [12]. Social network theory has offered several insights of great value. The diffusion studies of Rogers highlighted the nature of communication networks in the interorganisational spread of innovations; the explanatory and practical value of the concept of homophilous and heterophilous networks; and the distinct yet complementary contribution of strong and weak ties [13]. More recently studies have explored the situatedness of innovation discourses within social networks [14] and the role of users in the constitution of innovative networks of practice [15].

Actor network theory is another conceptualisation of the sociotechnical network. Callon [16, p. 83] points to the particular orientation of ANT, concerned with the ''steps from the birth of an idea (invention) to its commercialisation (innovation)'', achieved through description of the links between human and non-human elements, thus people, organisations and artifacts are constructed into an interacting system which changes over time [16−26]. It uses the principle of symmetry between the social and natural world, and aims to ''describe given heterogeneous associations in a dynamic way and to follow, too, the passage from one configuration to another'' Callon [16, p. 100]. The concepts of ANT include the process of negotiation and enrolment that actors go through to join the network. The dynamics of change are constructed through ''obligatory points of passage'', resulting in a construction of the sociotechnical network which is both stable and robust, while Callon uses the concept of 'translation' to explain the dynamic process of the network.

Network theories of innovation highlight the role of boundary spanning intermediaries in the network building process. Early work on gatekeepers by Allen and Cohen [27], and Tushman [28] emphasised the role of individuals. Tushman and Katz [29] found gatekeepers tend to be high performers and to facilitate information transfer. Conway [30], Kreiner and Schultz [31], and Allen [32] found that interpersonal communication is commonly how innovators collect and transfer ideas. The concept of gatekeeper can also usefully be applied to the role of certain organisations within a sociotechnical network which act as key intermediaries between other network actors.

Innovation networks can usefully be located within the field of sociotechnical transitions. The sociotechnical transition approach argues for analysis at a system level defined by the performance of a particular societal function [33]. The transitions approach defines a prevailing 'regime' as the currently dominant social and technological arrangements for the fulfilment of a societal function, and explores the dynamics and paths by which such a regime may radically change. One of the key sources of novelty upon which such a transition may draw are 'niches' which express emergent sociotechnical alternatives to the prevailing regime. Radical innovation is often suggested as being generated in niches [34−36]. However, transition paths may vary as to the degree of resistance, reconfiguration or replacement involved in the encounter between regime and niche.

The sociotechnical regime in our study is defined as the '*print-on-paper*' system, which fulfils the social function of text/graphic communication through the medium of an ink display on sheet material derived from wood fibre. It involves a diverse set of actors engaged in practices, which range from forestry to desktop printing to wastepaper recycling. Nanoparticle and deinking innovations may be seen as niches. Both regime and niche can be conceptualised as a sociotechnical network. Our research addresses the meso- and micro-level process of innovation within the 'print-on-paper' sociotechnical system and offers a theoretical and empirical approach to the investigation of the pattern of interactions in a network and whether they are likely to be conducive to the longer-term success of an innovation.

One of the limitations of many of the empirical studies on sociotechnical transitions is that they are retrospective in nature and primarily concern economic competitiveness in markets. The regime shift is identified after the event and, with the benefit of hindsight; its sources may be traced to niches where the novelty first arose. On the other hand, prospective analysis including the purposive societal pursuit of sustainability raises a number of fundamental challenges. The nature of a future regime shift will not be known for possibly some decades and the longer-term significance of current niches is highly uncertain. One response to this problem is to emphasise the contingent and inherently unknowable aspects of innovation as an argument for a precautionary approach and the avoidance of misguided attempts to positively shape the future. An alternative, which is what we propose, is to draw upon knowledge about innovation networks in order to map niches as emergent networks with the aim of identifying features, which appear conducive or inimical to their contribution to a transition toward a more sustainable sociotechnical regime. It does not seek to assess their fate in the longer-term future. However, in order to pursue this analysis it is necessary to identify specific areas of innovation within generic nanotechnology, which are engaged in downstream commercialisation in order to move on from an over general and abstract bipolar speculative debate about the merits and drawbacks of nanotechnology in general.

2. Mapping niches as emergent sociotechnical networks

Expectations of innovations offering a radical improvement of the sustainability of the print-on-paper regime were identified through a web based non-obtrusive approach. The two niches of deinkability and nanoparticles in the ‘print-on-paper’ regime were selected in this way. The particular challenge of such niches is that they are new and near market. Literature based methods applied to the past or to academic science is inappropriate to this task. Instead the web offers new possibilities for systematic capture of more ephemeral and contemporary traces of relevant activity through an ‘event based method’ [37].

