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COMMERCIALISING ECO-EFFICIENT NANOTECHNOLOGIES IN THE CONSTRUCTION INDUSTRY – The case of glass-processing in Finland

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ABSTRACT: New and advanced process technologies are growing in importance for highly industrialized countries which increasingly have to compete with rapidly-developing, low-cost, countries. Nanotechnology is an interesting example in this context. It may evolve into a platform for industrial renewal in a broad range of sectors, and can also offer eco-efficient applications to address environmental concerns related to climate change. This paper assesses facilitating and inhibiting factors in the commercialisation and use of eco-efficient nanotechnology in the Finnish glass-processing and construction industry based on company case studies. The focus on the construction industry is motivated by its large contribution to economies while it also stands to gain significantly from new eco-efficient applications such as those enabled by nanotechnology. While there is an active community of nanotechnology-dedicated companies and research groups in this field, commercialization is inhibited by the absence of large and technologically progressive companies which could act as lead users, provide test markets, critical longer-term funding, and aid in the transition from R&D and piloting phases to industrial production. Public technology programs have provided a good basis for further developments and the construction industry could gain from nanotechnology once its benefits and value proposition to consumers and the general public become clearer.

KEYWORDS: nanotechnology, eco-efficiency, commercialisation, technological systems, glass-processing, construction

CONTENT

1. INTRODUCTION

1.1. Background

New and advanced process technologies are growing in importance for highly industrialized countries which increasingly have to compete with rapidly developing, low-cost, countries. The focus of this paper is on nanotechnology – as an emerging and advanced process technology – and its application in glass-processing in the broader context of the construction industry.

Nanotechnology is drawing a great deal of attention due to high expectations that it can offer as a platform for both incremental and radical innovation, thus sustaining productivity increases and growth in a broad range of industries (Youtie et al., 2007). Nanotechnology is essentially a new processes technology, enabling new functionalities of materials in the range of 1-100 nanometres, and it can be particularly relevant for renewing traditional materials industries such as construction (see below for a more detailed definition of nanotechnology). Further, the science-based and emergent nature of nanotechnology also implies that this is a field in which highly industrialised countries might have a competitive advantage globally (compare with Palmberg et al., 2007).

The relationship between glass-processing in the construction industry and nanotechnology is interesting for various reasons. So far empirical research on nanotechnology has mainly been based on aggregate science and technology indicators, such as publications and patents. The involvement of companies in this technology field remains poorly understood, especially in the context of traditional materials industries (see Special Issue in research Policy on Emerging Nanotechnologies, for a discussion based on company case studies see OECD (2009) and the references therein). The case of glass-processing in construction is particularly relevant due to numerous nanotechnology business opportunities and applications that already now are materializing.

To a large part business opportunities for nanotechnology in construction relate to the increasing attention given to enhancing the eco-efficiency of buildings through the use of new and functional materials (Steinfeldt et al., 2007; ObservatoryNano, 2009). These opportunities have also benefited from the recent boom in construction that has been evident in many rapidly developing countries (even though the current economic crises has at least temporarily decreased demand), China being the foremost example. Further, glass-processing is an area where Finland has a long tradition and deep competencies as an illustration of an application field for nanotechnology outside the commonly touted `high-technology′ industries, e.g. ICT and pharmaceuticals. At the same time, however, glass-processing is still a very traditional and capital-intensive industry in which products and processes change slowly and in which the diffusion of new technologies is hampered by high fixed investments, low R&D intensity, and conservatism (Manseau and Shields, 2005).

1.2. Aim and structure

Nanotechnology is still in an emergent phase of development, and the concept itself is quite broad. Therefore not much is known about the specific features of this technology especially with respect to the various application fields and related industries. Against this backdrop, the aim of this paper is twofold.

The *first aim* is to highlight an application field for nanotechnology in the construction industry as one example of an important traditional industry, as well as to identify the related actors and institutions, their interrelationships, emerging value chains and industrial organisation. The focus will be on the role that small respectively large companies play in this application field, on the supporting R&D communities, intermediary products and machinery developers/suppliers.

Following the identification of these actors and institutions, the *second aim* of this paper is to interrogate in greater detail the facilitating and inhibiting factors for nanotechnology to enter the related value chain. The focus will be on the commercial drivers behind these applications, on the perceptions that university researchers and companies have concerning the commercialisation of nanotechnology, and on broader issues related to market formation and legitimation, resource mobilization and possible externalities (both positive and negative) that the application of the related technologies might have for the industry/economy.

The paper is structured as follows. It starts of, in the second section, with a presentation of the analytical framework used in the paper, while the third section describes key features of the construction and glass-processing industry, and identifies the focus of case studies which have been undertaken to address the aim of the paper. The fourth section briefly introduces the methodological approach of the case studies before describing the companies which have been subject to the case studies in the broader context of glass-processing in the construction industry. The fifth section ends the paper with a concluding discussion.

2. ANALYTICAL FRAMEWORK

2.1. Emerging industrial organisation in nanotechnology

With reference to the National Nanotechnology Initiative in the US nanotechnology is here defined as *"…the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modelling, and manipulating matter at this length scale."* (see http://www.nano.gov/). Beyond this relatively well recognized definition there are divergent viewpoints on the nature of nanotechnology. It is stressed that nanotechnology still is a very basic research-oriented and generic field, enabling innovation in a broad range of industries (Palmberg and Nikulainen, 2006; Youtie et al., 2007). This observation is backed up by data on scientific publishing and patenting related to nanotechnology. Emerging value chains have also been identified, even though it might be too early to talk about a nanotechnology industry per se.

Despite its common use `nanotechnology´ is still mainly an umbrella term for a whole bundle of different scientific and technology fields at the intersections of physics, chemistry and biology. Accordingly, it is important to focus on specific technological sub-fields to uncover whether, and which types of new companies, value chains and industrial organisation are emerging (compare with OECD (2009)). In such exercises some guidance may be provided by technology life cycle models as these focus on the role of different types of companies during the emergence of technologies.

In technology life cycle models the role of small entrant companies are highlighted as the initial carriers of emerging technologies, especially in cases when the technology is discontinuous with respect to the knowledge base of the established, incumbent, companies (for a seminal paper see Tushman and Anderson (1986)). Over time, as the technology matures, the incumbent companies will regain their position due to the complementary assets that they possess. They will assimilate new technology through takeovers and eventually shift the loci of competition from innovation to prices. This becomes visible in the dominance of new small companies during the emergent phases of a technology field, followed by a gradual concentration of activities later on to a few incumbent companies.

Relevant modifications to these models have, among others, been provided by Rothaermel (2001) and Hill and Rothaermel (2003). They suggests that incumbent companies may also be in a better position to adapt to discontinuous technologies through strategic alliances with entrants if the incumbents possess complementary assets further downstream, e.g. related to production, marketing and retailing. These types of symbiotic relationships between entrants and incumbents are typical between pharmaceutical companies and small dedicated biotechnology firms, and they may also be relevant in nanotechnology (Luukkonen, 2005).

Turning to nanotechnology, what is the role of entrants versus incumbent companies in commercialisation, and how is industry dynamics unfolding? An assessment of this question is speculative in this early phase of developments. Nonetheless, it seems that at least present day nanotechnology is more likely to enhance rather than destroy the knowledge bases of incumbent companies. By this logic, large established companies in the end-product segments of value chains should be in a good position to assimilate nanotechnology. On the other hand, nanotechnology also contains discontinuous elements that might be disadvantageous for established companies (compare with Rothaermel and Hill (2005)).

