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Generation And Diffusion Of Innovations In A District Innovation System: The Case Of Ink-Jet Printing

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JEL Codes: O31, O33, Q55

Abstract: This paper provides an in-depth case study of the ink-jet printing (IJP) technology that emerged from a mature industrial sector in the Castellon region (Spain) in the first decade of 2000. We propose an analytical framework that combines the theoretical perspectives of Industrial Districts and Innovation Systems, and exploit a qualitative methodology that includes information from patent and scientific article databases, technical literature and 21 interviews. Our results show that IJP is a major innovation that breaks with the tradition of machinery innovations in this industry in Spain. We provide micro-level evidence of the complex external and internal relationships in the innovation process. Internal ties, trust relations and strong in-house R&D were the determinants of the IJP innovation. In contrast to the literature, we find that secrecy and patenting play key roles in the sharing of knowledge and the innovation strategy.

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1 Introduction

Regional agglomerations of industrial activity have long been recognized as potential sources of innovation, and important for successful economic development (Cooke, 1996; Porter, 1998; Malerba, 2002; Becattini et al., 2009; Menzel and Fornahl, 2010). Since the contributions of Lundvall (1992), Storper (1993, 1997), and Asheim (1996, 2007), among others, greater attention has been paid to the roles of learning and systemic interactions in the process of generation and diffusion of innovation as a determinant of regional technological and economic performance. Despite extensive research on innovation in clusters and Industrial Districts (ID) that draws on evolutionary economics approaches, our understanding of systemic and relational networks and how innovation emerges and evolves in them is relatively poor (Malerba and Vonortas, 2009; Cantner et al., 2010). Mothe and Paquet (1998) and Iammarino (2005) maintain that little progress has been made towards empirical analysis of the dynamics of the learning processes involved in local and regional innovation systems (LRIS) and the importance attributed to proximity, localized knowledge generation and diffusion of innovations.

This paper provides an empirical research from this perspective which in Spain is still limited (Molina-Morales, 2002; Boix and Galleto, 2006, 2009; Boix, 2009). We present a case study of an innovation that emerged in the Castellon region in the first decade of 2000: that is, Ink-jet Printing (IJP) technology. This technology has been described as part of a 'digital revolution in the ceramic industry' (Hutchings, 2009; Giacomini, 2010). The Castellon region concentrates over 90% of Spanish ceramic tile production (Escardino, 2001; Tortajada et al., 2008). Over the years, various printing techniques have been used to decorate tiles. Traditional contact printing methods include screen printing, flexography and rotogravure (De Carlo and Montani, 2003; Berto, 2007).

Several authors point to innovations in ceramic tile decoration enabled by the introduction of IJP technology is opening new opportunities in the ceramic industry and other economic sectors (Hutchings, 2009; Moreno et al., 2010; Sanz et al., 2011). This study analyses the generation and development of the IJP innovation from the perspective of ID, LRIS and learning regions (Becattini, 1990; Storper, 1993, 1997; Florida, 1995; Asheim, 1996, 2007; Sforzi, 2006). Specifically, we apply an evolutionary theoretical lens to technological change in relation to the following dimensions: 1. **absorption** of new knowledge (including exploration and acquisition of available knowledge); 2. **generation** of new knowledge, technology and innovation; and, 3. **diffusion** of innovation throughout the regional 'learning system' (Caniëls and Romijn, 2003; Iammarino, 2005; Iammarino and McCann, 2006; Herrschel, 2010). Our main research questions are related to:

- the nature (type, characteristics) and dynamic of the knowledge flows and drivers of the learning process in IJP technology;
- the agents involved in IJP technology generation;
- the generation, appropriation and diffusion of IJP technology.

Our principal purpose is to provide micro-level (individuals and firms involved in the innovation processes) empirical evidence and contrast it to the findings in the research literature. The paper is organized as follows. Section 2 describes the theoretical framework of ID as an *innovation system* and a *local learning system*. Section 3 describes the research context and the structure of the agents in the Castellón Ceramic District

Innovation System (CCDIS), Section 4 discusses the research methodology and Section 5 presents the results of the case study. Section 6 concludes the paper.

2 ID as innovation and learning systems

The term ‘region’ takes on different meanings in different disciplines and may embrace sub-national and inter-national spaces, and can be associated with several conceptual constructs such as clusters, districts, milieus innovateurs, new industrial spaces and local production systems (Belussi, 1996; Moulaert and Sekia, 2003; Cooke, 2009; Porter and Ketels, 2009). Cooke (2001) proposed two distinct definitions of region: a) a geographically-defined, administratively-supported arrangement of innovative networks and institutions that interact with innovative outputs of firms on a regular basis, and b) a ‘socio-cultural’ entity or a series of cultural aspects related to the concept of embeddedness, which emphasizes systemic interconnectedness and interdependency. Lundvall and Borrás (1997, 39) affirm that ‘the region is increasingly the level at which innovation is produced through regional networks of innovators, local clusters and the cross fertilising effects of research institutions’. From this point of view, a basic premise of the regional innovation system (RIS) approach is that regional innovation performance depends directly on the systemic character of the region’s innovation activities, which involve complex and dynamic external and internal relationships. A RIS should be considered to be an integrated system consisting of components, relations and attributes, that is, a set of networks of public and private agents that interact and provide mutual feedback within a specific territory, and exploit the internal dynamics of regionally embedded socio-cultural, economic and institutional structures in order to adapt, generate and extend knowledge and innovation (Buesa et al., 2005; Iammarino, 2005; Buesa and

Heijs, 2007). Clusters and RIS are also closely related. It is commonly argued that clustered firms –particularly in the case f Small and Medium Enterprises (SMEs)- enjoy advantages in terms of innovation performance through processes of localized learning. This means that clusters and RIS may co-exist in the same territory and the regional innovation system may in fact contain several clusters. But a cluster is not by necessity part and parcel of a regional innovation system.

Doloreux (2002) claims that the RIS encompasses a normative and a descriptive approach that aims to capture how technological development takes place within a territory. From an evolutionary perspective on economic development and technical change (Dosi, 1982, Dosi et al., 1988; Nelson, 1995; Iammarino and McCann, 2006) the theory of RIS stresses the role of 'collective learning', which, in turn, refers to deep, cooperative and competitive relationships among system members (Cooke and Morgan, 1993; Edquist, 1997; Cooke, 2002). In this perspective, innovation is the result of a process that includes acquisition, generation/recombination, diffusion and use of knowledge, in which the interaction between the agents in the process (built on feed-back), cumulative aspects, problem-solving, knowledge capabilities, among other aspects, are evident (Lundvall, 1992, 2007; Cooke, 2005; Dosi et al., 2006; Sforzi, 2006).

Herrschel (2010) and Cantner et al. (2010) highlight the role of social networks and interactions at several levels within the regional system (e.g., intra- and inter-firm) and across system borders. Although the barren debate over the conceptual differences between clusters, IDs and RIS (Harrison, 1992; Moulaert and Sekia, 2003; Heidenreich, 2005; Porter and Ketels, 2009) the definition of LRIS covers all these theoretical constructs in the sense that all are founded on the idea of 'networking' (Cooke and Morgan, 1993; Vonortas, 2009; Cantner et al., 2010). In this respect, research on ID and clusters is moving from a predominantly static approach to more dynamic analysis to understand how spatial concentrations and networks emerge and evolve along time (Gordon and McCann, 2000; Lorenzen, 2005; Braunerhjelm and Feldman, 2006; Zirulia, 2009; Menzel and Fornahl, 2010).

In this paper we investigate innovation linking the notions of ID, (sectoral and regional) innovation systems and learning regions, by developing an analytical framework that combines innovation systems theory related to the generation and dissemination of knowledge (learning) with networks of relational interactions among agents and institutions in a socio-cultural space. We adopt the concept of District Innovation System (DIS), which includes all these aspects to explore the Castellon region free of the empirical constraints of concepts of clusters and ID, which tend to focus on horizontal and vertical linkages and cooperation within the location, but overlook the role of external linkages (Motoyama, 2008; Gabaldón et al., 2009). Figure 1 depicts the definitions, elements, characteristics and complementarities that converge in the DIS approach. We consider the 'relational assets' or 'untraded interdependencies' as sources of learning that enable certain regions to innovate and adapt effectively to changes in the external market environment (Storper, 1997).