An event based method was used to trace emergent innovation networks in these niches of deinkability and nanoparticles. The type of event sought was a ‘knowledge interaction’ event with an online ‘record’ of proceedings. All events selected were international workshops/conferences with a significant number of presentations on the innovations of interest. A set of events was identified for each innovation niche. The approach has some similarities with the event based approach of Van de Ven [38] that observes records and analyses the events of the innovation process in different organisational settings. However, the events analysed were not specific to a particular organisational context but instead represented a distributed innovation system. Van de Ven’s innovation journey [38] indicates the importance of engaging in relationships with others to achieve desired outcomes and such events were used as the empirical foundation for a social network analysis of interactions between organisations. A list of organisational actors was derived from these events based on the organisational affiliation of individuals who presented at the event. These were defined as the actors constituting an emergent innovation network.

The network relationships between the actors in our empirical study were measured and defined in terms of copresence at events and coauthorship of presentations. A link represents knowledge flow and social interaction between the actors. A copresence network link between two actors was deemed to exist if they were presenters at the same event. A further coauthor network link was allocated if two actors jointly authored a conference presentation. The two sets of relational data were recorded as an affiliation-by-affiliation Excel matrix. The configuration of the emergent innovation networks was explored using the visual mapping software, NetDraw. The merits of visual mapping of innovation networks are that they allow a variety of relational and attribute data to be combined enabling a mix of quantitative/qualitative and micro/macro analysis. The Excel matrix file was imported into the social network analysis software, Ucinet, and transformed into Ucinet dual-file format. These Ucinet relational data files were used in NetDraw to enable the network to be visually mapped. One hundred and one presenters from 65 organisations from the nanotechnology industry and 109 presenters or participants from 48 organisations from the deinking industry and in relation to paper industry are gathered to form two sets of relational data.

The primary purposes of the network mapping were as follows: to show the overall network configuration through a spring embedding graph-theoretic layout; to identify clusters within the network through faction analysis; to assess the homogeneity/heterogeneity within and between these clusters using nodal multiple attribute data; and to identify actors who occupied gatekeeper positions in the network by the use of a betweenness centrality measure.

Attribute data were assigned to actors in terms of type of organisation that they belong to (node shape), country of origin (label), number of individual innovation actors from the same organisation (node size) and their technology focus. These addressed the innovation journey concepts of ideas and outcomes (technology focus), people (organisation members), relationships (collaborative links) and context (type of organisation national location) [38] and organisational diversity in the distributed innovation process [12,30,39–46].

An attribute file was created in relation to the matrix file in Excel and imported to Ucinet in order for Netdraw to incorporate it into the network diagram. The two innovation networks were mapped and analysed separately and were then combined together. Interpretation of the network was made using an enhanced and combined network map.

A further event analysis was undertaken to identify innovations in the nanoparticles and deinkability areas. These events were ‘*innovation occurrence*’ events, which were identified through an online search for reports of these events published in a comprehensive Pirabase paper industry database and US/European patent database. All innovation actors (Fig. 1) were included on the network map and were added as isolates if not present in the network based on the knowledge interaction event analysis.

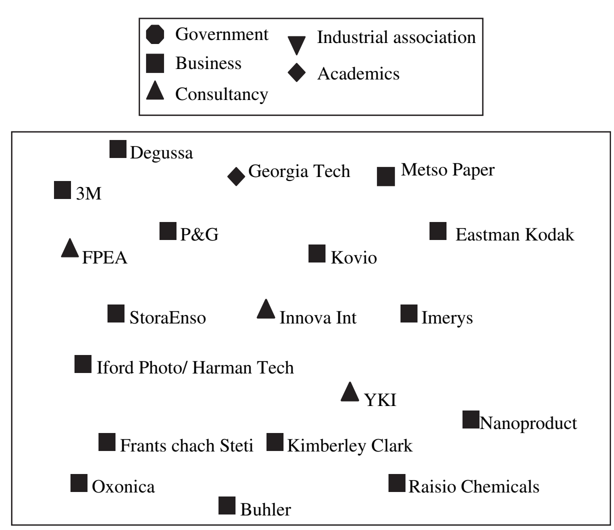

Fig. 1. Organisations identified as innovators.

3. The deinkability innovation network

Information technology has contributed to the problem of deinkability of cut sheet office papers with the widespread growth in the use of laser and inkjet printers [8,47]. The first two depend on toners, dry fine powder (with pigments) which bond the paper fibres together. These cause particles that do not float or sink in paper recycling processes causing ‘speckling’ of final paper products. With water based inkjet inks, dyes dissolve and attach to the paper fibres during the recycling process, causing discolouration of the final paper [48]. Three categories of chemical are involved in ink, the pigment or dye, the vehicle and additives which all contribute to the ease of deinkability [49]. In general, the chemical composition of ink is designed to maximise the properties and appearance of the final print, rather than to facilitate deinking during recycling. This implies there may be a conflict between printing and deinking characteristics.