The discussion of whether nanotechnology is a competence-enhancing or competence-destroying technology for incumbents can be enriched by a distinction, commonly used, between `top-down´ and `bottom-up´ approaches to nanoscale engineering. The former approaches existing materials through traditional lithography, cutting, etching or grinding techniques, of relevance especially in the electronics industry, and may therefore be competence-enhancing. The latter one creates new materials at the nanoscale through chemical synthesis or self-assembly of atoms, molecules and ultimately their macrostructures, such as crystals, films or tubes. This latter, and also more futuristic, approach is therefore more likely to be competence-destroying (Hall, 2005)

2.2. Facilitating and inhibiting forces for emerging technologies

As suggested above the emerging and enabling nature of nanotechnology implies that empirical analysis of its commercialisation requires a narrow focus on specific application fields; it is harder to arrive at specific findings and policy implications if the particular business environments and other contexts of application fields are not taken into account. Analytically the literature on technological systems, their emergent properties and dynamics, provides a viable way to narrow down the case study while it also constitutes a good framework for identifying and discussing key policy issues.[1]

The concept `technological system´ seeks to capture, in a systematic way, the fundamental sources of economic growth at a disaggregated level of technologies, actors and related insitutions. A technological system was originally defined as *"…a network of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilize technology"* (Stankiewicz and Carlsson, 1991, p. 111). *Agents* typically cover companies throughout the relevant value chain, universities, research organisations, industry associations, bridging and interest organizations, as well as policy organisations e.g. involved in R&D funding. *Networks* can also be of various types. Given the focus of this paper on emerging technologies, networks related to R&D are the most relevant ones to consider. The *institutional infrastructure* affects the technology itself, as well as the action of the agents. They foremost comprise of various norms and regulations

Following the seminal paper by (Stankiewicz and Carlsson, 1991) various refinements have been made to make the concept more operational for empirical analysis. One useful stream of this literature proposes a functional approach to analysing technological systems. Among others Bergek et al. (2008) specify a set of key processes, or "functions", that a technological system must fulfil, in order to support the generation, diffusion and utilization of a particular technology sub-area. In terms of policy analysis these functions can be considered as avenues along which policymakers may support the emergence and further development of new technologies. These functions are simplified and summarized in Table 1 and discussed further below.

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1 Related concepts include innovation systems, cluster and competence blocs. Especially these latter two concepts shift the focus towards product areas or individual products as the level of analysis and are thereby better suited for more mature technology fields in which clearly defined value chains and commercialization avenues already are identifiable.

Table 1. Functions of a technological system and their empirical counterparts (based on Bergek et al. (2008).

Function of a technological system	*Identifiable empirical counterparts*
Knowledge development and diffusion	- Learning and innovation processes throughout networks of researchers, companies and other actors
Influence and direction of search	- Public R&D funding and programs, new regulations, market developments, customer preferences etc.
Entrepreneurial experimentation	- New company formation, R&D investment and other risky and experimental activities of large incumbent companies
Market legitimation and formation	- Existence of lobbying or advocacy coalitions and other such institutional frameworks, existence of early test-trial markets, articulation of demand, standards etc.
Resource mobilisation	- Existence of human, financial and physical supportive resources

The first function of *knowledge development and diffusion* is at the heart of a technological system. It covers learning and innovation processes related to R&D projects and other knowledge-intensive activities that contribute to the scientific and technical knowledge base of the technological system under examination. Thus, such learning and innovation processes might be identified within the research community, amongst companies and throughout networks of actors constituting the system.

Influence and direction of search covers various inducement mechanisms that influence the direction of R&D and other types of learning processes in a technological system vis-à-vis competing technologies, applications, and markets etc. Such mechanisms are shaped by the interpretations of business opportunities that companies (and sometimes also universities and research organisations) have. They foremost relate to users and consumers perceptions of an emerging technology, general market and demand drivers. However, policy initiatives – such as R&D programs – can also play an important role in influencing and directing search. Regulatory and other institutional changes in the business environment can also have a similar role in inducing specific pathways for R&D in the system.

The function of *entrepreneurial experimentation* relates to the commercialisation of knowledge in a technological system. In other words, for its development a technological system naturally also requires the entry of new companies or an active stance of established incumbents to experiment with, and select, innovations which eventually become successful. With reference to technology life cycle models, the role of entrants may be particularly important in the emerging phases of such a system, while incumbents regain their position later on (Tushman and Anderson, 1986). However, Maine and Garnsey (2006) find that entrants in nanotechnology often face heighted technical and market uncertainties due to specificities of this technology area. More generally, Carlsson and Eliasson (2003) also stresse the role of larger incumbent companies with competencies for taking innovations to industrial scale production. Entrepreneurial experimentation thus not only refers to new company formation. It can also require risky investment decisions by large and incumbent companies.

Market formation covers the creation of an early test trial market as this, often per definition, is lacking in the case of emerging technologies. Previous research has often pointed to the importance of early and experimentally oriented `lead users´ for successful innovation in new fields (for seminal contributions see Von Hippel (1988); Lundvall (1992)). The existence of such leading users is important in technological systems. However, there are also examples when policy initiatives, e.g. related to new regulations, standardization and technology procurement, directly can contribute to market formation (Edler and Georhiou, 2007). Market formation may also require *legimitation* of the technology in a broader societal sense among consumers, regulators, politicians, and other relevant stakeholders.

The function of *resource mobilization* refers to the ability of a technological system to mobilize human capital (education of the emerging technology sub-field itself as well as managerial aspects), financial capital (both public and private funding, including venture capital), as well as complementary assets in terms of supporting instrumentation, technologies, processes, products, services etc.). Finally, reference is made to the ability of a technological system to generate *positive externalities* and thereby contribute to economic growth at higher levels of aggregations. Positive externalities are largely an outcome of the fulfilment of the previously discussed functions of a technological system, and will thus not be dealt with here in any greater detail.

3. Eco-efficiency, the construction and glass-processing industries

3.1. Technological change and eco-efficiency in construction

Construction is one of the most traditional and oldest industries, having been around for almost as long as mankind. Over time significant technological changes have occurred mainly in the way in which buildings are erected, e.g. through advancements in the mechanization of construction activities and the use of prefabricated elements, and ICT for logistics. These developments foremost relate to process innovations that have enhanced the productivity of the industry. However, construction is still considered as a laggard industry that remains labour-intensive, while the increase in labour productivity has been slower compared with most other industries (Manseau and Shields, 2005). Nonetheless, new challenges and opportunities are emerging that are affecting the industry in important ways.

Partly these new challenges and opportunities relate to broader trends in the world economy, such as globalisation and increasing concern about climate change and related environmental issues. The increasing use of ICT has partly supported the entry of a range of new engineering and consultancy companies from adjacent industries as providers of specialized construction expertise, services and maintenance. Meanwhile especially the downstream segments of the industry are consolidating through vertical integration amongst large companies that are increasingly multinational in scope.