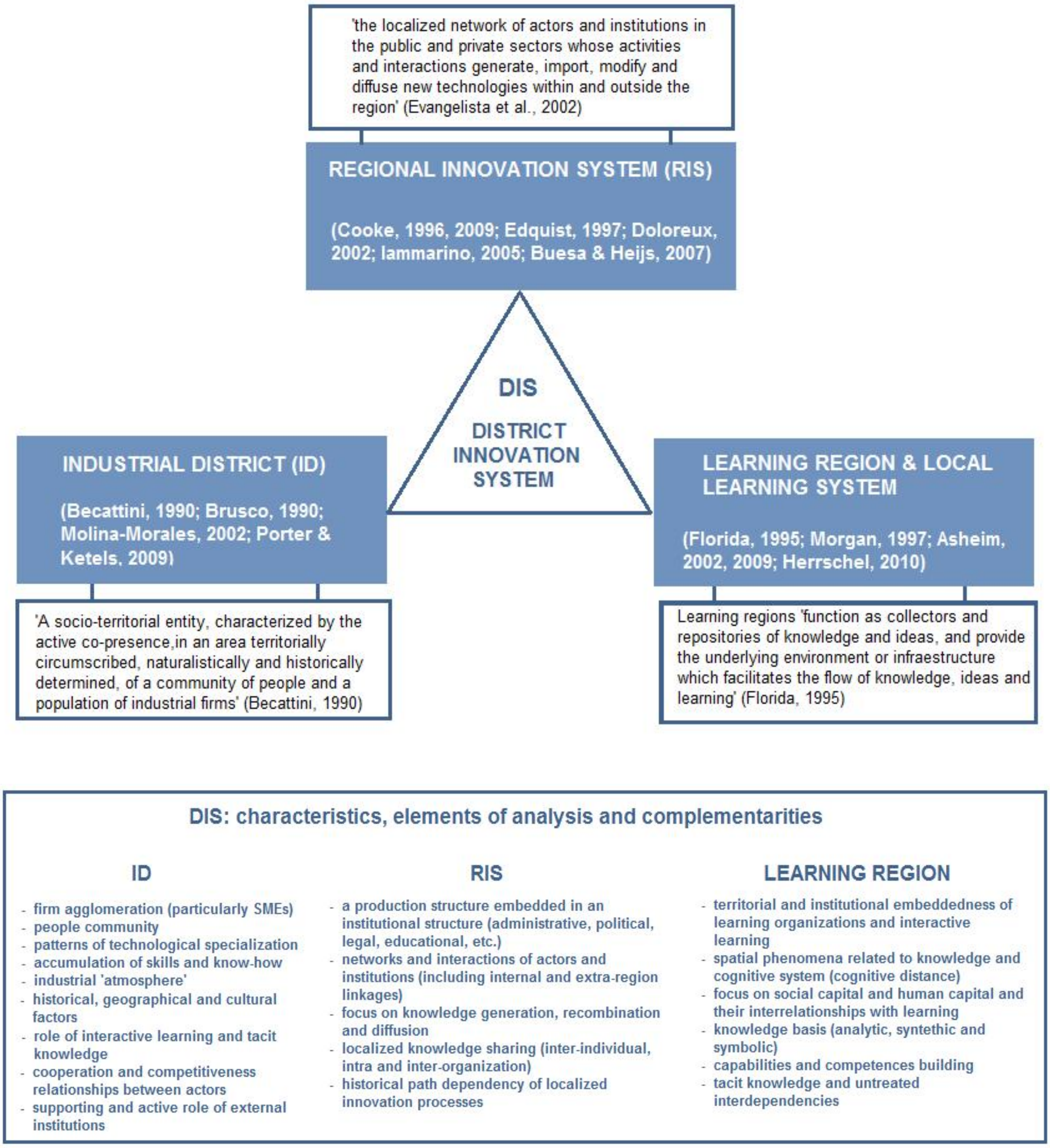

Figure 1. The DIS approach (Source: own elaboration)

DIS can be seen as an evolution of social and economic 'self-organized' systems based on recursive interactions among their components and with the environment (Belussi, 1996). DIS can be considered cognitive systems whose knowledge background comprises firms' and territories' learning mechanisms and knowledge creation processes. This *contextual* knowledge is not easily replicable and it is important to investigate the 'learning' processes that configure the cognitive system (Mothe and Paquet, 1998). Our approach allows an examination of the evolution of innovation through a study case of the CCDIS that takes account of the systemic infrastructure and relational and socio-cultural embeddedness in 'slippery' spaces (Granovetter, 1995). Knowledge is a mixture of experience, values, contextual information and insights, which create a framework for assessing and incorporating new experiences and information (Davenport and Prusak, 2000). Knowledge flows can occur through several sources, learning mechanisms and instruments, embracing individuals and inter-firm interactions, formation of new enterprises and mobility of skilled personnel among firms (Keeble and Wilkinson, 1999). The learning environment and innovation processes are shaped strongly by knowledge bases and absorption capabilities (Cohen and Levinthal, 1990; Asheim, 2007).

3 The CCDIS and the existing literature

Previous studies of the ceramic industry in the Castellon region focus on particular aspects of the phenomenon of innovation using the cluster concept (Albors, 2002) or the theoretical constructs of ID (Ybarra, 1991) or a combination of both approaches (Molina-Morales et al., 2002; Molina-Morales and Martínez-Fernández, 2004, 2009a; Expósito-Langa and Molina-Morales, 2010). According to the literature strong sectoral cohesion, highly skilled human resources, optimal use of technological resources and support from public and private institutions are the main factors that contribute to the development and economic success of the Castellon region (Escardino, 2001; Albors, 2002; Molina-Morales et al., 2002; Molina-Morales and Martínez-Fernández, 2004; Barba, 2005).

Figures 2 and 3 show the structure of the CCDIS and its agents: final firms (ceramic tile manufacturers), frit, glaze and colour suppliers, machinery and other services providers (manufacturers of trims, design, logistics, distribution, etc.). The CCDIS is organized around a set of very active producer associations that perform various activities such as training, commercial promotion, technical support, legal services and lobbying. The ITC

(Instituto de Tecnología Cerámica, Institute of Ceramic Technology) has links to the AICE (Association for Research in the Ceramic Industries) and is managed jointly by the local University Jaume I, the ceramic firms through ASCER (Ceramic Tile Trade Association) and regional government through IMPIVA (a regional industrial policy agency). The ITC employs around 100 scientists and has links with other smaller laboratories, such as the S. Carpi quality laboratory, and design groups such as ALICER (Association for Ceramic Promotion and Design). Some of these organizations –e.g. AICE and ASCER- are national as well as regional.