3.1. The deinkability network

The overall network includes 48 different organisations. The network is mainly comprised of business organisations from a range of European countries and the USA. There is an even spread of technological specialisation in inks, fibres and general processes with no apparent activity on paper coatings. There is low representation of academic research organisations and public bodies in the network.

3.2. Clusters in the deinkability network

The mapping algorithm visually represents clusters as groups of actors positioned closer together. There are six clusters in this network which are mostly heterogeneous in nature and mainly business-oriented. Three clusters have a technological focus on ink. One of them is a homogeneous cluster of French organisations mostly working on ink/toner technology. The second largest group also shows some technological variety with a mixture of interests in ink and fibre. The remaining clusters are smaller, though they all show international diversity combined with a narrower technology focus. Organisations in the central cluster, largely business-oriented, reach less than half of the organisations in the bottom right cluster (see Fig. 2). Only one organisation in the central cluster, Paper Technology Specialists, Germany (PTS_DE), a German consultancy has links with the actors in the left cluster. This organisation is a research and consultancy firm with a broad range of expertise. Half of the organisations in this cluster concentrate on fibre engineering. One-quarter of the organisations focus on ink/toner technology.

All of the organisations in the top cluster are linked to other clusters. The VTT Technical Research Centre, Finland (VTT_FI) and Confederation of European Paper Industry, Belgium (CEPI_BE) are important communicators between clusters. Papierfabrikation und Mechanische Verfahrenstechnik, Germany (PMV_DE) and Confederation of European Paper Industry, Belgium (CEPI_BE) link two clusters. VTT Technical Research Centre, Finland (VTT_FI) is the only connector between two clusters.

3.3. Gatekeepers in the deinkability network

Most of the significant gatekeepers are business organisations in the paper, printing and deinking sectors. Two international consultancies, two global manufacturers and one industrial association also appear in this role. The top five potential gatekeepers that have the largest number of connections with other organisations are as follows: INGEDE (119.31), Voith Paper (119.237), Centre Technique du Papier – The Pulp and Paper Research & Technical Centre (CTP) (114.44), UPM-Kymmene (110.373) and HP (103.417). Most gatekeepers are more connected to some clusters rather than others. INGEDE and Voith Paper connect four out of five different clusters, which shows that they are the most active in linking diverse innovation activities.

3.4. Innovation activities in the deinkability network

Some organisations have strong collaboration. Business practitioners, Web Offset Champions Group (France), Sun Chemicals (UK), SCA (UK) and West Ferry Printers (UK) discuss leaner, faster and more efficient runnability issues. The business research institute, Centre of Technique du Papier (CTP) and business organisation, Kemira concentrate on the best surfactant strategy in relation to deinking. The academic business partnership of University of Oulu, Centre of Technique du Papier (CTP) and the engineering school of National Polytechnic Institute of Grenoble (EFPG) concentrate on deinking processes: cleaning, screening and flotation. The Finnish organisations, KCL and Helsinki School of Economics collaborate to seek appropriate sustainability indicators for new technologies.

The success of deinking depends on ink properties and printing techniques and conditions, along with the age of the print and paper surface. From the industry perspective, deinking is seen as a sophisticated way of recycling, and high-grade papers can be recovered by using these techniques [50]. The main deinking processes involve the removal of ink and other contaminants by screening, cleansing, flotation and washing from sorted and recovered paper (wastepaper). Non-impact based printing technologies such as photocopiers, laser printers and inkjet printers use a low level of additives but based on pigments in dry toner, they strongly bond to a large number of fibres and they do not float or sink and are retained in the deinked pulp in the paper recovering process. They are often described as of poor deinkability.

There are also industry moves to replace solvent based inks with more environmentally friendly water based pigment based inks to reduce VOC emissions. The main drawback is that papers printed by water based inkjet inks pose another problem for deinked pulp. Dye redissolves and cannot be separated out and therefore, subsequently moves into the fibres which make it difficult to produce high quality paper. From the deinkers’ point of view, it would be desirable to contain