Of particular relevance, when considering opportunities to apply nanotechnology in this industry, is the growing demand for eco-efficiency[2] of buildings as a response to environmental concern due to climate change (Manseau and Shields, 2005; UNEP 2008). New environmental regulations are being enforced, e.g. related to the Kyoto Protocol of the United Nations, which aim to increase the eco-efficiency and reduce energy consumption of buildings. On top of these developments governments have recently ear-marked large R&D investments for green technologies as a key component of their massive stimulus packages to

[2] The World Business Council for Sustainable Development defines eco-efficiency as the delivery of *"competitivly proced goods and services that satisfy human needs and bring quality of life while progressively reducing environmental impacts of goods and resource intensity throughout the entire life-cycle to a level at least in line with Earth's estimated carrying capacity"* (World Business Council for Sustainable Development, 1992; Wikipedia 2009).

counter the current economic crises (OECD, 2009a). These investments may therefore also benefit the development and commercialisation of green nanotechnologies in construction.

Nanotechnology addresses environmental concerns in construction through many routes. The enabling nature of nanotechnology implies that it can provide traditional construction materials with completely new and eco-efficient functionalities. Recent reports indeed highlights various emerging applications for nanotechnology in construction (Nanoforum, 2006; ObservatoryNano, 2009). The most interesting application areas relate to enhancing the functional properties of concrete, steel, wood and glass as the primary construction materials. Specifically, the embodiment of nanoparticles in the micro matrices, or through coatings on the surface areas, of these materials can improve their strength, stress tolerance and durability. This, in turn, reduces the use of wasteful raw-materials during the production and/or processing of these raw materials. Further, energy usage becomes more efficient in buildings due to enhanced insulating and heat absorbing properties. Box 1 presents some further examples of the application of nanotechnology in construction.

Box 1. Examples of nanotechnology-enabled applications in construction.

- Long-lasting scratch resistant floors using nanostructured materials
- Super strong structural components using carbon nanotubes
- Healthier indoor climates using nanoenabled filter technology
- Antimicrobial steel surfaces using nanoscaled coatings
- Improved industrial building maintenance using nanoenabled sensors
- Lower energy consuming buildings using electrochromic 'smart' windows
- Self-cleaning low maintenance windows using new nanosclaed coatings

Source: Freedonia (2007)

The case of glass-processing, as the focus of this paper, appears as particularly promising in a not too distant future. One application relates to self-cleaning functionality that can be achieved through various nanoparticle coatings and infusions e.g. through sol-gel respectively flame-spray technologies. Such coating will reduce the need for detergents during cleaning. Further, such coating can also enhance the possibilities of glass to control the amount of light and heat entering or exiting buildings and thus reduce energy consumption (Nanoforum, 2006). This application area will be the focus on the ensuing case study as there are a couple of nanodedicated companies that are active in this field in Finland.

While technological change in construction hence far primarily has contributed to process innovation during on-site construction, it appears that nanotechnology could also contribute to product innovations, possibly also of the more radical and discontinuous kind. The low visibility of product innovations in the industry is due to the fact that these tend to be quite incremental and typically embodied in larger systems, and are thus more difficult to observe and quantify (Dorée and Pries, 2005). Especially following the entry of a range of specialized component, machinery and equipment companies from adjacent industries narrow statistical classifications of the construction industry have become superfluous. Rather, a broader cluster-oriented viewpoint should be adopted that also includes suppliers of raw-materials, machinery and equipment, building component suppliers, assemblers, building owners and managers, as well as related services and maintenance (Anderson, 2005).

3.2. The Finnish glass-processing industry

The Finnish construction industry, here defined as a cluster of supporting machinery, services and related industries, altogether employs some 500 000 people (the total population of Finland is 5 300 000) and is thus a significant economic sector. In terms of output the estimated total value of construction in 2007 in Finland was EUR 27.4 billion, while the construction product segment contributed with a volume of EUR 7.9 billion during the same year.[3]

While glass products do not show up significantly even if these figures are broken down by branches, Finland hosts a value chain in glass-processing that transcends most parts of the construction cluster. The Finnish glass-processing industry has been influenced by broader international developments. Originally the flat glass industry (primarily window glass for the automotive and construction industry) in Europe and elsewhere largely relied on US licenses covering mechanized glass processing technologies.

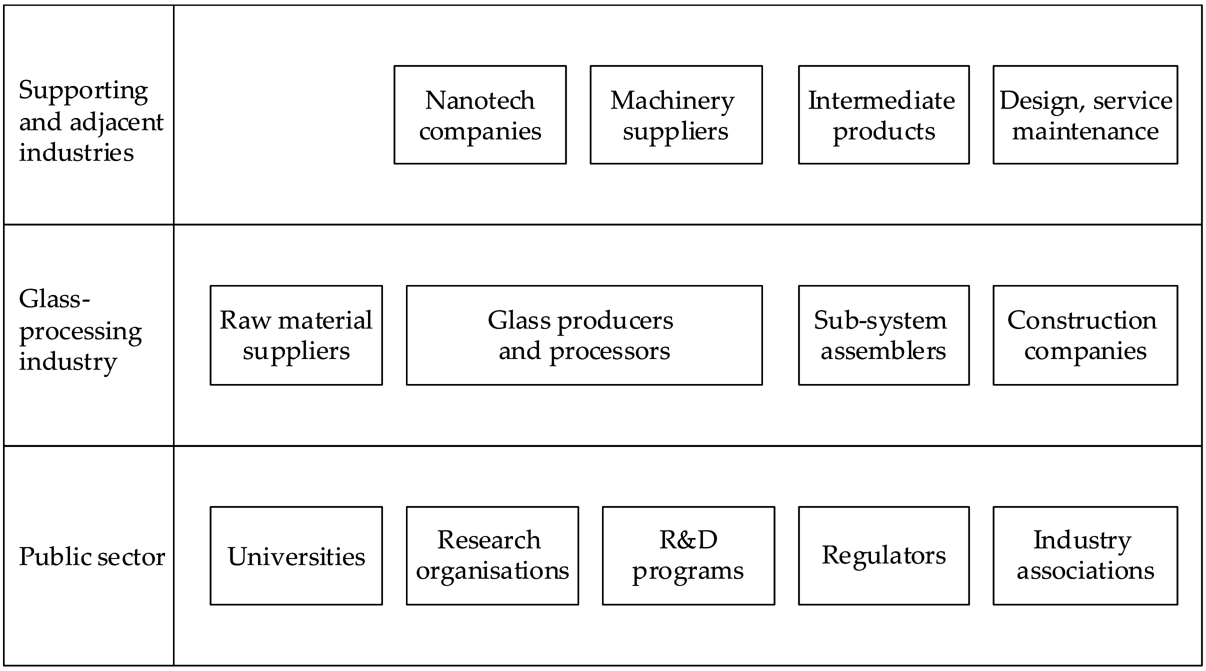
[3] http://www.rakennusteollisuus.fi

In 1959 the English company Pilkington introduced the so-called float glass process as a discontinuous new technology as flat glass now could be produced continuously and much more cost efficiently. The float glass process gradually replaced previous labour-intensive technologies and also transformed the industry into a capital-intensive one, while also consolidating it (Uusitalo, 1995). Today the glass-processing industry is dominated by four major companies accounting for 67 percent of total production output volumes, namely Nippon Sheet Glass/Pilkington (Japan/UK)(Nippon Sheet acquired Pilkington in 2006), Saint-Gobain (French), Asahi (Japan) and Guardian (US). Out of the total production of float glass 70 percent is consumed in windows for buildings, 10 percent for automotive applications and 20 percent is used in furniture and other interior applications (www.pilkington.com).

