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Value chains as a linking-pin framework for exploring governance and innovation in nano-involved sectors: illustrated for nanotechnologies and the food packaging sector

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Abstract

Nanotechnology is often referred to as an entity in itself, a promising technoscience that may enable a vast array of products that will affect and change society. Looking beneath the umbrella-term of 'nanotechnology' what is actually occurring with regards to the emergence of product/applications? And what does this mean for governance of emerging nano-involved product development and societal uptake? The article argues that one must move beyond the broad umbrella term of nanotechnology to explore governance challenges. It posits that for exploring governance of nano-applications, a much ignored level of analysis - the industrial value chain - is a promising level of analysis in both identifying the current activities and potential impacts of nanotechnology and the modes of governance that are in play, how they evolve and how they could be shaped.

Focusing on value chains is important for the near and mid-term in order to evaluate and characterise the smorgasbord of techno-scientific promises stemming from nanotechnology and the effects of broader sectoral changes on potential nano-enabled products that may reach citizen-consumers. As nanotechnology enters various parts of the agrifood sector, the emerging governance arrangements of nanotechnology meet incumbent (and still developing) governance regimes, consumer positions and actor arrangements. The paper further articulates this claim, closing with an outlook on what sort of approaches could be used for foreseeing potential developments in nanotechnology, their impacts and potential frameworks for exploring and modulating nanotechnology governance.

1. Introduction

Novel science and technologies emerge with both promises of enabling tremendous innovation potential and recognition of (and even warnings about) the enormous uncertainties and often unknowns. In the past decade, this has been brought to the fore in the emerging field of nanoscience and nanotechnology, were anticipation has been rife of possible new processes and materials may herald a vast array of technology applications and products.

1.1 Nanotechnology

Unlike previous high-technology waves like biotechnology and genomics, nanotechnology covers diverse fields of sciences and engineering (Nightingale et al. 2008, Delemarle et al. 2009, Robinson 2010) with very different dynamics, and crosses boundaries by its utilization of fundamental characteristics of matter by manipulation and control at the nanoscale. The broad term 'nanotechnology' has become an umbrella term [2] and continues to be used because of the rhetorical and resource-mobilization force it has. (Rip 2006) Research and development at the nanoscale both require and enable a large degree of integration, from convergence of research disciplines in new fields of enquiry to new linkages between start-ups, research centres, infrastructure and facilities. There is a multitude of visions of what nanotechnology is, or could be (Robinson 2010). Such framings of nanotechnology can emphasize:

a. The gradual improvement of instrumentation for visualising and interacting with the nanoscale,
b. The total control and manipulation of matter at the atomic scale,
c. An enabling technology that may provide many applications in a variety of industrial sectors.

Besides providing a stimulus at the level of scientific and technology research (framings (a) and (b) above) the 'nanohype' (Berube 2006) has led to support for further development of nanotechnology through government programmes and financial investments mobilised through utopian visions and high expectations which go beyond the promised technoscience advances. Much of this anticipation is focused on how nanotechnology will disrupt existing, or create new, industries (related to framing (c) mentioned above). Some areas of anticipated industrial impact are extensions of what was already happening, for instance the scaling down of silicon-based integrated circuits (the backbone of the International Technology Roadmap Semiconductors) towards the nanoscale has led to nano-scale lithography and nano-scale conducting structures. But in the same domain of semi-conductors, an alternative approach, bottom-up nano-electronics, is emerging which is no longer an extension, but an alternative approach to developing electronic circuits and structures. (Schaller 1997) In addition, new networks are forming based around expectations and promises of altogether new technologies made possible by manipulation at the nanoscale.

The anticipated far-reaching industrial/product impacts of nanotechnology touted by both proponents and critical commentators of the emerging field create a pressure to do something about them. This includes exploration of the possible and desirable directions for the field of nanotechnology with a focus on governance of the interactions between nanotechnology and society (Renn & Roco 2006, Robinson 2010). One example is that the encounters between nanotechnologists and government and societal actors around concerns arising from uncertainties of nanotechnologies have led (and continue to lead) to a new discourse on 'responsible innovation' (the label of 'responsible development' is also used). The idea carried by the label 'responsible innovation' is that innovation activities should take social aspects, desirability and acceptability into account. With the emphasis on societal impact and embedment of nanotechnology applications, and the recent general acceptance of possibilities of environmental and health risks of nanomaterials, there is an extension to 'responsible research' (for example, in the Code of Conduct for Nanoscience Research, proposed by the European Commission to the Member States in 2008) which may become a locked-in part of the discourse of Nanotechnology R&D.