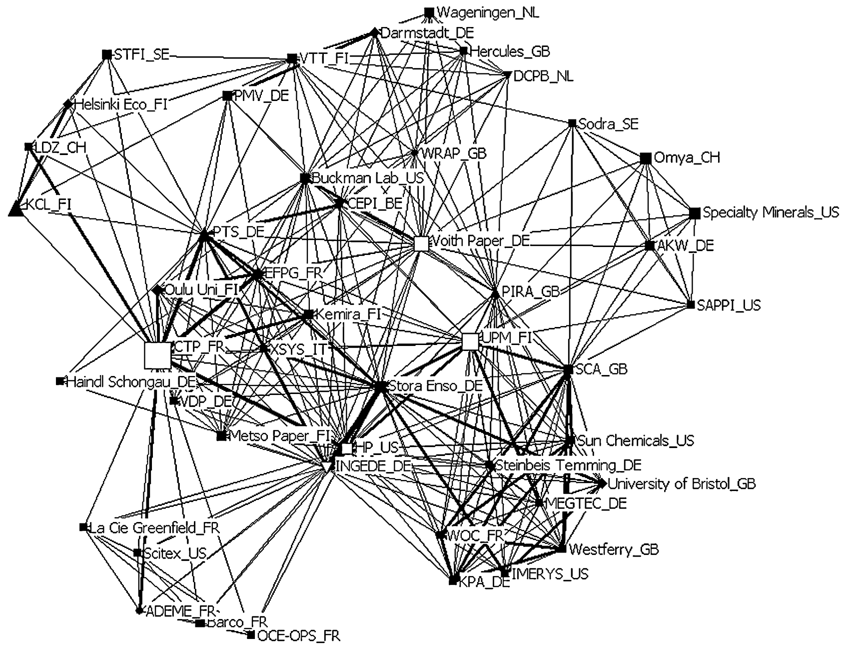

Fig. 2. Deinkability network.

as few chemicals as possible in order to reduce contamination of the deinked pulp and to increase the possibility of producing high quality brightness of office paper. But from the papermakers' point of view, the optimisation of additive and sizing agents to paper is both a cost reduction and paper quality one as minerals such as china clay, chalk and titanium dioxide will improve sheet formation, surface smoothness, printability, dimensional stability, opacity and brightness [51]. One of the complexities of recycling in the high quality printing and writing paper industry is that it involves a wide diversity of actors with their individual conflicting objectives in the paper chain, from ink manufacturers, publishing and printing companies, waste collection and sorting companies, consumers and recycled paper mills and the quality of recovered high-grade writing and printing papers depends on their cooperation.

The increasing challenge for pulp deinking is to maintain standards of both yield and quality as paper collection gets increasingly mixed and the amount of virgin fibre in recovered paper decreases due to recycling. Recovered paper is a delicate business which can be affected by decisions on printing and publishing: "To maintain the achieved standards, it is also necessary that everyone involved in the paper chain – including parties giving the order and design of print products – give due consideration to the requirements of recycling" [48]. This requires an understanding of the life cycle implications of such products. Paper fibres are only suitable for recycling between five and ten times before they start to disintegrate and become unusable. Recycled pulp differs from fresh pulp in a number of ways, such as the age of the fibre, ash content, the mix of fibre content and origin and its bonding ability. Also, it contains various contaminants including, chemical additives from the original paper production and the deinking process. Carre and Magnin [8] found a wide diversity of successful deinking, commenting that "dialogue is necessary with inkjet ink manufacturers' to promote the use of inks which are most successfully removed at the recycling phase". Most studies of deinking toner prints have been carried out in North America, showing high contamination of residual black impurities.

The demand from customers regarding paper environmental impacts can also act as a driving force for change, and there is a growing interest of customers in viewing the actual performance of paper mills [52]. At the same time, there is customer demand for brighter paper which requires higher grade input and in many cases a greater proportion of virgin fibre pulp. Ulrich Hoke, the Chairman of INGEDE, comments that the problem of increased recycling is that the quality of recovered paper gets worse and both digital and flexo prints make more difficult the recovering and deinking process. Future challenges lie in recovering a greater percentage of higher quality paper, avoiding non-deinkable paper preventing non-removable adhesive applications [53].

The process of deinking involves the tasks of separation of the non-paper components, and removal of the printing ink film from the paper fibres. With coated paper the ink does not touch the paper fibres, the coating disintegrates and the recovered paper is pulped. With uncoated paper there is adhesion of the printing ink to the paper fibres and ink removal is dependant on paper properties.

There are many process complexities in deinking printing and writing paper and barriers to investment in a recycling facility for this type of high quality paper. Deinking practice can profoundly alter the proportion of fibres and fine materials in the recovered material; substantial fibre loss can result from the deinking process [49] and need a diversity of approaches "regulation of printing ink compositions, incineration of contaminated paper to recover its energy value, producing paper from renewable resources and continuing subsidies for paper recycling programs''; to ''help sustain the marginally economic advantages of deinking operations'' [50].