The Nordic market has been too small to support a rapid and indigenous shift from hand-blown and mechanized flat glass processes to the dominating float glass process. Originally several glass-processing companies co-existed in Finland up until the 1970s as the entry of multinational companies lead to the consolidation of the Nordic industry. In 1976 Pilkington started float-glass production in Sweden. In 1978 Saint Gobain overtook much of the remaining production in Sweden while in the same year Pilkington acquired a 50 percent share of the largest glass-processing plant in Finland (the Lahti factory). In the mid 1980s Pilkington built a new float glass production line and set up production in 1987 as the first and only float glass factory in Finland. Meanwhile the main Finnish flat glass companies had exited the market (Uusitalo, 1995).

Apart from Pilkington, the glass-processing industry is now populated by smaller companies in the field of container glass, household and art glass using other processes. The contours of the Finnish glass-processing value chain, including the cluster of supporting and adjacent industries (to which this report also counts the new nanotech companies), as well as relevant public sector organisations, are illustrated in Figure 1 below as an organizer for the ensuing empirical analysis.

Figure 1. The glass-processing value chain in Finland



The core value chain of the glass-processing industry is illustrated in the middle row of the figure. Raw material suppliers mainly comprise of minerals producers, such as Partek Industrial Minerals and SP Minerals as the main Finnish supplier of quartz, the primary raw material for glass. In addition there are also other specialized raw material suppliers of relevance to nanotechnology applications. The glass-producers are next in the value chain, and this segment is still dominated by Pilkington in the case of the float glass process. Other companies are mainly much smaller glass-processors in the container, household and art glass businesses. Some of these companies do also produce their own glass using more traditional processes.

Sub-system assemblers are found further downstream from the glass-producers and producers. These companies develop various joinery products based on pre-cut and processed glass sheets produced by the multinational companies. The final segment of the value chain is populated by the bigger construction companies.

Apart from this core of the value chain there are a couple of glass-processing machinery companies, illustrated in the upper part of the figure, that have also earned a significant international market share in their respective fields. In addition a few dedicated nanotechnology companies are entering the industry as suppliers of intermediary products and machinery. Building design, service and maintenance companies should also be included. Finally, the bottom part of the figure illustrates public sector organisations and other actors that constitute the institutional infrastructure of particular relevance for the application of nanotechnology in the Finnish glass-processing industry.

4. THE USE OF NANOTECHNOLOGY IN GLASS-PROCESSING

4.1. A brief note on the methodology

As indicated earlier, this report mainly draws on an empirical case study on the use of nanotechnology in the construction industry. The analytical framework related to technological systems has been used loosely as a way to narrow the case study focus. One may thus refer to the use of nanotechnology in glass-processing, in particular for achieving self-cleaning functionalities, as the emerging technology system which the case study focuses on.

The methodological approach uses qualitative face-to face interviews. The primary aim of the interviews has been to identify key challenges in the development and commercialization of nanotechnology-enabled new applications for achieving self-cleaning functionalities for glass. In order to include the viewpoint of as many relevant actors as possible the first part of each interview was dedicated to identifying the whole value chain of relevance to the case study, including companies in supporting and adjacent industries as well as relevant public sector actors (this resulted in Figure 1 as introduced above, for the interviewees see Appendix 1 and the interview structure see Appendix 2). The interviewee subjects were then chosen to represent each segment and part of the value chains (each box and row in Figure 1). The remaining parts of the interviews focused on themes related to the five functions of a technological system as the main analytical dimension of the study (see Table 1 below).

All interviews were undertaken during summer and autumn 2007, they were recorded, transcribed and analysed during Autumn 2007 and Spring 2008 along with the drafting of first versions of this report. It should be noted that the finalization of this report awaited the first findings from case studies undertaken within the GNNC project in Sweden and Denmark, whereby its publication has been delayed from the timetable originally envisioned. In the meanwhile, the first drafts of the company case study descriptions in the subsequent sections of this report were sent to the interviewees and companies for validation during spring 2008. Web-based searches and enquires were undertaken during spring 2009 to ensure that the company descriptions and main findings of the report remained up to date.

4.2. Nanotechnology and the glass-processing value chain

4.2.1. Dedicated nanotechnology firms

According to a recent survey there are about 200 companies in Finland that take an active stance towards nanotechnology, either in terms of own in-house R&D or as users of this emerging technology.[4] From the viewpoint of the glass-processing industry two of these are especially relevant, namely *Beneq Oy* and *Millidyne Oy*. In addition, there are a couple of university research groups as well as the Technical Research Centre of Finland (VTT) with ongoing activities related to the development and use of nanotechnology in glass processing.

Beneq Oy

The first nanotechnology dedicated company Beneq Oy was founded in 2005 as a spin-off from Nextrom, a developer and supplier of machinery for the production of fibre optics for the global ICT industry. Beneq employs some 20 people with rapidly growing sales; the company received a growth-company award in 2008 for its achievements and it has also been considered as one of the 50 most promising Cleantech companies in the Nordic market. Thus Beneq has, very quickly, managed to commercialize nanotechnologies successfully in their application niche. The personnel have a strong backgound in both business and R&D, primarily in applied physics.

Beneq Oy offers applications, related equipment and machinery based on two generic process technologies, namely Hot Aerosol Layering (nHALO) and Atomic Layer Deposition (ALD). nHALO is a flame spray technology used mainly for applying coatings on glass and ceramic tiles. These coatings add self-cleaning, colouring, solar control as well as antimicrobial functionalities to glass or ceramics either through the deposition of necessary nanosized particles on the surface or through the infusion of other types of substrates into the actual matrix of the material. Both of these technologies are sold through licensing, while Beneq also produces and sells ALD equipment.

The nHALO technology, of particular interest in this context, has its origin in research during the early 1990s in the field applied materials at the University of Art and Design in

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[4] See http://akseli.tekes.fi/opencms/opencms/OhjelmaPortaali/ohjelmat/NANO/fi/etusivu.html

Helsinki, as well on aerosol physics at the Tampere University of Technology. Originally nHALO was commercialised through ABR Innova, a company founded in 1995 to develop photonics-related technologies that gradually shifted towards tailored colouring technologies for household and art glass. Through external ventures ABR Innova stimulated further entrepreneurship through the funding of the companies Liekki Oy, Fotonium Oy and Innolasi Oy as suppliers of related machinery and equipment. Meanwhile ABR Innova started to establish foreign sales offices and also extended R&D collaboration towards other universities and research institutes both in Finland and abroad. In 2005 ABR Innova was merged with Beneq Oy.

In terms of upstream R&D Beneq has mainly collaborated with the *Aerosol Physics Laboratory* at Tampere University of Technology, the *Process Chemistry Department at the Åbo Akademi University* and *Micronova*, and the company also participates in the FinNano nanotechnology program commissioned by the national Agency for Technology and Innovation, Tekes. [5] Collaboration further downstream extends to subcontractors in the supporting and adjacent machinery end engineering industries. However, Beneq is also strong in product life cycle, network and business management. Thus this company has the capacity to offer a broader range of complementary engineering and commercialisation services related to functional nanotechnology coatings.

A lot of expectations are held for various existing and new application of the nHALO technology in the glass-processing industry and the development of the related machinery for industrial scale production. Collaborative initiatives and discussions have been underway with various Finnish glass-producers and -processors. Still growth is foremost expected in foreign markets in which both the predecessors Nextrom and ABR Innova, as well as Beneq, have established sales offices and various partnerships.