There is widespread uncertainty about impacts and risks (Renn and Roco 2006), while there are also proposals for regulation (Hankin et al. 2011), and NGOs which advocate a precautionary approach. There is additional uncertainty about consumer and citizen reactions to new nanotechnology-enabled products and processes, which includes fears of innovators about a public backlash and about barriers to public acceptance. This can then be channelled, even locked-in, in a specific direction, as appears to happen now in the strong political push for labelling of products when they 'contain' nanotechnology (see Throne-Holst and Rip in this special issue). What is clear is that there is anticipation on societal impacts, not only through exaggerated promises that are part of resource mobilisation strategies of technology developers, but also in the strategies and actions with regards to how governmental agencies, non-governmental organisations and societal actors respond.

This brief diagnosis reveals a situation of:

1. Promising research in nanoscience and nanotechnology that are spread across many traditional scientific disciplines,
2. Promising applications stemming from the research which are triggering action in a variety of existing sectors or creating new ones,
3. Concerns about, and attempts to change/create, governance mechanisms that would provide societally desirable technologies and products.

1.2 Value chains as an entrance point

Many studies of nanotechnology governance look at the enabling nanotechnologies (mostly nanomaterials) themselves to explore the risks, regulation and standards for nanomaterials. Another approach is to look at the potential application envisioned in the future, and to speculate on the governance arrangements that will be needed to mitigate the risks, and promote the benefits, of nano-enabled products. Studies of innovation show that there is a translation of promising technoscience into products in society. The translation occurs at the level of industries in particular sectors, in (usually) stabilised configurations of actors involved in adding value in the conversion of the original technology into a workable device/product that is embedded in society. The concept often used to describe this consecutive up-valuing of a material or technological device is the value chain model.

The concept of the value chain is used in strategic analysis: as a tool it has been used for three decades now to analyse the firm, its major competitors, and their respective performances, in order to identify and address performance gaps (Peppard & Rylander 2006, Porter 2001). A value chain is 'the series of activities required to produce and deliver a product or service' (Porter 2001). The chain is constituted around the activities required to produce it, from raw materials to the ultimate consumption of the finished product. Layers in a value chain have been described in terms of a sequence comprising suppliers, manufacturers, distributors, and consumers. For example, one of the more well-researched chains - the wireless communication (mobile phone) chain, includes equipment companies; infrastructure companies/network operators; Steinbock 2003), which interact with a multitude of specialized companies (software intermediaries; financial intermediaries; content providers; resellers; cf Peppard & Rylander 2006); which in turn engage with the end customer (Li & Whalley 2002). Scanlon (2009) includes a 'reverse supply chain', which re-connects the user with the original equipment manufacturer whenever phones are returned for repair or disposal. In semiconductor manufacturing, the main engineering and manufacturing tasks that involve integrated circuit (IC) design, (physical) manufacturing, and systems integration of these ICs (cf. Lee & von Tunzelmann 2005), have over the past three decades become organizationally separated; different companies address different parts of the chain (design houses; mask houses; wafer companies; pure-play foundries; and back-end processing and electronic packaging).

We can use the value chain model to explore the emergence of nanotechnologies within an incumbent sector, in order to explore the potential innovations that may emerge (contextualising the techno-scientific promises stemming from the world of research), locating the governance issues and arrangements that are relevant (both for the nanotechnologies themselves as well as the sectors that nanotechnology is or may be a part of) and to current situation of nanotechnologies entering a sector

1.3 Structure of the paper

To explore nanotechnologies for a particular sector, this paper focuses on nanotechnologies in the food packaging sector (Robinson and Morrison 2009) which has been identified as the most promising area for the first application of nanotechnology in the food industry (Chaudry et al. 2008). So what is actually occurring at present with regards to nanotechnology and food packaging? How is the incumbent packaging industry anticipating, reacting, co-evolving with these promising technologies? What dynamics are at play and how are they shaping the emergence of nanotechnology options in the food packaging sector? To answer these questions, I will first describe the packaging sector itself (Section 2) by locating it in the broader setting of nano and the food sector. This will present some of the drivers that are providing and impetus for nanotechnology and a description of the packaging value chain (with a sneak preview of two families of nanotechnologies that are already entering the packaging value chain).