A German professor of paper technology places much emphasis on the operational difficulties such as poor deinkability of different types of printing and writing papers such as woodfree copy paper, commercial inkjet paper and woodcontaining recycling paper by. His expectation is to develop better deinkable inkjet ink systems and collective efforts from all parties (e.g. designers of printed products). He recommended that designers of printed products should give consideration to the requirements of recycling [51].

A French senior research scientist, from the Recycled Fibres Group of the Centre of Technique du Papier (CTP) has concentrated on printing technologies and their effects on deinking since 1999. He has concluded that oil based inkjet inks on coated paper and dry toner are the preferred technologies compared to various other digital prints consisting of dye- and pigment-based inkjet, normal toners (high speed black and white and colour, liquid and dry) and UV curable technologies (overcoats, ink and toner). He does not clarify which new technologies could possibly make deinking easier [8].

The International Association of the Deinking Industry (INGEDE) believes that ''more recovered paper can and should be recycled…for higher quality graphic papers recovered paper can be used as a resource. In order to keep these products light, to avoid them getting darker even going through multiple recycling, the ink has to be removed…through a deinking process. This process should harm the environment as little as possible, and it should also lead to a high quality product. To achieve these goals, everybody involved in these steps has to cooperate''. INGEDE therefore cooperates with other players in the field of recycling, as with printing ink and machinery manufacturers, paper finishing industry and suppliers of additives. The current members are 37 paper mills and research departments of paper mills from Austria, Belgium, Finland, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland, the Czech Republic and the UK. The workshop ''Deinking of Digital Printing Inks'' addressed the growing importance of digital printing processes by photocopiers, laser prints and inkjet prints. It was pointed out that ''the manufacturers hardly think about the fact that the print products created by these processes contribute to the wastepaper collection by the users. Almost all of these products harm the paper recycling process rather than contributing to the recovery of valuable resources – they ought not to get into recovered graphic paper, because the ink systems that are being used can be removed either poorly or not at all. Most companies did not realise the importance of this kind of discussion. Recyclability did not improve or got even worse for some quality parameters'' [52].

Faul (2005) suggests that sustainability in recycling printed-paper products could be difficult to achieve at present. He acknowledges the importance of paper recovery, but expresses concern that the type of inks and kinds of printing process could lead to difficulties in the deinking process [52]. He added that for printed-paper products to be recyclable, they have to be repulpable, adhesive applications must be removable by screening and cleaning and deinkable. In particular, the deinking process consisting of flotation and washing could lose up to 55% of fibres. The Royal Society of Chemistry's chemical science network stressed that the problem of deinking is not new, recyclers had experienced the difficulties in deinking from the recycled wastepaper in the past. Faul stresses that, ''for the sustainability of the paper loop a sufficient deinkability is necessary'' [53] and emphasises the need to include recyclability as a criterion from the design stage of the product life cycle: ''when designing a print product, good recyclability should be considered''.

4. The nanoparticle innovation network

The potential applications of nanotechnological innovations to deinkability fall into three major areas: nanocoatings, nanoinks and nanofibres. The global chemicals, inks, paper, printing and machinery manufacturers all play a role in shaping the future of deinking technologies. Thirteen specific nanoparticle innovations were identified as being at the stage of commercialisation. Of these 11 concerned coatings, the majority of which involved silica nanoparticles. Two were concerned with nanoparticles applied to ink technology.

4.1. The nanoparticle network

The overall nanoparticles network comprises 65 organisations. Business organisations represent the largest number of actors but there are also a reasonable number of academic organisations from the USA, Canada, Finland and the UK. Research interests in inks, fibres and coatings are present (Fig. 3).

4.2. Clusters in the nanoparticle network

The network is differentiated into five clusters. The centre of the network contains mostly of a heterogeneous mix of European, Canadian and US academics. Active knowledge interactions are shown within US academics and businesses whereby three or more clusters are dominated by the US organisations. There is a broader organisational interest on the nanoapplication to coating (including seven academic institutions from Canada, Switzerland, the UK and the USA; 12 business organisations from Japan, Finland, Germany, Sweden, Switzerland and the USA; two industrial organisations from the USA and Slovenia; one US government), and they are distributed across different clusters. In comparison, nanoapplications to fibres have received less attention compared to ink and coating formulations.