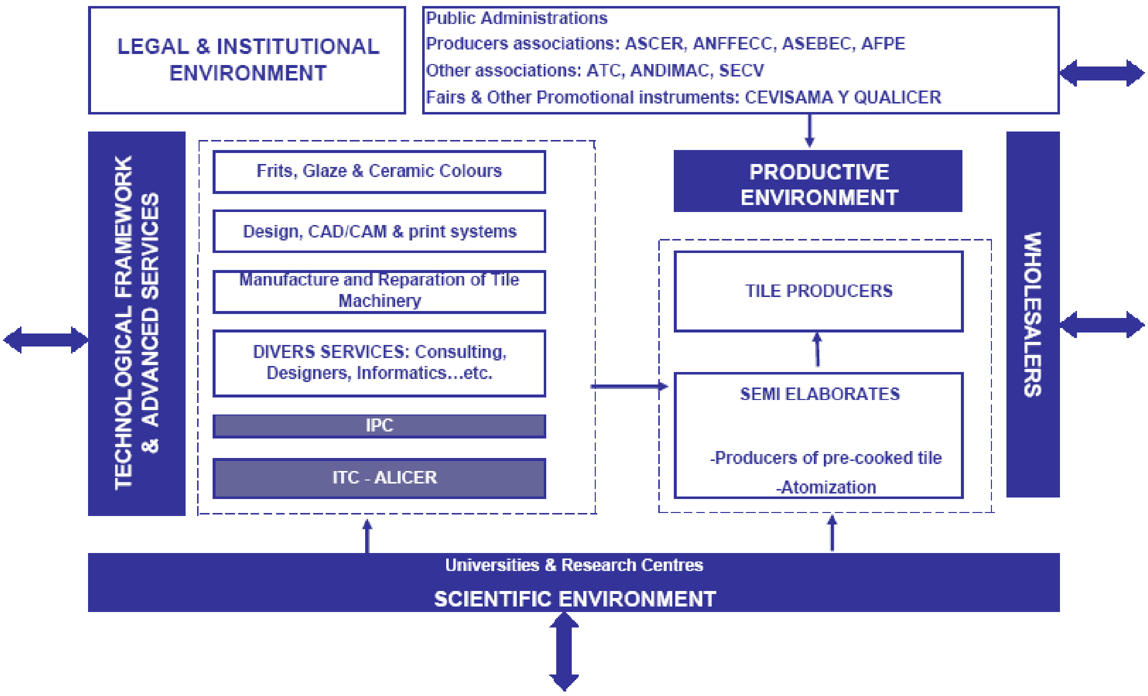

Figure 2. Global picture of CCD system (adapted from Fernández-De-Lucio et al., 1996). ITC (Institute of Ceramic Technology), ASCER (Spanish Association of Ceramic Tile Manufacturers), ANFFECC (Spanish Association of Frit and Glaze Manufacturers), ASEBEC (Spanish Association of Ceramic Machinery and Equipment Manufacturers), ATC (Association of Ceramic Technicians), ALICER (Association for Ceramic Promotion and Design), FUE (University-Companies Foundation), representatives of ANDIMAC (National Association of Ceramic Distributors and Construction materials, Asociación Nacional de Distribuidores de Cerámica y Materiales de Construcción) and SECV (Spanish Society of Ceramic and Glaze, Sociedad Española de Cerámica y Vidrio), CEVISAMA (Annual sector fair) and QUALICER (Tile Quality World Biennial conference).

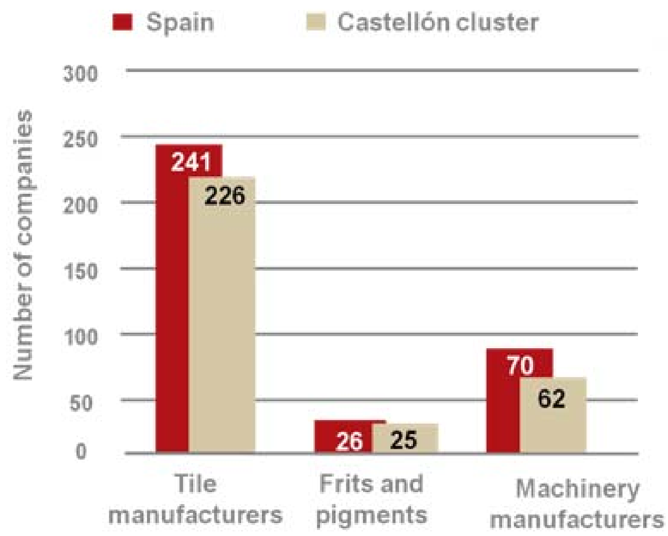

Figure 3. Cluster and sub-clusters (agglomerations of firms) at the CCDIS. (Source: ITC, 2011)

The CCDIS is characterized by dynamism based on its technological product and process innovations in materials, machinery and frit, glaze and colour. Several studies highlight the predominance of technological innovation in the frit and glaze sub-sector (Escardino, 2001; Albors, 2002; Meyer-Stamer et al., 2004; Tortajada et al, 2008; Gabaldón et al., 2009). A study by Gabaldón et al. (2009) shows that patenting activity in the CCDIS is mostly in this sub-cluster and that ceramic tile producers are generally involved in non-technological innovations.

Innovation processes are originated in the collective actions of a number of firms and actors that are connected by networks, informal contacts and a common knowledge base. Knowledge is acquired and diffused through personal contacts among firm members, suppliers, users, research centres and other actors, facilitated by local proximity in an environment of close cooperation-competition relationships (Molina-Morales, 2002). Proximity among the actors facilitates the building of an environment characterized by frequent contacts and formal and informal relationships building a particular environment, i.e., ‘industry is in the air’. Constant flows of information and new knowledge promote a continuous stream of incremental innovations based on combinations of tacit and codified knowledge and experience of *learning by doing*. Although no single firm in the ID controls or possesses all these resources they are unavailable to firms outside the cluster. Molina-Morales et al. (2002) show that product or process improvements are a collective endeavour that cannot be assigned to a single firm or institution. Forms of legal protection such as patents, copyrights or licences are rare in the CCDIS and suggest the existence of non-contractual protection mechanisms based on the firms’ social embeddedness. However, studies from the perspective of social capital (Molina-Morales and Martínez-Fernández, 2009b; Expósito-Langa and Molina-Morales (2010) argue against a simplistic association between knowledge diffusion and proximity within a district, and propose that while proximity facilitates trust in internal relations it simultaneously hinders access to external sources of knowledge. These authors highlight the role of local institutions –particularly the ITC- as repositories of relevant knowledge and intermediaries that can provide access to external networks and exploration of new opportunities.

4 Methodology

We adopt a qualitative approach and a case study methodology, in which the technological innovation (IJP) produced by the CCDIS is the unit of analysis. A case study is a history of a past or current phenomenon, that draws on multiple sources of information and evidence. It is a powerful instrument that captures the complex dynamic of the innovation process (Eisenhardt, 1989; George and Bennett, 2005). We describe the innovation process and the events and relationships leading to the emergence of the IJP technology. They are constituted by a series of interdependencies and a wide range of actors and temporary or informal relationships, which are difficult to capture. This allows us to take account of how a phenomenon is influenced by its context and to gather data from a variety of sources. Specifically, we considered patents, scientific articles, and secondary documents such as organization reports and technical articles from the literature (Web of Science, Scopus, Ceramic abstracts, etc.) and the information in patent databases (Esp@cenet, la Oficina Española de Patentes y Marcas (OEPM, Spain); PAJ and the Derwent Innovation Index) using the Matheo Patent software (Breschi and Lissoni, 2004). We consulted the annual reports of Gold Alfa's Award of the Spanish Society of Ceramics and Glass (2010), which is a prestigious annual award that has been presented at the CEVISAMA Fair since 1975 in recognition of the most important innovations in the sector. To obtain an in-depth understanding of the sector we conducted 21 interviews during January to July 2011, with the principal actors involved in the generation, development and diffusion of the IJP technology using an hermeneutic-dialectic method where the interviewer played an active role, and interviewer and respondent shaped the interview 'content' together (Jørgensen and Phillips, 2002). The selection of items was based on feedback from a panel of experts and a some pilot questionnaires.