Section 3 will give an overview of the nanotechnology R&D activities that are currently underway and promising technologies for the food packaging sector. This is important because it reveals the types of activities at the lab and prototype level which are expected to impact the food packaging sector. This section will also provide some illustrative examples of products that are already on the market (mostly in the form of packaging materials or sensors). Section 4 provides a glimpse at the regulation and risk aspects that are at play affecting the 'nano-involved' food packaging value chain (where nano-supply chains meet packaging value chains). Section 5 looks at governance aspects arising later on in the packaging value chain, where it combines with food value chains and enters markets. Section 6 provides a glimpse where locations (or arenas) of agenda setting, evaluation and selection are opening up, with a particular focus on nanotechnologies and food packaging, but applicable more generally. This section gives an indication of how various non-technology actors are influencing the potential technology options at early stages of emergence. Section 7 concludes with a discussion and outlook with regards to adding the value chain perspective in the analysis of future-oriented technology analysis and governance. The scope of this article means that it is a large article but also not exhaustive - each section provides illustrative examples and elements that are important. To mitigate this, I provide lots of references to further material.

2. Food packaging: an industrial perspective

The agrifood industry is the largest manufacturing sector in Europe, and according to the European Technology Platform Food for Life [3] 'the agricultural sector employs over 11 million people (2.3% of the population of the enlarged EU)' and 'the food and drink industry had a turnover of 810 billion euro in 2004, transforming over 70% of the EU's agricultural raw materials and employing over 4 million people, the majority within the SMEs sector.' In the past the industry was driven by improvements to mass production and supply, however, increasing consumer interest and concerns over where and how food is produced, processed and delivered, means that this system is now largely reversed (at least in the developed world). More variety and catering for smaller and more diverse sub-populations of consumers is becoming the norm for the agrifood industry (Robinson & Morrison 2009). Coupled with nutrigenomics, the number of tailored functional foods is increasing, and a vast array of new (and old) technologies are being employed and boosting this trend. Agrifood is closely linked to environmental concerns; the most visible is the use of agrochemicals such as pesticides and fertilisers. Another is about secure and sustainable food supplies - which links with concerns about monitoring, creating disease resistant strains of crops and cattle, and more globally about sustainability relating to waste (agricultural waste, processing waste, packaging waste).

2.1 Drivers and trends in food packaging innovation

In the food packaging sector, there are a number of drivers that are creating an incentive to finding new solutions, of which nanotechnology could be one.

2.1.1 General trend in improving food packaging performance

Traditionally, packaging has been developed to protect food from heat, light, moisture, oxygen, microorganisms, insects and dirt. Food preservation has also been a key requirement. In the past decades there has been an increase in required functionalities of extending the shelf life of foods and beverages by controlling bacterial, enzymatic and biochemical reactions within the packaging via a number of strategies such as oxygen removal, controlled release of salts, carbon dioxide etc.

2.1.2 Population and consumer changes

(i) higher standards of living in western countries has led to the transportation of exotic foods over large distances leading to a need to maintain freshness - leading to an increase in packaging, (ii) a general trend towards urbanisation which has created a greater distance between food producers (rural areas) and the consumer (urban areas) and (iii) a shift in lifestyles towards more convenience foods such as ready meals.

2.1.3 Waste Disposal policy and practice

In agrifood the food and beverage packaging sector faces a specific societal challenge in the form of waste disposal. The volume of waste generated by the European agrifood sector is of increasing concern; in fact Europe's fruit and vegetable industries generate around 30 million tonnes of waste a year. Food packaging waste is predicted to increase as a result of an ever increasing demand for convenience food, and individual wrapping of fresh produce (such as fruit). One example of policy shifts with regards to waste disposal is the recent move in the UK where the Government stated that that in 10 year's time, 75 per cent of all household waste should be recycled, 'Early next year we will consult on what recyclable and compostable items should be banned from landfill and how a ban will work,' said a statement from for Environment, Food and Rural Affairs (DEFRA).

Using figures just for the UK: Approximately 10.5 million tonnes of packaging enters the UK waste system every year (DEFRA) more than half of this is related to food and drink. The cost of the raw materials for this is about 4.5 billion Euros per year and this cost does not include disposal and recovery costs or wider social and environmental costs such as the accumulation of plasticizers in underground water, or the production of dioxins by, for example, PVC and paper based packaging materials. This not only means a real incentive behind the grand challenge of packaging waste management but also the size of the problem. The waste management solution (or portfolio of solutions) should be aligned with the food packaging material options (and vice versa).