The three cases of nanoparticle fibre applications only appear in two clusters located in the centre part of the network. The eight organisations which focus on ink/toner nanoparticle technology appear as isolates. Together with the isolates, there is a high degree of homogeneity in ink/toner technology in two clusters and most organisations are US oriented firms. They may share the expertise to accelerate the ink/toner technology development with Cabot Corp, Sandia Lab, Flink Ink, Xerox, HP, Sun Chemical and Nanoproducts. The most popular

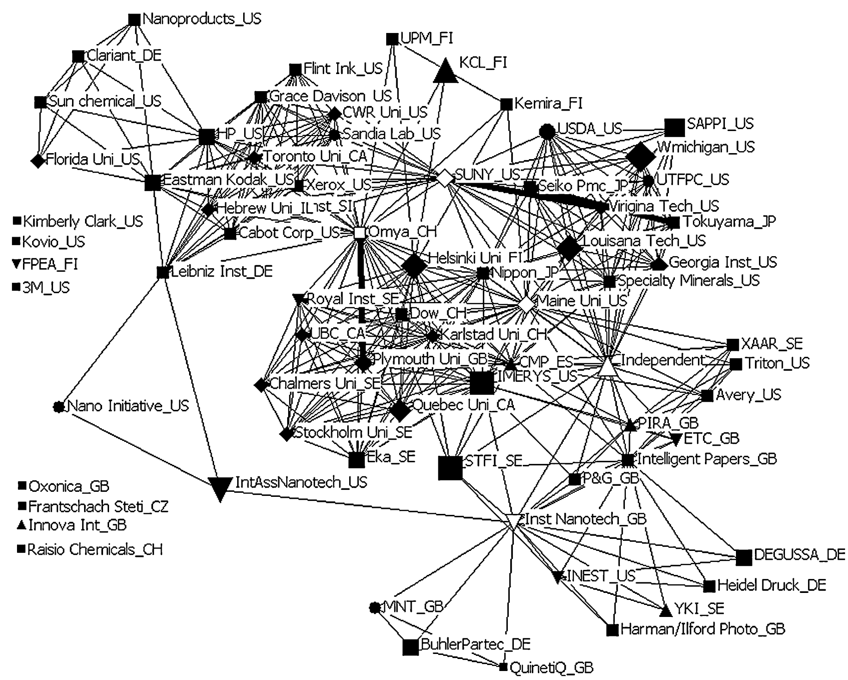

Fig. 3. Nanoparticle network.

choice of nanoparticle applications is coating technology, where organisations are positioned centrally in the network map. More knowledge sharing and collaborations in coatings are present among Eka Chemicals, Imerys, Maine University, Omya, Quebec University and Plymouth University.

4.3. Gatekeepers in the nanoparticle network

The gatekeepers represent a mixture of business, academic and consultancy organisations. The top five potential gatekeepers that have the largest number of connections with other organisations are as follows: Omya (402.461), Institute of Nanotechnology (304.029), Independent Consultants (224.502), State University of New York (219.736) and Maine University (203.74). Most connections are found to connect three clusters.

4.4. Innovation activities in the nanoparticle network

Advocates of nanoparticle innovations in print-on-paper with claims for sustainability are found among consultants, academics and industrial organisations. A Finnish paper consultant, from Jaakko Poyry suggests that incorporating nanoparticles could make the deinking process more efficient, as nanoparticles have a larger specific surface area their greater reactivity could increase flotation process efficiency [54]. Another Finnish paper consultant, from KCL Science and Consulting suggested that application of nanotechnology could produce new end products with desired properties by controlled barrier/sorption properties, tunable adhesion and other properties with new coating and converting techniques. New controlled barrier/sorption can result in better printability. Tunable adhesion would control the release of substances. New coating and converting techniques could decrease the amount of coating required and solve part of the recycling problem by replacing the difficult-to-recycle coatings. The visions of the future are that nanotechnology application could bring factor-10 improvements [56]. A UK consultant from PIRA International, a UK paper research consultancy holds an optimistic view of this particular technology. He believes that nanotechnology has a lot of potential for sustainability [57].

Academic contributors tend to be more cautious. A professor of the US Institute of Paper Science and Technology within Georgia Institute of Technology pointed out that nanotechnology has potential to contribute in many areas; it is too early to confirm if nanotechnology can help in the deinking process and thus encourage paper recycling.

“Although nanotechnologies have been widely used in many areas and exciting applications in paper and papermaking have been proposed, it is difficult to give an example for deinking. The possible applications of nanotechnology in deinking may include surface modification of ink particles and fibres using nanostructured particles or molecules; using nanosized inks (easy for washing); nano-air bubble interaction with ink particles have not been studied so it is difficult to say whether it will be good or bad. In summary, nanotechnology may improve ink removal, but it is too early to say that” [55].