Millidyne Oy

The second nanotechnology dedicated company of relevance in this context, Millidyne Oy, was founded earlier in 1997. Millidyne specializes in various functional coatings for a broad range of materials, including glass and ceramics. This company employs around 10 people

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[5] Micronova is an R&D centre for the design, development and fabrication of micro- and nanosystems, run jointly by the VTT Technical Research Centre of Finland and Helsinki University of Technology

with sales of some 1 million based on information from 2006. The growth of this company has been moderate at an annual rate of some 20 percentage. Millidyne is a spin-of from the Tampere University of Technology, although it is partially owned by the pulp & paper machinery conglomerate Metso Oy. The idea behind the founding of this company relates to a collaborative R&D project tailored to specific needs of Metso, and this partnership has provided a good basis for the further diversification towards other industries and application areas.

Millidyne provides ceramic powders for thermal spraying, sol gel coating raw materials and speciality coating resins for various surface applications. Of these the sol-gel technologies are of particular interest for the glass-processing industry. Sol-gel technologies basically achieve some of the similar coating functionalities as flame spray technologies although it also, to a greater extent, involves wet chemistry. Sol-gels are suspensions containing nanoparticles for specific functionalities that can be gelled on the surface of the target material to form a solid coating. It is thus easy to process and apply. The connection to nanotechnology thus comes with the competencies that this company has in blending a whole array of different types of nanoparticles with sol-gels. Millidyne sells these nanotechnology-enhanced sol-gels as tailored raw materials for specific applications.

Sol-gels have accounted for a lesser share of the turnover of this company, but a lot of business potential has been envisioned especially in the field of anti-bacterial glass and ceramics for the construction industry, and on markets abroad. Exports accounted for a significant share (30 percentage) in 2006, mainly related to corrosion protective coatings for the machinery and equipment industry through the partnership with Metso.

Various collaborative contacts have been developed with the research community in Finland, among others with the Ceramic materials and Surface engineering Laboratory at the Tampere University. Millidyne has also participated actively in relevant public R&D projects, including the Tekes PINTA and FinNano programs. Collaboration in the field of R&D mainly covers material technology where attempts are made to diversify the use of sol-gel technologies for various different types of materials beyond metals as the first major application field. As suggested above, Millidyne is also actively probing different entry points into the glass-processing value chain in collaboration with glass processor, sub-system supplier, and construction maintenance companies in Finland and abroad.

4.2.2. Glass producers, processors and sub-system assembles

The glass producers have an important role to play in the application of nanotechnology as they master the capital-intensive flat-glass process as the dominating one in the industry today. As this segment of the value chain is populated by a few global players it seems that the application of nanotechnology – at least on a grander scale – has to involve Nippon Sheet Glass (NSG)/Pilkington, Saint Gobain, Asahi or Guardian.

Nippon Sheet Glass/Pilkington is a particularly interesting company in this context as this company has production activities in Finland (Pilkington Finland and the Lahti factory). These production activities also included a float-glass factory until June 2009 when the economic crises lead to its closure. The economic crises has also been felt amongst other glass-producers, processors and sub-system assemblers, apparently to a relatively larger degree that the nanotechnology-dedicated entrants further upstream in the value chain.

Pilkington Finland Oy

Pilkington Finland only constitutes a small unit of NSG/Pilkington, employing 1200 people primarily at the factories in the towns of Ylöjärvi, Lahti, Nivala and Tampere. Pilkington Finland focuses on automotive glass, but also produces glass for the construction industry as well as speciality processed glass. Accordingly, Pilkington Finland can be considered both as a glass-producer and -processor in the glass-processing value chain. Overall the R&D activities of NSG/Pilkington is organised centrally close to the headquarters in the UK, while the Finnish unit primarily is involved in production. Nonetheless, the Lahti factory has had a certain strategic role in the overall R&D and productive capabilities of NSG/Pilkington as it has been an advanced pilot factory especially well suited for the production of thinner glass sheets, also called microfloat.

NSG/Pilkington is a technologically advanced company with a long history of technology development and innovation, not least as exemplified by the invention of the float glass process in 1959. This company has also been an early mover in nanotechnology through the introduction of Pilkington Activ, the world's first self-cleaning glass introduced in 2001 to the markets. Subsequently Pilkington Activ has become an important new business area although major breakthroughs are still lacking. This nanotechnology application is based on the coating of glass with TiO_2 nanoparticles during the manufacturing process which has the functionality of breaking down organic dirt to subsequently be washed away by rain. This application is thus both a competitor to, but also a possibly target for, various other nanotechnology glass coatings using the sol-gel and flame-spray technologies.

The limited R&D resources that Pilkington Finland has imply that the role that it can take in the application and commercialisation of Finnish nanotechnologies in glass-processing is marginal. Further, the recent closure of the Lahti flat-glass factory, which acted as a pilot production, will probably make Pilkington Finland a less important node in the value chain and thereby a less viable test-trial ground for the nanotechnology dedicated companies that seek business opportunities in this industry.

While the glass-producing and -processing segment of the industry in Finland is dominated by Pilkington Finland, and the bulk of glass sheets for further processing in the construction industry originate from the large multinational companies, there are numerous other smaller glass-processor and sub-system assembler companies. Of particular interest in the context of the construction industry are the window producers, represented here by Fenestra.

Fenestra Oy

This company is the leading window and door supplier in Finland with activities throughout the other Nordic and Baltic countries as well. It belongs to the Paloheimo family company founded in 1889. Today Fenestra employs some 1100 people with sales of approximately 150 million euro. Fenestra’s business operation is divided into six different sectors: construction companies, high-rise renovation, house building factories, retailers, agents and export. The company's has production plants in Finland at six different locations with sales offices in the vicinity of all major towns, the primary customers being DIY chains and construction companies. Fenestra is thus a major outlet for processed glass for the construction industry at large.

As opposed to the dedicated nanotechnology companies and the glass-producers, such as Pilkington Finland, Fenestra represents a possible user of nanotechnology. In fact Fenestra has already linked up to nanotechnological developments through the early application of Pilkingtons Activ glass in 2002. Being a major developer and producers of window elements Fenestra was among the first pilot customers for launching this nanotechnology enhanced product, along with some other companies in small countries such as Ireland and Austria. The initiative for this piloting came from the R&D unit of NSG/Pilkington in the UK, and it involved some vocational training, especially amongst sales personnel, as well as some reorganization of production lines. One challenge was to manage incompatibilities between the structures and materials used when framing glass into wooden elements and the nanoscale coatings used for the Activ glass. Even though Active glass provides a new and interesting business area for Fenestra the share of turnover of window elements that use this nanotechnology application is till very small. Nanotechnology-enhanced window elements are priced above the traditional ones and such new technological solutions primarily attract a younger generation of private house builders.

Apart from piloting Activ glass Fenestra is also involved in some other nanotechnology-related R&D activities, mainly representing the user perspective. The in-house R&D activities of this company are fairly limited and R&D projects are typically outsourced to the VTT and university groups. One R&D project is underway to investigate the application of Sol-Gel techniques to protect the wooden window frames from adverse effects of moisture and rain. These activities have been part of the Tekes PINTA program and also introduce Fenestra to the smaller nanodedicated companies in the field. Overall environmental concerns, related regulations and demand for eco-efficient construction sub-systems are the main drivers behind an interest in new technologies.