5 Origins, development and diffusion of the IJP technological innovation

IJP technology refers to a variety of techniques used to generate droplets of ink which are propelled towards a predetermined surface. They include several IJP techniques such as continuous (binary, multi-level, greyscale), drop-on-demand (DOD)/valve jet (shutter, array) and impulse jet (activated and chevron), among others (Wijshoff, 2008; Garnsey et al., 2010). The IJP industry emerged in the 1970s[i], disrupted the dominant design of dot matrix desktop printing in the late 1980s, entered a growth phase in 1990 related to office computer system applications, and reached maturation at the end of the 1990s (Hutchings, 2009; Garnsey et al., 2010). When development was transferred to the industrial field, various issues emerged that made complicated technology transfer and development (Sanz et al., 2011). The first studies of IJP technology applied to fine ceramic decoration were conducted in 1980 by W. Roberts of British Ceram Research Ltd (UK). For some 10 years research focused on the adaptation and upgrading of ink properties, particularly flowability and conductivity, and testing of different printing methods and substrates. Developments in IJP technology as a new method of decoration on an industrial level appeared in 1997 in the Castellon region. To explore the history of this technology we ran database searches using some general keywords, such as inkjet, ceramic, tile, etc., identifying documents related only to ceramic tile manufacture and rejecting applications for the design and manufacture of printed circuit boards, ceramic processing tools and fine ceramics, etc. (e.g. a patent registered in 1975 mentions the IJP technology in reporting a procedure for flexographic printing). Figures 2 and 3 show the number of patents and scientific articles published between 1975 and 2011.

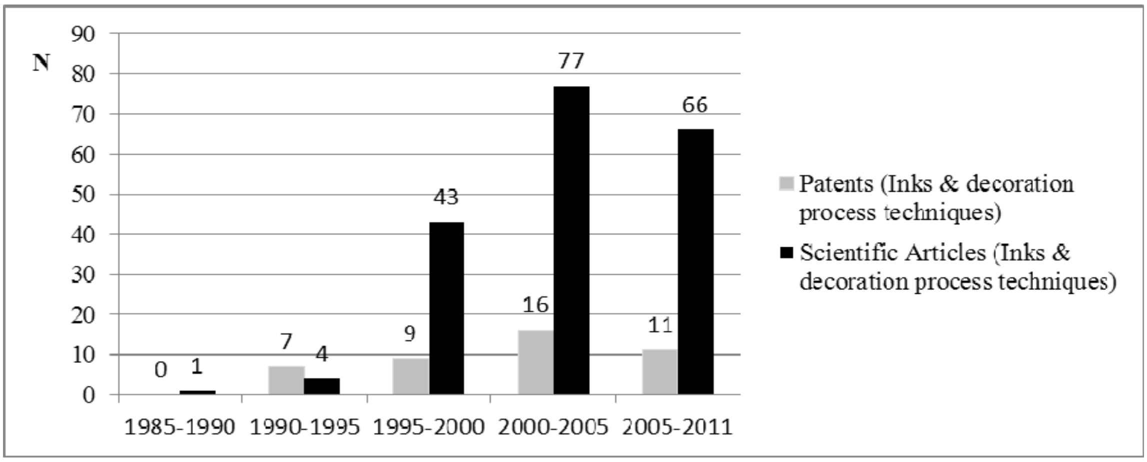

Figure 2. Number of patents and scientific and technical journal articles published on inks and decorative techniques for IJP technology in the ceramic tile sector (we consider five-year time intervals before and after the first machine exhibition at the CEVISAMA Fair)

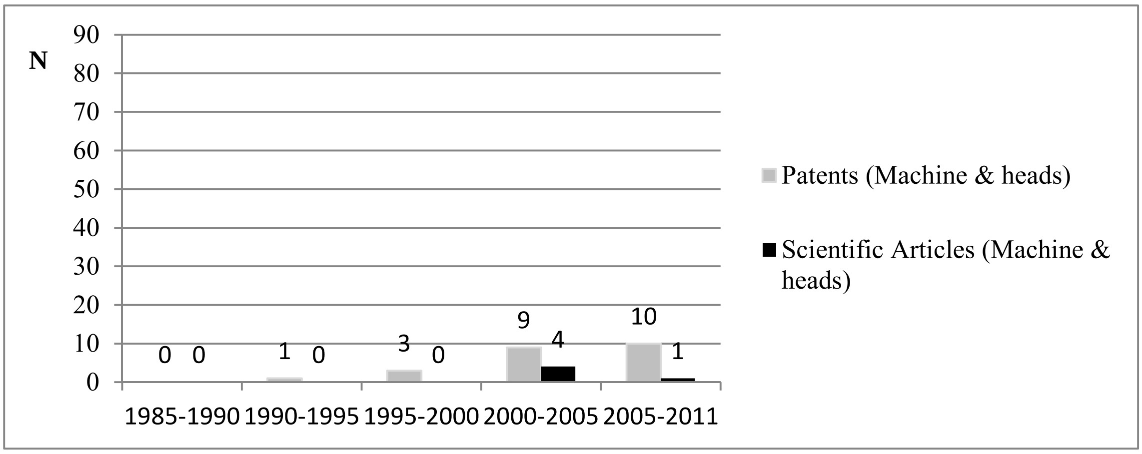

Figure 3. Number of patents and scientific and technical journal articles published on development of print-heads and machines for IJP technology in the ceramic tile sector

Analysis of patents shows that finding appropriate inks was critical for the development of the IJP technology in the ceramics industry because ceramic inks have certain particularities and properties. Their most important characteristics are: (a) high levels of stability and precipitation; agglomeration and changes in viscosity can clog the injectors (about 50µm); (b) strong tints, such that small amounts can cause problems in the substrate (7-70pL), may decrease the intensity of the colours achieved and result in poor quality decoration (surface tension, drying rate of the drop); (c) neutral pH required to prevent corrosion of the heads, (chemical compatibility between nozzle and the ink). Information obtained from the interviews shows the non-linearity of the innovation process, and the level of secrecy and competition among firms in the search for an appropriate ink.

The first IJP machine prototype for the ceramic tile industry was introduced in 2000; its inventors received the Gold Alfa Award of the Spanish Society of Ceramics and Glass. The period 2000-2005 saw the development of several prototypes and the first commercialization and diffusion of the technology in the ceramic sector. The first industrial IJP machine was developed by José VicenteTomás Claramonte (JVTC), owner of a small supplier company dedicated to computer engineering for ceramics in Villarreal, a town with a long tradition of ceramic tile manufacture in the CCDIS. He bought a print-head and conducted printing tests with Rafael Vicent Albert (RVA), an engineer working in the firm, and Antonio Querol, a chemical engineer who was working in the R&D department of Ferro Enamel Española S.A., a subsidiary of the Spanish multinational Ferro Corporation.

5.1 First stage: exploration and absorption of knowledge

Several technicians and engineers working in different firms were keen to introduce this technology, but the complexity, and the high cost of the research related to raw materials and inks required to adapt printheads for use on an industrial scale, made this new technology unpopular. One of the inventors of the ink jet printer (AQ) we interviewed commented that:

> 'all people had the idea ... the idea of this development **was in the air** ... the possibility of printing ceramic surfaces in similar forms that in paper or board ... we knew about some intents and proofs but it was a very complex problem, requirements of ceramic materials are very different'

The developers attended to the Drupa Fair, the world's biggest printing equipment exhibition in the world, held every four years in Messe Düsseldorf in Germany. They observed

> 'Many people worked in ink-jet printing in imaging and graphic arts… IBM mixed flexography … curiously all developments led to a long and large print-head, only INCA [a firm] attempted to develop digital plotters and a single-pass printer' ...

‘Our proposal can be distinguished from alternatives from the viewpoint of the technological solution, we proposed a single-pass mechanism defining the state-of-the-art and this idea was attractive and viable on an industrial scale’. (RVA, developer)

‘The inks were the main constraint because the particle size of the pigments was stable and formed agglomerates larger than the size of the injector nozzle which is approx. 50µm. Although we were thinking of obtaining soluble inks, there were no appropriate solvents or additives’. (AQ, developer)

This milestone in the development of IJP technology corresponds to the phase of ‘sequence of problems’ and ‘auto-catalysm of knowledge’ related to resolution of an initial problem (Coombs et al., 2003). The process was described by one of the inventors:

‘we began to experiment with different printheads to find more appropriate soluble salts, doing hundreds of tests ... the problem was that printheads do not allow the use of water, which damages the electrodes, and other solvents attacked the adhesives that linked the piezoelectric material to the printheads’. (AQ., developer)

There were five firms, four in the CCDIS and one in France, that were attempting to adapt printheads and solve the problems related to the inks.