2.1.4 Recyclability and biodegradation

Plastic packaging (useful for its water-tightness and rigidity) has been designed with little consideration for disposability or recyclability, resulting in concerns over the environmental impacts when they enter the waste stream (Robinson and Salejova 2010). Numerous initiatives aimed at reducing agricultural waste (or finding novel uses for it) have been launched. For example the UK Government recently stated that within 10 years, 75% of all UK household waste should be recycled or composted (Freedonia 2009). Many national policies are focusing, not on reduction of packaging, but the management of it via sustainable sourcing of materials and increasing pressure to recycle or compost packaging waste (DEFRA 2011). The impact of biodegradable plastics in food packaging to date has been limited. This is because most sustainable bio-based plastics have poor characteristics.

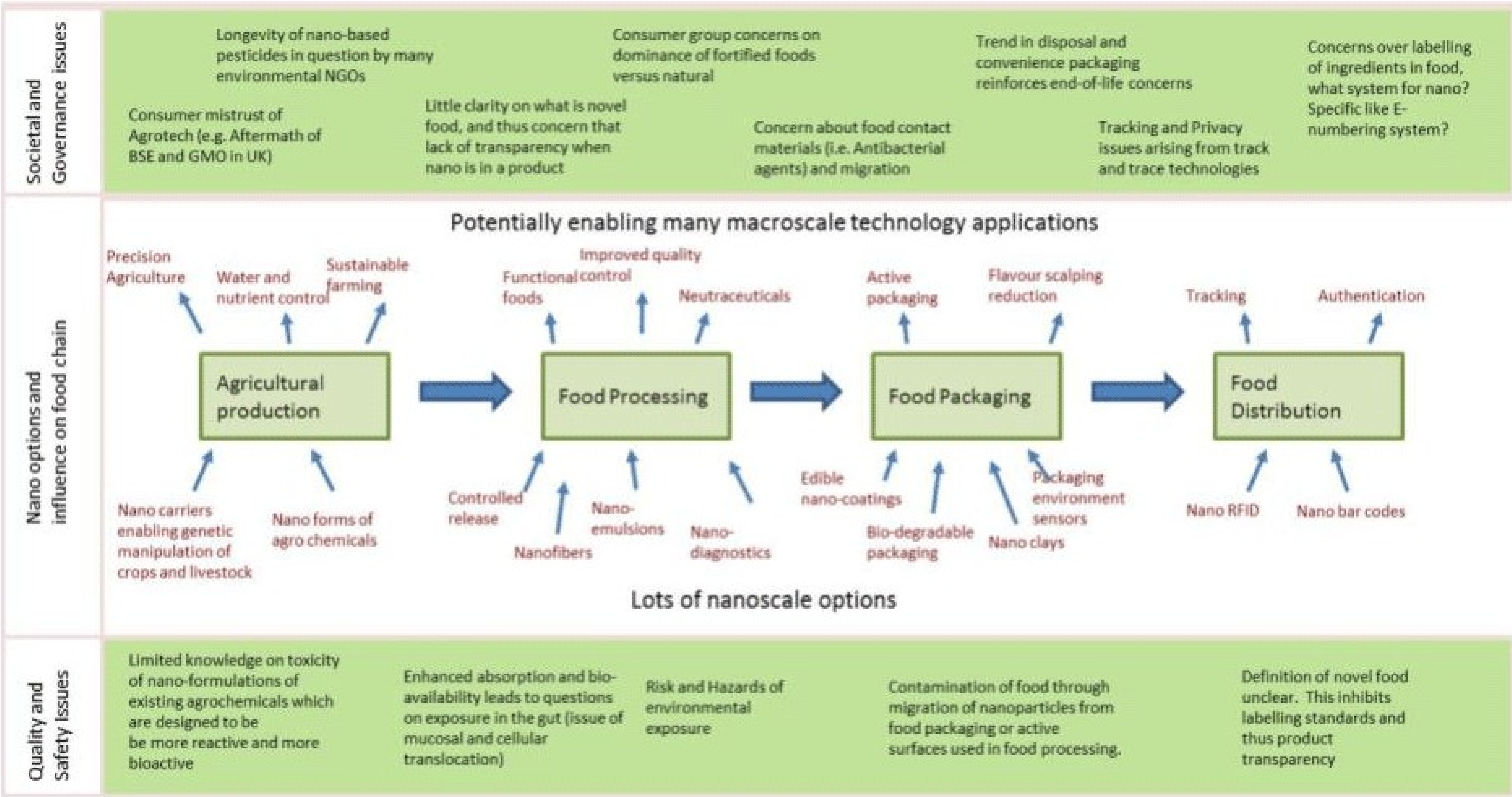

Figure 1: The food production chain from farm to fork.