4.2.3. Suppliers of machinery and intermediate products

Following the consolidation of the glass producing and processing industry to a few multinationals, including Pilkington, Finland has primarily become renowned in the field of glass-making machinery. Currently Finland hosts a number of such machinery suppliers, perhaps the most well-known internationally being Tamglass Oy. As suggested already earlier machinery suppliers can also play an important role as nanotechnology essentially is an immature process technology that enables product innovations. Machinery and instrument suppliers develop the necessary machinery the diffusion of which thereby becomes instrumental for the development and commercialisation of nanotechnology-enhances products.

Tamglass Oy

Tamglass Oy is part of the Glaston Corporation. Glaston Corporation was formed in the summer of 2007 to overtake all business activities of Kyro, the forerunner family corporation established in the late 19th century. Today Glaston Corporation is a major glass processor and machinery supplier for applications in the construction, automotive, and furniture industries worldwide.

Tamglass focuses on the development and production of safety glass in these application industries. Out of the total float glass production globally around 40 per cent is processed into safety glass. According to Glaston Corporation around one half of this has been processed using their machinery implying a global market share in this particular industry has been more than 50 per cent. This makes Tamglass a major player in the field, also internationally. In 2006 this company employed 600 people with manufacturing units in Finland, the US, Brazil and China. The R&D share of turnover is in the range of 3-4 percentages and most of this is still accounted for by units in Finland. Nonetheless, the current economic crises has also impacted this company and lead both to rationalizations of their machinery business as well as the divestment of the glass processing business which was overtaken in April 2009 by the German company Interpane AG.

Nanotechnology developments in the glass-processing industry are of direct interest to Tamglass as new types of functional coatings also eventually will require new types of machinery. The company takes a relatively active stance in monitoring nanotechnology developments, among other activities through the organisation of the biannual Glass Processing Days, and internationally recognised event in the industry. Further, some R&D projects have already been initiated with the dedicated nanotechnology companies that also involved research groups at universities and the VTT. One challenge in this segment of the value chain in Finland is the lack of glass-producing and -processing companies as lead users of new technologies, especially following the closure of the Pilkington Finland float glass factory in Finland.

Apart from glass-machinery suppliers, another example of an adjacent industry that might impact the diffusion and commercialisation of nanotechnology is the insulation and adhesive products industries. These industries supply important intermediate products mainly for the sub-system suppliers, such as the window element companies. Here one example of a company supplying such intermediate products is Kiilto Oy.

Kiilto Oy

Kiilto Oy is a company in the chemical industry, founded in 1919. The company develops and produces various adhesives and related products at their head-office location close to the city of Tampere. The main application areas are found in the construction industry, including renovation and interior decoration for both professional and private consumers. However, Kiilto also supplies adhesives for industrial use in the wood products, metal, shipbuilding, paper and packaging industries, mainly for the domestic and Baltic markets. Kiilto employs some 200 persons, out of which some 35 percentage are involved in R&D and related testing activities. A large part of the R&D is directed to the polymerization of new adhesives, which is undertaken in house despite the small size of the company. Kiilto is thus a technologically progressive company despite the traditional nature of the main industries that it serves.

Nanotechnology is a new area for this company. It is yet unclear whether nanotechnology really can bring value-added to the existing product portfolio of Kiilto. Nonetheless, some probing has been done into new opportunities together with nanodedicated companies. The consequence of nanotechnology for intermediate products suppliers, such as Kiilto, appear to relate to the possible incompatibilities between nano-enhanced new glass coatings and the chemical ingredients of existing adhesives, insulations, paints at other such products. New functional coatings containing nanoparticles might chemically interact in new ways with existing intermediate products, thus perhaps requiring new standards for better compatibility.

4.2.4. Construction companies, real estate management and maintenance

The primary user segment of the glass-processing value chain comprises of construction companies which procure various construction elements, sub-systems, as well as related civil engineering and architect services, and other technological solutions (e.g. communications, energy and water distribution systems) for overall integration and coordination during on-site construction. Construction companies might be considered as system integrators. They commercialize new technologies in the context of complex and interdependent systems (e.g. the compatibility of various construction materials and elements) where changes can create secondary and tertiary effects that might be difficult to anticipate. (Manseau and Shields, 2005).

Construction companies have to calculate the costs and benefits of the procurement and integration of new technologies when taking into account the total lifecycle of buildings, as well as the nature of end-consumer demand (real estate owners). They will thus, in the end, play a key role in considerations of the cost-efficiency e.g. of new nanotechnology applications in the glass-processing industry. Some construction companies also provide real estate renovation, management and maintenance services and thereby take an interest in new technologies which increase functionality and productivity, a good example being various ICT solutions.

As in many other countries in Finland this segment of the value chain is also relatively concentrated and populated by a few larger companies, some of which are diversified multinationals. The main construction companies active in Finland include the Swedish owned multinationals Skanska and NCC as well as the Finnish companies Lemminkäinen and YIT. Skanska and NCC entered the market through acquiring Finnish companies in the aftermaths of the economic recession of the early 1990s that hit this industry especially hard. Thus, Lemminkäinen and YIT are the only large Finnish construction companies with activities of relevance to various nanotechnology applications. YIT is here taken as an example of a technologically progressive systems integrated in this downstream segment of the value chain.

YIT Oy

YIT Oy was formed in 1987 through the fusion of three smaller companies in the industry. The company spans four major business areas, namely Building Systems, Construction, Services for Industry, Networks and IT. This relatively diversified structure enables the company to provide a broad range of products and services, ranging from the construction of new buildings, renovation, various utility installation services to maintenance and real estate ICT support services. The company employs some 25 000 people with a turnover in 2008 of 3.9 billion euros, and thereby ranks among the largest companies in Finland. The main markets are in the Nordic and Baltic countries as well as in Russia.

This company does not organize R&D activities centrally but engages in various development projects on a project basis. These projects are often undertaken in collaboration especially with the Technical Universities and the VTT. YIT Oy is also a frequent participant in technology programs commissioned by Tekes in which it represents the user perspective of new construction technologies and solutions. A major part of these projects relate to IT and energy systems, the main drivers being a search for increasing productivity as well as the trend towards increasing the eco-efficiency of buildings.

The Construction business area of YIT Oy is the one that primarily may benefit from nanotechnology developments, such as those in the glass-processing industry. This business area comprises of new construction and renovation of housing, business premises and industrial facilities as well as construction and maintenance services for infrastructure. Nonetheless, although there is an interest in, and awareness of, nanotechnology developments, cost considerations have hence far worked against the introduction of new applications, such as self-cleaning windows. Apparently nanotechnology enhanced construction elements still have to prove their cost-efficiency and value proposition from the viewpoint of consumers of new buildings. However, in a longer term perspective concerns about productivity and eco-efficiency can pave the way for increasing uptake of nanotechnology applications. This could concern especially applications for reducing energy consumption in line with new regulations, as well as the use of ultra precision sensors to monitor maintenance needs of buildings.

5. A CONCLUDING DISCUSSION: FACILITATING AND INHIBITING FACTORS IN COMMERCIALIZATION

The company case studies provide interesting snapshots of facilitating and inhibiting factors in the industrial uptake and commercialisation of nanotechnology from the viewpoint of different segments in the glass-processing value chain in Finland. As stated earlier the company perspectives have also been complemented with interviews with researchers, other stakeholders and informants – as well as with available public documents, reports and www-pages – to give as complete a picture as possible.