‘Other technicians tried to create a machine using propellants with soluble inks but they failed … ‘there were other attempts in France and in other two firms in Castellón. I think that they saw the opportunity considering that the decorating machines were monopolized by Italians and for each drawing design we had to make four rolls of silicone’. … ‘This invention was very secret but here [in the

> CCDIS] we get information through a web of networks of friends'. (VS, researcher at ITC).

The literature shows that radical innovations and innovations with a high degree of originality and 'radicalness' face more obstacles to acceptance by industry (Expósito-Langa and Molina-Morales, 2010). During the first trials with printheads, JVTC presented his ideas for developing ink jet printing to a number of companies in the sector, but none of them considered the development feasible. He and his friend travelled to the Cambridge ink jet cluster and presented their ideas to the then CEO of Cambridge Consultants Ltd., which is linked to the Xaar Group[ii] from which they acquired their first printhead. However, the Xaar Group also was not interested. In contrast to the findings in the literature (Morales and Martínez-Fernández, 2004; Expósito-Langa and Molina-Morales (2010) the innovation in our case came from a small firm with no relationships with local research institutions that might have acted as information suppliers.

5.2 Second stage: new knowledge generation

Our interviewees confirmed that the main constraint was inks. It implied a paradigm shift in chemistry and research on nanoinks and nanopigments.

> 'In the industry there was a myth about the size of the pigment particles … we would not go down to the microscopic size the pigments powder disappeared' (EA, CDTI).

After several months of experimenting with hundreds of pigments through trial and error, JVTC and his partners were able to demonstrate the viability of the inks R&D to Ferro Enamel Española SA, a subsidiary of Ferro Corp. in Castellón. Ferro's long (92 years) experience as a leading global supplier of technology-based materials for a broad range of manufacturers, and its well established R&D activity, provided the necessary knowledge and experience in inks. The reciprocity and strong trust among the three developers were a key element, they set up a company called KERAjet to conduct R&D to develop electronics, software and inks (Ferro, 2001).

> 'The R&D began in December 1998, when we managed to print a first tile with Xaar (printhead) with a photograph of my daughter'. (AQ, developer).

Thus Ferro Enamel Española SA, attracted by local opportunities, acted as a 'learning interface' (Belussi and Asheim, 2010). It also was an intermediary between Enginyeria PC and and Seiko, a printheads supplier from Japan. It was the first machinery innovation that broke with the tradition in Europe of machinery innovations originating in Italy. Confidence, cooperation and secrecy were crucial in this stage of the IJP development.

> 'José Vicente is an entrepreneur and a very good engineer but he didn't know about problems with inks. Ferro gave him knowledge on inks… Ferro also solved his problems with Xaar heads that were not functioning properly, Ferro made possible the contact between Seiko, a leading manufacturer of print heads in the world and José Vicente'. (VS, researcher at ITC).

KERAjet worked with two printheads developed by external firms: Xaar (UK) and Seiko (Japan). Xaar printheads, which are used for high quality printing, do not have to run at such high speeds on line and do not involve very dark colours; Seiko's printheads are used for high quality printing in multiple colours, for high speed glazing lines and for very deep-coloured tile production. On 14 October 1998 JVTC applied for a patent at the Spanish patent office and on 27th September 2000 sent an application to the European Patent Office. The patent was for a device comprising at least two independent print modules easily replaceable with a single-pass mechanism, where only one pass is needed to complete the decorative motif (Tomás Claramonte, 1999, p. 2). This characteristic allows considerably faster printing speed (with a print quality of 200dpi). The first IJP prototype had 20 print heads with a printing width of up to 700mm and images up to 1.365cm wide at speeds of 50m/min. Two of the machine's inventors said that the multiple printheads and the single-pass method distinguished it from other technological solutions which mostly used single head systems. A major problem in this first development was achieving yellow and brown colours, which are in high demand from the ceramic sector. In 2001, Ferro Corp. patented a 'New yellow ink for the decoration of ceramics and glass using inkjet technology' (Querol Villalba and Guaita Delgado, 2002). Between 2000 and 2003 various competitors in the CCDIS made unsuccessful attempts to deploy the IJP technology using soluble inks using DOD (drop on demand) and CIJ (continuous ink jet) methods. In 2004, Ferro introduced the INKCID® system based on pigment inks. Tables 1 and 2 present the principal technological and scientific knowledge contributions in the form of patents and scientific articles, related to the development of IJP technology.

Table 1. Scientific articles, reports and patents on pigment inks for decorating ceramic

Inventor or author	Firm/organization	Patent/s article	Pub. date	Description	Pigment size	Ink type
Anthony C. Airey	British Ceram Research Ltd.	GB19910004171	1991	Ink jet printer ink for printing on ceramics or glass	d_{50} 0.2 – 2 µm	Aqueous
Sherry A.	General Electric Company PLC	WO9851749	1997	Sedimentation free jet ink composition	d_{50}< 50 nm	Termoplástica Cambio de fase (solvente orgánico)
Seong-Jin Kin; P.E. MCkean	Samsung IBM	Article	1998	Aqueous TiO2 suspension preparation and novel application of ink-jet printing technique for ceramics patterning. *Journal of materials science letters* Vol.17, 141-144.	TiO2 - 50nm	Aqueous
Oishi Tomohiro	Gifu Seramikussu Gifutsu	JP2001081363	1999	Color ink for inkjet printers has inorganic pigment or mixture of inorganic pigment and glass frit, of smaller particle diameter, and dispersing agent with inhibits precipitation of inorganic pigment or glass frit.	d_{50} 0.3 - 2 µm	Aqueous
Pfaff , P. Ragnetti M.	Degussa	DE19991021925	1999	(In)direct ink-jet printing of decor on solid, especially fireproof materials, e.g. glass, ceramics, enamel or metal, uses paste with high inorganic content and molten thermoplastic medium and heated ink-jet head	---	Termoplástico Cambio de fase a 45º -60º
Sereni; Juncosa; Jovaní	Colorobbia España	ES2170667	2000	Photosensitive ink for ceramics ink jet decoration, consists of inorganic temperature resistant fraction and an organic fraction also containing photo initiator(s) and photosensitive components.	d_{100}<10 µm d_{50}< 1 µm	Reactivo (fotosensible +fotoiniciador)
Murota Masamichi; Shirono Hirokuni; Arai Masahide	Degussa AG	JP20000200794	2000	Aqueous nanoparticle ceramic agglomerate dispersion for forming ink-absorbing layer of ink-jet recording medium.	d_{50} 0.05 – 0.3 µm	Aqueous
Doyle J; Megher, P	Carey Brothers Limited	EP1223201	2001	Ink, for ink jet printing method including firing to fuse ink to substrate, comprises carrier material, having melting point for phase change of ink, pigment; and fusible vitreous agent.	D_{100}< 10 µm preferiblemente 5 µm	Termoplástico Cambio de fase a 50º
Querol Villalba, A.M.. Guaita Delgado, F.J,	Ferro Spain SA	ES2209634	2002	Nueva tinta amarilla para la decoración de artículos de cerámica y vidrio mediante tecnología inkjet (Translation: New ywllow ink for decorating ceramic and glass with ink-jet technology)	TiO_2 coloidal d_{100}<0.1 µm preferiblemente d_{100}< 0.05 µm	Non Aqueous (disolvente alifático)