A number of innovations within the area of nanotechnology in relation to printing and writing paper with relevant applications have been identified. For example, Degussa, a German business has been developing small-scale pigments to work with print heads. Nano Products, a US business, is using nanoparticles in dispersion and inks, for pigment and coating materials. Degussa has products that integrated nanopigments for use with inkjet inks. Kodak, the manufacturer of traditional imaging products has been involved in making polymeric nanoparticles composed of simple or complex (entangled) chains of molecules. These can be used to make mordants – substances that help to bind ink dyes to surfaces such as inkjet printer paper. A patented Kodak mordant is used in Kodak inkjet paper. Mordants are made of cationic polymeric nanoparticles and other materials, which form a film on coated paper. They claim that nanoparticulate mordants are very effective because the smaller size particles are more densely packed in a coating.

When compared to other nanoparticle applications, nanocoating is well established and near the market. Growing silica monomers into clusters (nanoparticle technology) in wet end chemistry has been used by papermakers since the 1980s to improve retention and drainage systems. This composition improves formation, retention, drainage and dry strength of paper. Since then, it has continued to make continual improvements in terms of combining structured nanoparticles with colloidal silica sols and synthetic cationic polyacrylamide (C-PAM) that has resulted in cleaner fine paper. Silica spheres form strong covalent siloxane bonds that cannot be easily broken by paper machinery. Nanoparticle application in papermaking results in reduced steam production as well as paper with higher brightness [54].

In 2000, a Compozo Select system combined anionic trash catchers (ATC), cationic starch, C-PAM and further additional nanoparticles were applied in a closed recycled paper system. It is claimed that it is favourable to apply to a system involving broken/poor quality secondary fibres and it controls soluble and redispersible components (sticky residues) at all levels of water closure. New nanocoating and converting techniques in recent years are claimed to bring dematerialisation in terms of decreasing the amount of filler and coating required and to solve part of the recycling problem by replacing the difficult-to-recycle coatings.

Recent developments in nanotechnology are beginning to offer novel opportunities and are increasingly being considered by ink manufacturers and customers, to enable inks to be developed with superior performance properties. Nanoparticles are also used in colloids, which in turn are being used in printer inks.

Inkjet inks are another area where nanoparticle technology is being utilised. In 2005, Oxonica (a European nanomaterial company) and Buhler Partec (a process technology manufacturer for making printing inks, pigments and chemicals) announced their nanoinks research concerning the replacement of the conventional colourants with nanoparticle dyes and nanosized pigment particles. They claimed that the newly developed nanoparticle dyes will never fade and produce a high quality image. Global chemical manufacturer and supplier, BASF is also working on making nanomaterials to provide colours without the use of dyes or conventional pigments. They claim that the colours of their nanoinks are generated by dispersions of uniformly sized nanoparticles in the same way that colour is created by the ordered, textured surface of butterfly wings. A key question is whether this may help deinkability.

Ongoing research has been undertaken in the USA to develop the next generation of fibre recovery and utilisation through the use of nanocatalysts to liberate cellulose, hemicellulose and lignin components, separation of wood into fundamental architectural constituents such as microfibrils and nanofibrils and use of nanofibrillar cellulose as building blocks.

In Sweden, research has been directed to the use of nanoparticles for surface/interface modification of pulp fibres and wet end applications in order to achieve high performance retention/drainage with the addition of nanocolloids for tailored surface properties.

5. Interaction between the nanoparticle and deinkability networks

5.1. The nanoparticle-deinkability network

There is not a great overlap of actors between the two networks. In identifying the gatekeepers, there is scope for them to catalyse other actors into action as well as work together to put forward possible technological partnership to face challenges in the paper recycling industry. The ten organisations that participate in both networks and play an important mediator role in communicating between two innovation networks are all business-oriented: HP (digital printing manufacturer), Imerys (chemical and coating manufacturer), KCL Finland (paper consultancy), Pira International (paper consultancy, conference organiser and information provider), Metso Paper (paper equipment and machinery provider), SAPPI (paper manufacturer), Specialty Minerals (paper chemical manufacturer), STFI-Packforsk (paper recycling consultancy), Sun Chemical (printing ink and pigment manufacturer) and UPM (paper manufacturer). More radical innovations would require interactions among a wide diversity of players including those significant actors mentioned above in the future (Fig. 4).

5.2. Clusters in the nanoparticle-deinkability network

The combined network is not as clearly differentiated as the separate networks. The prominent clusters represent the persistence of the large strong clusters in the nanoparticle network. Essentially it shows a low level of integration of the nanoparticle innovation activities with the deinkability innovation activities.