With reference to the analytical framework introduced earlier in this paper the subsequent discussion will be structured by the key functions that a technological system has to perform in order to generate positive externalities and economic growth (Bergek et al., 2008)(see also Table 2 for a summary). Even though the companies covered in this paper are part of the glass-processing value chain it should still be stressed that important viewpoint may be missing. It should also be stressed that the focus here only is on the perceptions of the interviewees on developments in Finland. Some of the companies also have significant activities overseas which fall outside the scope of this paper. Finally, the current economic crises has been highlighted when relevant but further assessments of its impacts on the commercialisation of nanotechnology has not been possible to undertake.

Table 2. Summary of the functional performance of the technological system

Function	*Performance, facilitating and inhibiting forces*
Knowledge development, diffusion	- *Good performance* - *Facilitating factors*: a community of researchers and dedicated companies engaged in collaboration based on division of labour covering necessary areas, public research programs (PINTA, FinNano, FUNCOAT), close personal contacts and science-based origin of companies - *Inhibiting forces*: lack of large and incumbent companies in community to achieve critical mass in R&D, funding and industrial scaling of pilot production
Influence and direction of search	- *Relatively good performance* - *Facilitating factors*: early influence of public PINTA technology programme 2002-06, recognition of the significance of eco-efficiency and the longer-term construction boom in rapidly developing countries - *Inhibiting factors*: variety reduced through overly focus on hyped applications in high-technology industries, less recognition of potentials of cross-over between bio- and nanotechnologies, lack of large incumbent companies as lead users
Entrepreneurial experimentation	- *Poor performance* - *Facilitating factors*: new nanotechnology entrants although application areas partly still remain unsettled - *Inhibiting factors*: uncertainty regarding entry point

	into value chains, lack of entrepreneurial experimentation amongst larger and incumbent companies, lack of smaller glass-producers and processors as lead users prior to industrial scale production, risk aversion and conservatism of construction industry
Market legitimation and formation	- *Poor but potentially better performan*ce - *Facilitating factors:* new nanotechnology entrants strongly focused on existing markets, market legitimation based on clear demand-oriented incentives - *Inhibiting factors:* limited availability of early test-trial markets, articulation of demand complicated by unclear points of entry to the value chain and unclear value propositions of new applications, passive lobbying and advocacy coalitions
Resource mobilisation	- *Relatively good performance* - *Facilitating factors:* public R&D funding appear sufficient but may be biased against applications in traditional industries, research community in place - *Inhibiting forces:* insufficient company funding of R&D, lack of certain specialised competences and research instrumentation

The first function of a technological system refers to learning and innovation processes that need to occur throughout networks of researchers, companies and other actors to support *knowledge development and diffusion*. This function essentially covers the breadth and depth of the scientific and technological knowledge base that companies have to rely on for R&D, innovation and larger scale production. As suggested earlier the knowledge base discussed in this paper concerns nanotechnology-enabled functional coatings for glass in construction, in particular related to self-cleaning and anti-bacterial functionalities.

By and large it seems that there is already a relatively well-established, but small, community of researchers within this field in Finland. While individual researchers have pursued various research paths it seems that the interest towards nanotechnology applications for ceramics and glass has increased in response both to broader trends and policy initiatives. The broader trends relate to growing demand for eco-efficient construction materials, the availability of new instrumentation and techniques, and an increasing awareness of the potentials of new materials. The policy initiatives foremost relate to the PINTA program on clean surfaces commission by Tekes 2002-2006, some of the projects of which were subsequently continued in the FinNano and other programs.

This research community includes researchers from the Åbo Akademi University Process Chemistry Centre, the Aerosol Physics Group and the Ceramics materials and Surface engineering laboratories at the Tampere Technical University, a couple of groups at the VTT, the Technical University of Helsinki and Micronova, as well as at Joensuu University. The cross-over between physics, chemistry and glass-processing has also drawn in designers and architects from the University of Art and Design in Helsinki, as well as researchers in the field of agrotechnology (surface hygiene research). Collaboration also extends abroad, for example to glass-related research in Sweden.

This community has developed a relatively clear division of labour with activities covering the basic characterisation of ceramic and glass surfaces, the application and measurement of nanotechnology coatings, as well as the development of some of the related machinery, and the pilot scaling of these processes for industrial production. As indicated, Beneq Oy and Millidyne Oy are also quite active in this community. Even though this R&D community appears to be well-connected the further involvement of larger incumbent companies would be necessary to achieve critical mass in R&D as well as funding. One may thereby conclude that this function of the technological system is performing relatively well but is inhibited by lack of involvement of large and incumbent companies with critical mass. This lack of critical mass concerns especially capabilities to up-scale R&D from pilot to industrial-scale production.

The second function of a technological system relates to various inducement mechanisms that *influence the direction of search in terms of R&D, learning and innovation processes*. Given that nanotechnology still is an emerging and immature field it is naturally difficult to make any ex-post assessment about which direction of search is the `best´ one. A useful guideline could be to stress the importance of variety in terms of the degree to which a technological system can support multiple directions for R&D, learning and innovation as well as some amount of competition between these directions. Nonetheless, the trade-of between variety and specialization, e.g. in terms of the allocation of R&D funding, is hard to establish especially in smaller countries such as Finland with limited financial, human and others resource constraints, as well as a limited home market.

As was hinted above the growing demand for eco-efficient construction materials has had a significant general influence on the direction of search. This relates to new regulations which have been enacted in the construction industry; these regulations also give rise to new business opportunities for technology-intensive companies.[6] Company interviewees also recognized the construction boom in rapidly developing countries, such as Russia and China, as an inducement mechanism to probe into opportunities provided (even though the current economic crises at least temporarily has decreased demand). An underlying enabler for developing relevant technologies for these business opportunities has been certain patented process inventions which largely have been developed in Finland. The inventions have directly benefited from new types of interdisciplinary collaboration and instruments that can be attributed to nanotechnology developments.

The PINTA programme during 2002-2006 appears to have had a particularly important role in influencing and directing the R&D projects, learning and innovation processes in the early 2000 and has evidently contributed to increasing collaboration and coherence throughout the R&D community in the field. The PINTA programme investigated the usability of functional coatings on many different types of materials but put particular emphasis on atomic layer deposition (ALD) and sol-gel technologies that are now the two main R&D paths that are being followed for applications in Finnish glass-processing. Some R&D projects continued in the FinNano programme. A new programme named Functional Materials was established in 2007 by Tekes with a duration until 2013.

Even though the public R&D programs have been facilitating in this context some concern was also raised that applications in high-technology industries have been prioritised too much and at the cost of many promising areas in the more traditional industries such as construction. One reason for this may be that natural scientist, especially in the field of physics, often are preoccupied with applications in the electronics industry almost, while they are less alert on opportunities outside 'high tech' areas. Further, the cross-over between nano- and

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[6] Examples of recent regulations include The Finnish Land Use and Building Act of the year 2000, as well as the European Union's Directive on the Energy Performance of Buildings which was implemented in Finland through the Act on Energy Certification of Buildings starting from 1 January 2008.

biotechnology has tended to be excluded or neglected in the nanotechnology dedicated programs with inhibiting effects on diversification towards e.g. bioactive glass and other new and interesting areas. Concern was also raised that nanotechnology dedicated programs may support the diversification of R&D activities towards hyped areas rather than areas which are traditional strongholds.