Bishop P; Dalton, J.	Johnson Mattey PLC	WO2005052071	2003	Digital printing ink composition useful for coatings substrates, e.g. ceramic comprises particles glass frit of metal and dispersion medium	d_{100}<2 µm d_{50}< 0.7 µm	Aqueous
Corts Ripoli, J.V; Sanmiguel Roche, F.; Concepción Heydorn, C.	Torrecid S.A.	WO2006077273	2005	Industrial decoration ink	d_{100}< 3 µm	Non Aqueous
Green; Warren; Pele Dh	Jettable	WO2006126189	2005	Pigmented ink useful in drop-on-demand inkjet printing for decorating ceramic comprises pigment of specific particle size, a dispersant and a medium exhibiting specific surface tension	d_{50}< 1 µm	Non Aqueous
Kimura Takashori; Endohiroki	Nippon Amu KK	JP2007084623	2005	Ink for ink-jet printer, contains solvent, dispersing agent, and inorganic pigment having present median size and particles of present diameter.	d_{50} 0.8 – 1.7 µm	Non Aqueous
Querol A.M.; Guiata F.	Ferro Spain SA	ES2289916	2006	Dispersión coloidal de pigmentos cerámicos (Ceramic pigments colloidal dispersion).	d_{50} 0.3 - 2 µm	Non Aqueous
Yokoyama Ohata	Gifu Seramikussu Gifutsu	JP2007238400	2006	Marking method of industrial commodity e.g. ceramic products, involves preparing ink by adding specific amount of dispersing agent with respect to inorganic pigment and performing inkjet printing to mark ceramic structure.	----	Non Aqueous
Dondi; Matteucci; Gardini	CNR – ISTEC CERICOL	Working document	2006	Industrial ink-jet application of nano-sized ceramic inks. *TTP*	d_{90} 10-50nm	Non Aqueous
Gardini D.; Dondi M.; Costa A.L.; Matteuchi F; Blosi M.; Galassi C.; Cinotti E.	CNR-ISTEC CERICIL	Article	2008	Nano-sized ceramic inks for drop-on-demand ink-jet printing in quadrichromy. *J. Nanosci Nanotechnol.* Vol. 8(4), 1979-88.	d_{90} 10-40nm	Non Aqueous
Cavalcante, PMT.; Dondi, M.; Guarini, G.; Raimondo, M.; Balbi, G.	Universidad Federal do Rio de Janeiro - CNR-ISTEC - CERICOL	Article	2009	Colour Performance of Ceramic Nano-pigments. *Dyes and Pigments*, Vol. 80, 226-232.	d_{90} 10-40nm	Non Aqueous
Obata, S.; Kato, M.; Yokoyama H.; Iwata, Y.; Kikumoto Y.	Gifu Seramikussu Gifutsu Tajimi City Pottery Design and Technical Center Faculty of Engineering, Gifu University	Article	2011	Syntesis of nano CoAl2O4 pigment for ink-jet printing to decorate porcelain. *J. Ceram. Soc. Jap*. Vol. 119 (1387), 208-213.	d_{50} 70nm	Aqueous

Table 2. IJP devices and machines patented for decorating in ceramic tile industry (In colour grey the Spanish contribution)

Titular	Inventors	Tittle/description	Priority date
Tomas Claramonte, J. V.	Tomas Claramonte, J.V.	Dispositivo para decoración de baldosas cerámicas (Translation: Device for decorating ceramic tiles)	14/10/1998
Hegedus G; Kocsis A; Florian G.	Hegedus G; Kocsis A; Florian G.	Liquid Dispensing Apparatus	09/03/1998
SACMI COOPERATIVA MECCANI	Ricci Claudio; Acerbi Pierugo	Method and device for decorating ceramic tiles	08/09/2004
System Spa	Stefani Franco	An apparatus for decorating ceramic products	07/02/2006
KERAJET S A	Tomas Claramonte, J.; Vicent Abella, Rafael; Gasso Arcas, Pedro	Modulo autónomo de impresión por chorro de tinta (Translation: Inkjet printing autonomous device)	28/11/2006
GRUPPO BARBIERI & TAROZZI	Tarozzi Fausto	Decoration method and system for decorating ceramic products	17/04/2007
XENNIA TECHNOLOGY LTD	Yeong Kay K ; Hirt Thomas	Method, printing device, and formulations for decorating glass or ceramic items	19/02/2007
CRETA PRINT, S.L.	Blasco Claret, Victor	Sistema de impresión en azulejos cerámicos (Translation: Printing system for ceramic tiles)	06/06/2008
MACCARI ANTONIO	Maccari Antonio	Plant and method for decoration by means of ink-jet technology	08/11/2006
ARGON HT SRL	Manoukian Harutiun	Screen printing machine having a replaceable IJP unit	04/06/2002
KERAJET SA	Tomas Claramonte, J.; Vicent Abella, Rafael;	Sistema de mantenimiento de máquinas de impresión por chorro de tinta, de gran formato (Translation: Maintenance system for ink-jet printing machines for large formats)	09/02/2009

5.3 Third stage 3: IJP technology diffusion

Technological diffusion is the process by which innovations – whether new products, new processes or new management methods - spread within and across economies. There are two stylized facts related to technological diffusion: spread - the S-curve – when diffusion rates gradually rise and then fall over time. There is a period of relatively rapid adoption sandwiched between an early period of slow take up and a late period of slow progress to satiation); and economic and social factors. Economic and social factors influence individual decisions to begin using the new technology based on the costs and benefits of its adoption. The benefits of IJP technology compared with previous decorating techniques, such as gravure printing and flat screen-printing technologies, were undisputed. However, its diffusion in the ceramic sector was not as rapid as expected. There were problems related to the stability and low chromatic intensity of the inks for application in an industrial process. These aspects and the high price of materials (Ru, Au) acted as barriers to the rapid expansion of IJP technology in the CCDIS. KERAjet SA intensified its research efforts on colour range and intensity and ink and enamel stability in order to obtain acceptable colours.

> ‘The road was to investigate intensely pigment inks, with inorganic pigments in its composition and the characteristics required for this process’. (AQ, developer).

IJP technology began to spread in the ceramic sector after the appearance of a new option on the market in 2005. Torrecid, a multinational frit, glaze and ceramic producer, launched a range of pigment inks in collaboration with Durst Phototechnik AG, a company devoted to image processing, and Fujifilm Dimatix (Spectra), a printhead manufacturer (Sanz et al., 2012). Information from interviews show that a range of different strategies was employed. These included experimenting with equipment developed by companies with experience in design and engineering of coupling printheads already on the market (KERAjet JETTABLE in Israel), collaborations and joint marketing strategies involving a manufacturer of frits, glazes and ceramic colours and a specialist in digital printing machines (TORRECID and DURST, using binary Fujifilm Dimatix heads), and a manufacturer of machines for ceramic decoration and a specialist in digital printing machines (CretaPrint and the Italian firm TENOITALIA with Xennia). In 2012, there are at least 13 different machines available in the market and the most widely used printheads are piezoelectric provided by Xaar, Spectra and Seiko.

> 'We should not forget that it is a very recent technology and it is understandable that it should be adopted by the most important firms before the other follow their example' ... 'it would require a big change in production mentality'. (VP, fabricator)

The first Tecnargilia Design Award in 2010 to celebrate the latest technological innovation in this sector was for digital decoration. Tecnargilia is the most important international fair for technological and stylistic innovations for the ceramics industry. Figure 4 depicts the progressive adoption of IJP technology. It shows the number of companies that have manufactured machines since 2000 and the number of machines installed in April 2010 (N=373 machines) (Giacomini, 2010). The number of machines in April 2011 was 664, 48.6% of which are Spanish in origin and 31% are Italian.