5.3. Gatekeepers in the nanoparticle-deinkability network

The top five potential gatekeepers that have the largest number of connections with other organisations are as follows: Hewlett Packard (HP) (771.77), Imerys (655.761), Pira International (647.717), Institute of Nanotechnology (582.85) and Omya (518.231). Although there is some continuity with the gatekeepers in the separate networks there are also new actors, which appear to have a greater significance in the combined network. However, the connectedness between the principal gatekeepers is low.

6. Conclusion

The research has shown that there is an emergent network of innovation activities on nanoparticles applied to the print-on-paper regime. However, this network is so far poorly linked to the emergent network of innovation activities on deinkability.

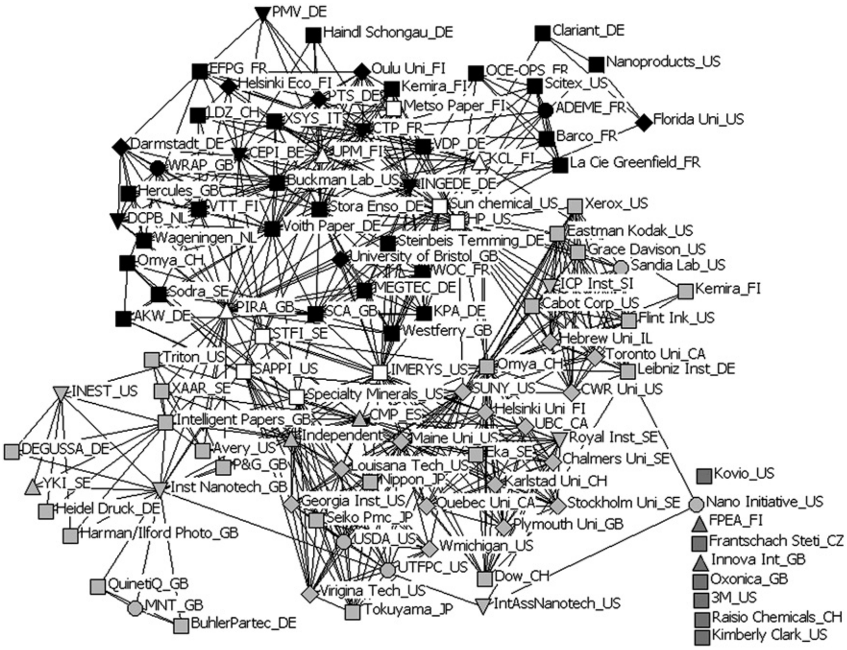

Fig. 4. Combined nanoparticle and deinkability network.

This suggests that the sustainability expectations for nanoparticle innovation are not being very effectively fulfilled. This is borne out by the nature of the nanoparticle innovations currently at the stage of commercialisation. They are primarily concerned with traditional commercial performance concerns such as ‘printability’ rather than new sustainability objectives such as ‘deinkability’ for enhanced recycled fibre in print-on-paper. Examples of nanotechnology applications to printing and writing paper are limited at present. Three major areas of the current technological innovations are identified: inks, fibres and coatings. Nanocoatings receive the most interest in the nanoparticle network from business organisations yet little research is carried out on how they could assist the deinking process.

Both nanoparticle and deinkability networks have some similar characteristics. They are fairly heterogeneous in terms of nationality and type of organisation which is a positive characteristic in terms of innovative potential. However, both networks are fragmented into clusters, lack cohesiveness and do not show any strong innovation path at this time. There is little overlap between the two networks.

A key difference in technological focus is that the deinkability organisations do not generally recognise coatings as very relevant to assisting deinking operations but more than one-third of the organisations in the nanoparticle network are focused on nanocoating. Conversely fibre technology is neglected in the nanoparticle network where there are only two organisations working in this area. There is interesting scope for mutual learning between the two networks in relation to these areas. Gatekeepers identified in separate networks could act as catalysts in bringing organisations with a similar focus together (e.g. HP in relation to ink/toner technology and Imerys regarding coating applications).

The lack of nanotechnological innovation relevant to deinkability may be due to technical difficulties in achieving reasonable quality of recovered paper or a lack of interest among paper and ink manufacturers, printers, recyclers and deinkers. The complexity of paper deinking and recycling depends on a series of interrelated technological systems, which need a high level of interaction. The gatekeepers who represent the channels of interaction between the two networks have a potentially significant role in changing this situation, both in terms of influencing technological change and contributing to the success of innovation.

The evidence does not suggest that the aspirations for nanoparticle innovations contributing to sustainability goals in print-on-paper are as yet being translated into practice in the emergent innovation networks identified. A more explicit and purposive role of key gatekeepers could contribute to the pursuit of this though there remain many technical uncertainties. The emergent tendency is oriented to the performance goals of printability rather than to those of deinkability.

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