The early development phases of ALD and sol-gel technologies have directly benefited from the involvement of incumbent companies as early lead users. A general inhibiting factor, however, seems to be the lack of more such companies in the R&D community as these technologies are developed further for applications in the construction industry. The technological system related to the application of nanotechnology in construction barely manages to support these two competing technological alternatives but may nott be able to be sufficiently engage in R&D and other activities of importance to commercialising nanotechnology in this industry on a larger front.

The third function of *entrepreneurial experimentation* – touched upon already above – captures the capability of the technological system to commercialise new emerging technologies. It essentially relates to risk-taking either through the entry of new companies or the diversification of larger incumbent companies towards new fields. It is quite clear that this function of the technological system is presently underperforming and seems to be the main bottleneck for the further diffusion, industrial uptake and commercialisation of nanotechnology enhanced functional coatings for glass-processing and construction. Nonetheless, the reasons for this under-performance are diverse and multifaceted and partly also outside the direct influence of policy.

The entry of new companies is here foremost exemplified by Beneq Oy and Millidyne Oy while there does not appear to be any other nanotechnology dedicated companies that develop applications of direct relevance for the glass-processing industry. Given the enabling nature of nanotechnology, the glass-processing and construction industries only represent one out of many application areas for these companies. The multiplicity of applications implies that entrepreneurial experimentation is subject to both technical and market uncertainties; companies often have to monitor and adjust to a range of different types of business environments as they seek to identify the most viable applications (compare with the discussion in Maine and Garnsey (2006)). However, a bigger problem the lack of entrepreneurial experimentation amongst the larger and incumbent companies which could act as the lead users and first customers for the smaller nanotechnology-dedicated companies, and which also possess necessary complementary assets for commercialisations (e.g. retail chains, market resources, better IP management practices).

The lack of entrepreneurial experimentation amongst large and incumbent companies is to a large extent an inherent feature of the structure and nature of the Finnish glass-processing and construction industries. The glass-producing segment of the value chain, as the most obvious entry point for new nanotechnology dedicated companies, is dominated by a few multinational companies that master the prevailing and capital intensive float-glass process. This is especially the case in Finland where the only flat-glass production line has been owned by the multination NSG/Pilkington with main R&D activities in the UK; as noted this only factory has subsequently (in June 2009) been closed down. There is more fragmentation further downstream in the glass-processing and sub-system assembler segments, while concentration again increases amongst the construction companies that represent the system integrators and primary users of nanotechnology enhanced functional coatings for glass.

The availability only of a few companies in the glass-producing and –processing segment of the value chain inhibits entrepreneurial experimentation. There is less room for smaller glass-producers that could provide a stepping stone for pilot production towards full industrial scale with large and profitable volumes. This same problem, of the existence only of a few dominating companies, characterizes a possible entry further downstream in the construction company segment. Meanwhile it seems that the companies populating the intermediate and more fragmented glass-processor and sub system assembler segments of the value chain lack in-house R&D resources and risk-taking capability to become lead users for these new technological solutions. Thus, and in conclusion, it seems that the further development of this function of the technological system would require a stronger integration of supporting and adjacent industries with the main glass-processing value chain. Especially the renowned glass-processing machinery companies provide an important link for the commercialisation of nanotechnology as they could act as competent lead users and contribute to industrial scaling of pilot production.

From the viewpoint of the glass-producers and –processors, as well as the sub-system assemblers and construction companies, the lack of entrepreneurial experimentation is also a direct consequence of underdeveloped *market formation*. Market formation is in a very early phase even though the arguments for the *legitimation of a market* for nanotechnology-enabled glass are in place and primarily relate to the increasing demand for eco-efficiency in construction, including new regulations which also significantly contribute to this demand.

The construction companies, which eventually procure and integrate various construction elements and sub-systems, have to engage in detailed cost-benefit analysis that cover the whole life cycle of a new building. Even though nanotechnology-enhanced functional coatings can add value to glass the higher price of these coatings are still hard to transfer to consumers as long as the benefits of nanotech are not yet obvious and clearly superior when compared with existing applications. As touched upon earlier, many interviewees did identify eco-efficiency as a major driver for becoming engaged in the field. However, it seems that the communication of the environmental benefits, as well as health and safety risks, of nanotechnology require more and coordinated efforts that should could also involve industry associations, architects, civil engineers and other relevant stakeholders. Communication challenges are complicated further by the very different nature of the knowledge base of science-based nanotechnology compared with traditional glass-processing and construction industries, in which technology change is slow and foremost incremental.

The final function of a technological system is to generate and secure sufficient *resource mobilisation* to support the development of the knowledge base in question. Overall it seems that public technology programs and bilateral funding has proved sufficient even though some interviewees expressed concerns about inherent biases in the content of some of these projects. However a bigger problem is that company funding of R&D projects in the construction industry has declined steadily (and has probably been affected by the current economic crises as well), thus hampering entrepreneurial experimentation in nanotechnology further amongst large and incumbent companies.

Apart from financial considerations some concern was also raised about the lack of specialized expertise in the application of nanotechnology in the glass processing industry. The interdisciplinary nature of this field implies that physicists, chemists, glass-processing engineers, architects, designers and civil engineers have to work together. The knowledge base has to be quite large and diversified, and the importance of gate-keepers, which are able to integrate different disciplines for industrial applications, becomes pronounced. Finally, some specific and expensive research instrumentation is lacking, the access to which depends on international R&D collaboration. However, by and large resource mobilisation does not appear to be a significant inhibiting force in this context.

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Appendix 1: interviewed persons

Markku Rajala, ABR Innova, Beneq
Sampo Ahonen, Beneq
Tommi Vainio, Beneq
Petri Sorsa, Millidyne
Mika Kolari, Millidyne
Thomas Kronberg, IDO
Mervi Paapanen, Pilkington Finland
Tahvo Sutela, Pilkington Finland
Jorma Vitkala, Tamglass
Kalevi Hyvärinen, YIT
Mikko Viljamaa, Kiilto
Arto Kultamaa, SYKE
Veli-Matti Airaksinen, Micronova
Jyrki Mäkela, Tampere Technical University
Ann-Christina Ritschkoff, VTT
Leena Hupa, Åbo Academy University

APPENDIX 2: INTERVIEW STRUCTURE

1. Introduction
- Presentation of GNNC project
- Introducing nanotechnology
- Reasons for case study focus
2. Description of company/research group/stakeholder (variations by type of person interviewed)
- Main activities, competencies
- Relevance of nanotechnology
- Innovation and environmental strategy
- Collaborators
- Funding
3. Identification of value chain related to nanotechnology/glass-processing/construction
- Main companies and their role
- Supporting and adjacent industries
- Public sector actors including research groups, policy initiatives and other institutions
4. Facilitating and inhibiting factors in commercialisation (variations by type of person interviewed)
- Knowledge base issues
- R&D /commercialisation trajectories and their drivers/inhibitors
- Entrepreneurship, barriers to entry and collaboration
- Market formation and legitimation
- Availability/lack of resources (human, financial etc.)
- Role of policy, regulations and other framework conditions
5. Project timetable, follow-up

Thanks!