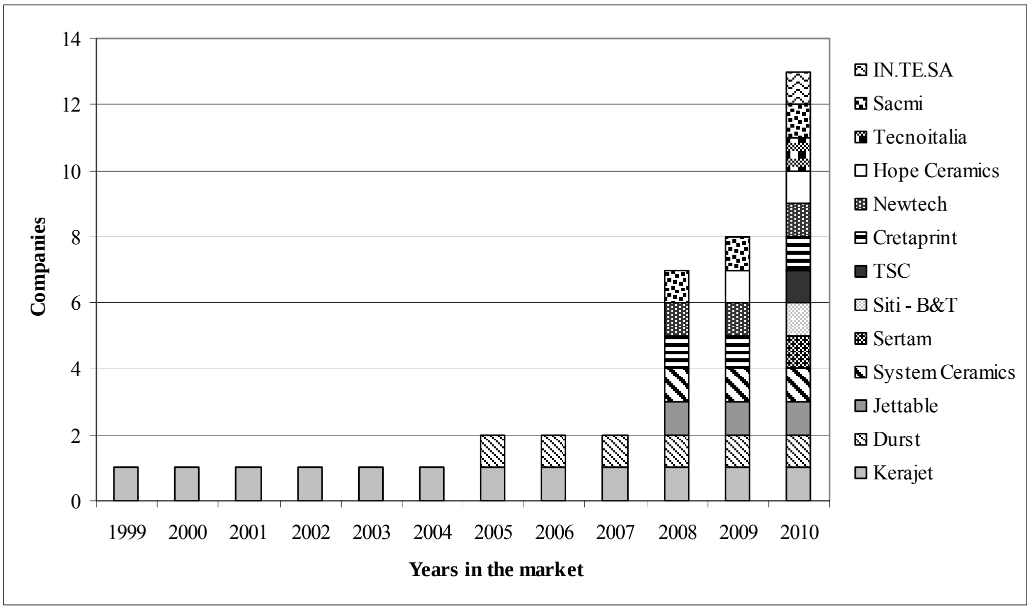

Figure 4. Number of companies manufacturing ink systems and machines for IJP technology for the ceramic tile industry (Source: Giacomini, 2011)

From 2000 to 2008, with the exception of JETTABLE which developed its own inks, tile firms were supplied exclusively by KERAjet-Ferro and Torrecid-Durst. This probably slowed the introduction of IJP technology in the sector. In 2009, KERAjet-Ferro and Torrecid-Durst began to supply inks from other certified sources. KERAjet developed a certification protocol for testing and control of ink quality and currently has a presence in several major ceramics centres in Spain, Italy, Portugal, China, and other countries. Through continuing investment in knowledge and accumulated competences the firm has produced several generations of machines. In Spain, and particularly in the CCDIS and the construction industry on which it depends, the economic downturn has had a major effect on tile manufacture. However, in 2010 KERAJet SA had 200 machines installed and functioning across the world, which is evidence of the success of IJP technology in the ceramics field.

The role of the ITC in the diffusion process is interesting. According to Molina-Morales et al. (2002) the ITC acts as an intermediary bridging to external knowledge and new technologies and supports exploration and exploitation activity. Our case study shows that the ITC did not participate in the exploration and R&D stages, but played a key role in the diffusion of and improvement to IJP technology. Figure 5 depicts the formation activities, transfer of technology and R&D joint projects developed by firms in cooperation with the ITC.

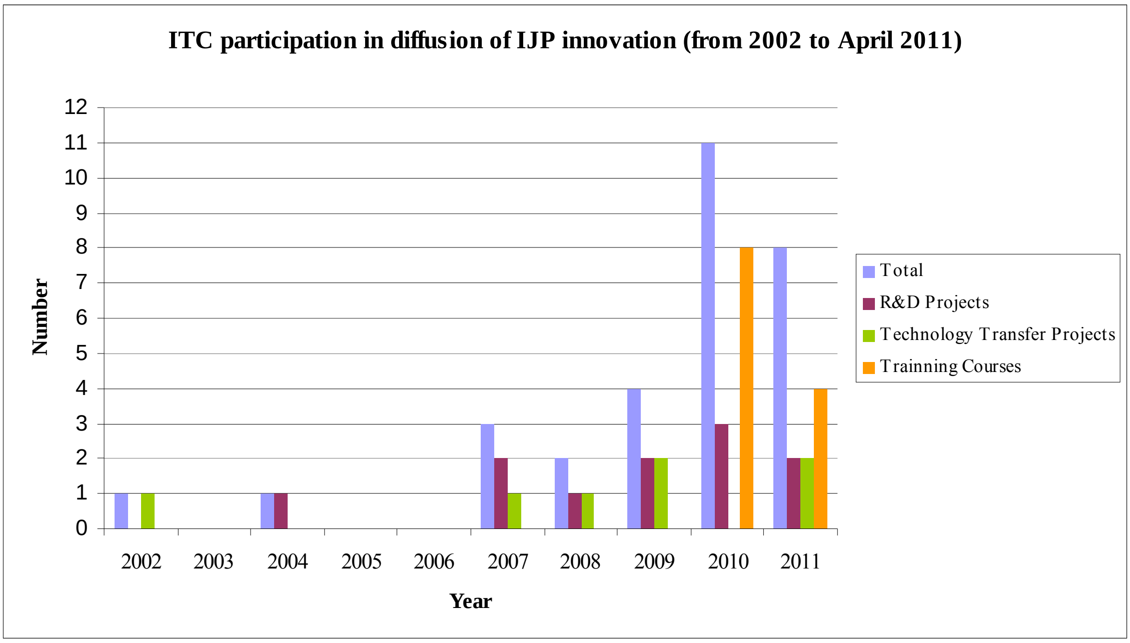

Figure 5. Activities developed in cooperation between firms and ITC related to IJP technology

Table 3 summarizes several aspects related to the process of innovation and especially the non-linearity of the knowledge flows.

<table>
<tr><th colspan="2" rowspan="2">Feature</th><th colspan="3">INNOVATION process</th></tr>
<tr><th>Exploration, acquisition and new knowledge absorption (before the first patent)</th><th>New knowledge generation (~1998 to 2005)</th><th>Innovation diffusion (after 2005)</th></tr>
<tr><td colspan="2">Knowledge basis: analytic, synthetic and symbolic (Asheim, 1996, 2007)</td><td>• Knowledge is created in an inductive process of testing, experimentation and practical work (synthetic knowledge)
• Codified and tacit knowledge combined
• Knowledge related to different printing methods and printhead devices (US and European patents)
• Limited knowledge available on soluble inks for industrial application in ceramic sector</td><td>• Combination of scientific knowledge with a relevant component of local synthetic knowledge (particularly previous experience, know-how and R&D competences related to inks field)
• Emergence of a new paradigm: the nano inks</td><td>• Strong impulse to R&D (nanoinks)
• Impact on design digitalization process, increasing the incorporation of sources of symbolic knowledge</td></tr>
<tr><td>Sources of knowledge and relevant actors</td><td>Internal networks (links in the CCDIS structure and with the local environment)</td><td>• Developers of the first IJP machine: JVTC (electronic engineer) director of a small enterprise supplier of software and electronic applications for ceramic industry (Enginyeria PC), his partner RV (industry engineer) and AQ (chemistry degree) from Ferro Enamel Spain S.A.
• R&D process begin with informal contacts between a small supplier firm and a Ferro, in the ‘core’ knowledge of the Frit and Glaze Subsector
• Other attempts to adapt printheads for industry ceramic</td><td>• 1998 Start R&D in adaptation of printheads and inks proofs (trial an error method)
• Joint venture constitution: KERAjet (spin-off of Ferro Enamel Spain S.A.)
• 2000 First prototype presentation at CEVISAMA
• 2000 Development of two new prototypes and Ferro began producing a range of CMYK (Cyan, Magenta, Yellow, Black) colour inks in solution
• (~ 2000) Other firms intended simoultaneously to develop inks
• 2001 Start commercialization
• 2002 Presentation of the Kerajet K560 Model and new inks
• 2004 to 2008 R&D agreement and technology transfer with Seiko (printheads supplier)
• 2004 Presentation of KERAjet k700 Model</td><td>• Consolidation of the KERAjet start-up
• Development of several Doctoral thesis related to inks properties (Jaume I University and ITC, University of Valencia)
• Links with universities and public research institutions (R&D projects; seminars, etc.)
• Leader participation of ITC in elaboration of reports on state-of-the-art, R&D and technology transfer projects (e.g. In 2011 the Technology Observatory published a study entitled ‘Ceramic Decoration by IJP technology’ and also disseminated the contents of this study among companies).</td></tr>
</table>

	External networks	• Visit to international printing fairs (DRUPA) • Trial and error activities with plotters and intents of the method of single-pass (other firm in France) • Contacts with consultants of the Cambridge printing cluster (the principal influence at CCDIS in this issue), particularly the prinbtheads supplier firm Xaar • Initial contacts with printheads suppliers: Xaar (United Kingdom) and Seiko (Japan)	• Contacts with suppliers, particularly Xaar (UK) and Seiko (Japan) • R&D and development of other prototypes based in other IJP technologies in other countries (Italy, Israel, Germany).	• Intensification of relationships with suppliers • Began commercialization of other firms. The first Durst digital decoration system with ceramic pigmented inks were tested in Spain in January 2005 and installed in Italy in July 2006. • Intensification of KERAjet exportation in the world and creation of KERAjet branches in Italy Portugal, China and SouthAmerica • Emergence of inkjet printing as a subsector? (it represents around 6% of exportation income) • 48.6% of the machines installed worldwide are of Spanish origin and 31% Italian one
Cooperation with other agents		• Trusting cooperation at individual level and inter-firm • Non-cooperation with universities and other research organizations (ITC) • Non-cooperation with the rest of agents at the CCDIS	• Cooperation began after the presentation in CEVISAMA of the first prototype (2000): Inter-firm, ITC, with other research institutions and universities within and outside of the CCDIS (e.g., in 2007 KERAjet and the Italian firm System Spa developed the Rotojet Kit) • Cooperation is the strategy followed by KERAjet with diverse local and external agents: firms such as Ferro, Xaar (UK), System Spa (Italy, 2007), Seiko (Japan, 2004-2008); universities (Jaume I, Universidad Autónoma de Madrid in 2005); with financial actors, etc.	
Cost & Funding		• Internal • High costs due the materials for inks experimentation • High uncertainty regarding the R&D advances and possibilities of industrial implementation	• High initial financial support from Ferro Enamel Spain S.A. • 1999 CDTI support for R&D projects • IMPIVA support for several R&D projects • Strong effort in R&D in-house of KERAjet	• Government support for building part of KERAjet industrial installations • Public funding of R&D projects • In 2011 KERAjet has 45 employees (34% of staff realize R&D activities)
Knowledge protection		• High confidence, trust and reciprocity • High secrecy in the initial development and competition with other firms within and outside CCDIS	• The second patent (inks) was a defensive one • Confidentiality agreement • High knowledge protection (monopolistic in the inks development)	• Change in knowledge protection strategy of KERAjet in 2008 (inks quality certification)

Human capital, competences	High level of local technical skills, knowledge and experience in inks development applied to ceramic sector	• Capabilities complementarity between KERAjet and Enginyeria PC	• New specific competences demand for the ceramic sectorITC leaders the offer of specific training courses • Cooperation between Kerajet and Colorobbia in the first training programs •
Principal obstacles	Knowledge barriers related to the emergence of new paradigm in inks research and development (from micro to nano-inks)	• Problems related to the stability and low chromatic intensity of the inks for application in an industrial process • High costs & risk • Demand of new specific skills is seen as a limitation for troducing IJP technology • Strong 'traditional' cultural environment	• Inks limitations (optimisation of the chromatic quality, improvement of properties stability, reduction of production costs, etc.) • R&D high costs • Firms need 'change' their mind about the new decoration trends • Risk of homogeneity trends in design • Impact of economic and financial crisis. However, according to Giacomini (2010, 2011) the area of ink-jet digital decoration has continued to receive investment during the recent years of stagnation in the ceramic sector

Table 3. Summary of results of case study

6 Conclusion and final comments

This paper investigated an innovation process in a DIS, highlighting some of the limitations related to ID and cluster theoretical approaches. We used this framework to describe the progress of an innovation in the ceramic industry from the evolutionary point of view, including processes, interaction and feedback involved in its generation, development and evolution. We consider the IJP innovation, that can be described not as a radical innovation but as a very 'relevant innovation' that is changing the ceramic sector.

Our in-depth case study showed that the IJP technology emerged as a result of local dynamic interactions in the CCDIS. Following ten years of intense R&D, digital printing in the ceramic sector is acknowledged to have changed thinking related to ceramic decoration. And also it represented a break in the pattern of ceramic machinery innovations originating in Italy. Our case study confirms findings from research on ID related to heterogeneity in the ceramic district (Molina-Morales and Martínez-Fernández, 2009a), informal relationships related to cooperation and information exchanges underpinned by mutual trust and face-to-face contacts and the role of in-house R&D in the innovation process, particularly due to the frit, glaze and colour providers (Albors, 2002; Tortajada et al., 2008; Gabaldón et al., 2009). We provide evidence of the importance of external ties and relationships with agents outside the Castellon region, aspects that are generally neglected by mainstream studies of ID. The CCDIS can be characterized as an 'open learning system' where the act of building external linkages and complementing internal knowledge with external knowledge (e.g. with the Cambridge 'district', the external suppliers Xaar and Seiko, the Drupa fair, etc.) was crucial for innovation performance in the case of the IJP technology development. The principal actors –an entrepreneur of a small firm and their friends, one of them from a multinational subsidiary- participated in an evolving process of exploration and absorption of external knowledge from other industry sectors. This collaboration was based on a common culture of trust and mutual reinforcing capabilities and provided informational and other benefits related to access, timing and referrals, in a competitive environment. Most of the knowledge was tacit and rooted in practice in the frit subsector. It was related to know-how (procedural knowledge rather than declarative knowledge) and the long experience of skilled workers in whom the knowledge was 'embedded' and influenced by social ties, friendship, trust, reputation, solidarity, norms, habits and co-evolved rules of conduct. Trust relations are assumed to reduce inter-firm transaction costs and to complement managerial and technological capabilities, and encompass a complex process of interrelationships of endogenous (knowledge feedback) and exogenous (knowledge inputs) mechanisms in the learning district system. Secrecy and patenting played a key role in the sharing of knowledge, and the search for exploitation opportunities and an innovation strategy. In contrast to the findings in the literature, our case study shows that research institutions (the ITC and universities) did not act as an intermediate agent in the early exploration and R&D stages (Molina-Morales et al., 2002). We attribute this feature to the degree of radicalness of the IJP innovation. However, the ITC and other research institutions participated in the diffusion of and improvements to IJP technology through collaborative R&D projects with IMPIVA and CDTI.

This paper contributes by providing empirical evidence for a better understanding of the complex and systemic characteristics of the innovation dynamics beyond the traditional economic perspectives of 'industrial clustering' and ID. This approach could be complemented by and extended with further studies.

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[i] Piezoelectric ink-jet (PIJ) printers are based on three patents from the 1970s. The first patent was taken out by Zoltan and the Clevite Company in 1972 (US Patent 3,683,212), the second belongs to Stemme of Chalmers University dated

1973 (US Patent 3,747,120) and the third is owned by Kyser and Sears from the Silonics Company registered in 1976 (US Patent 3,946,398) (Wijshoff, 2008). In 2005 M.A. Gröninger, M.J. van den Berg, and H.M.A. Wijshoff patented an 'Inkjet system, method of making this system and use of said system' (US Patent 20050285908).

[ii] Xaar Group plc spun-off in 1990 from CCL (Cambridge Consultants Ltd, a technological design consultancy, spun-off from the University of Cambridge). At the start of the 1970s CCL was working on various continuous ink jet printing technologies funded by the chemical multinational ICL. CCL was contracted to develop ink jet technologies for printing textiles at high speed, over large widths and in colour. Xennia was founded in 1996 by Alan Hudd, ex-Domino ink and R&D group leader, who saw an opportunity in industrial ink jet from DOD techniques that were being developed. Xennia has specific expertise in 'difficult' materials in IJP printing, such as inorganic materials e.g. metals, phosphors, pigments, biomedical fluids, structural scaffold materials, conductive inks and materials for displays (Clymer and Asaba, 2008; Garnsey et al., 2010).