2.1.5 Economic factors such as crude oil prices

Alternative food packaging materials, such as bioplastics, are receiving ever increasing interest because of the rise in the price of crude oil and natural gas which is driving an economic based assessment of bio-based polymers, rather than environmental or sustainable reasons. Waste Management encompasses new initiatives for the decrease in agricultural waste or finding novel uses for it. Summarising the above, alongside the general improvement of packaging, consumer shifts towards convenience foods, high fuel price, waste management needs, and environmental sustainability are providing an impetus for many innovators to find alternative and/or novel food packaging options.

2.2 Industrial expectations of nanotechnologies for food packaging

The food and drink industry has been interested in nanotechnology possibilities for over a decade (Renton 2006, Rip, Robinson and te Kulve 2007, Brody et al. 2008, te Kulve 2010). In a recent stakeholder forum, the FoodDrinkEurope Association articulated some of the hopes and interests of the European food and drinks industry: [4]

> 'The European Technology Platform (ETP) Food for Life's Strategic Research Agenda indicates nanotechnologies' potential uses in the food and drink industry. One example is From 2015 to 2020, nanotechnologies could be used improve products, processes and packaging, for example, nanoparticles could be used to provide a barrier to oxygen in a plastic packaging (reducing the possibility of food spoiling) or nanosensors could be developed to detect bacteria (reducing the risk of contamination).'
> FoodDrinkEurope, Autumn 2011 [5]

There is a large amount of activity exploring and developing nanotechnologies for the agrifood sector more generally and many national and international programmes are underway, for example in the European Commission (EC) Framework Programmes (www.http://cordis.europa.eu/fp7), the US 'Nanoscale Science and Engineering for Agriculture and Food Systems' and Nano4Vitality in the Netherlands. Figure 1 gives a glimpse of some of these nanotechnology developments and the promised applications for the breadth of the food production chain, from farm to fork. [6]

Figure 1 shows illustrative promising nanotechnology options which were being described and actively worked on during 2009. It shows how they may influence elements of the food production chain, with an indication of envisioned potential applications that may be derived from them. The shaded boxes give indications of some of the governance and safety concerns that have been in circulation in the food sector. For the purpose of this article, we zoom into food packaging, but for nanotechnologies across the whole chain, I recommend Robinson and Morrison (2009), and Frewer et al. (2011).

For the food packaging sector, expectations of nanotechnology impact on food packaging began to be voiced at the end of the 1990's and concrete initiatives began to emerge. In Europe, in January 1999 BIONANOPACK, a three year European research project, was launched to develop starch-clay nanocomposite materials for packaging applications. [7] Shortly after this initiative began, one of the major players in the food sector, KRAFT, launched the NanoteK consortium (Rip et al. 2007) an industry and research network focussing on applications of nanotechnologies in the food sector. Beyond this initial hype there seemed to be some stagnation (up to disappointment - in Hype Cycle terminology (Fenn 2008). In 2004 Kraft pulled out of the NanoteK consortium and over the years that followed it is difficult to find any indication of food industry players involved in nanofood R&D. [8]

However public funded research continued to grow, for example the EC funded SUSTAINPACK in 2004 and NAFISPACK 2009 projects where large consortia of European research institutes collaborated with the food packaging industry to develop applications based on nanofibres and natural antimicrobial packaging respectively. Today there is a large amount of activity in R&D and some commercialisation of nano-involved food packaging. The emergence of nanotechnology supply chains is visible, and is illustrated in the following subsection.

2.3 The food packaging value chain

Figure 2 shows the value chain of food packaging with two new supply chains. I use the value chain model to explore the incumbent arrangement of the packaging sector, locate actors and their relations, as well as the framing conditions that shape the production and selection of new options within that value chain. The nanotechnologies described in section 3 can be broadly grouped into two supply chains:

1. the nanomaterial supply chain (which includes, advanced barrier packaging, biodegradable recyclable or edible packaging materials and new food contact materials) and
2. the active and smart packaging supply chain.

Nanomaterial supply chains and their framing conditions. Three elements are important for the nanomaterial supply chain for packaging. The first is an indication of the commercialisation of nanomaterials, which companies are investing (if at all) and in what technology options. The second is the nanomaterial regulation more generally with regards to production of nanomaterials by material manufacturers. The third is regulation related specifically to nano-enabled food packaging. Below I give some details of these three elements.

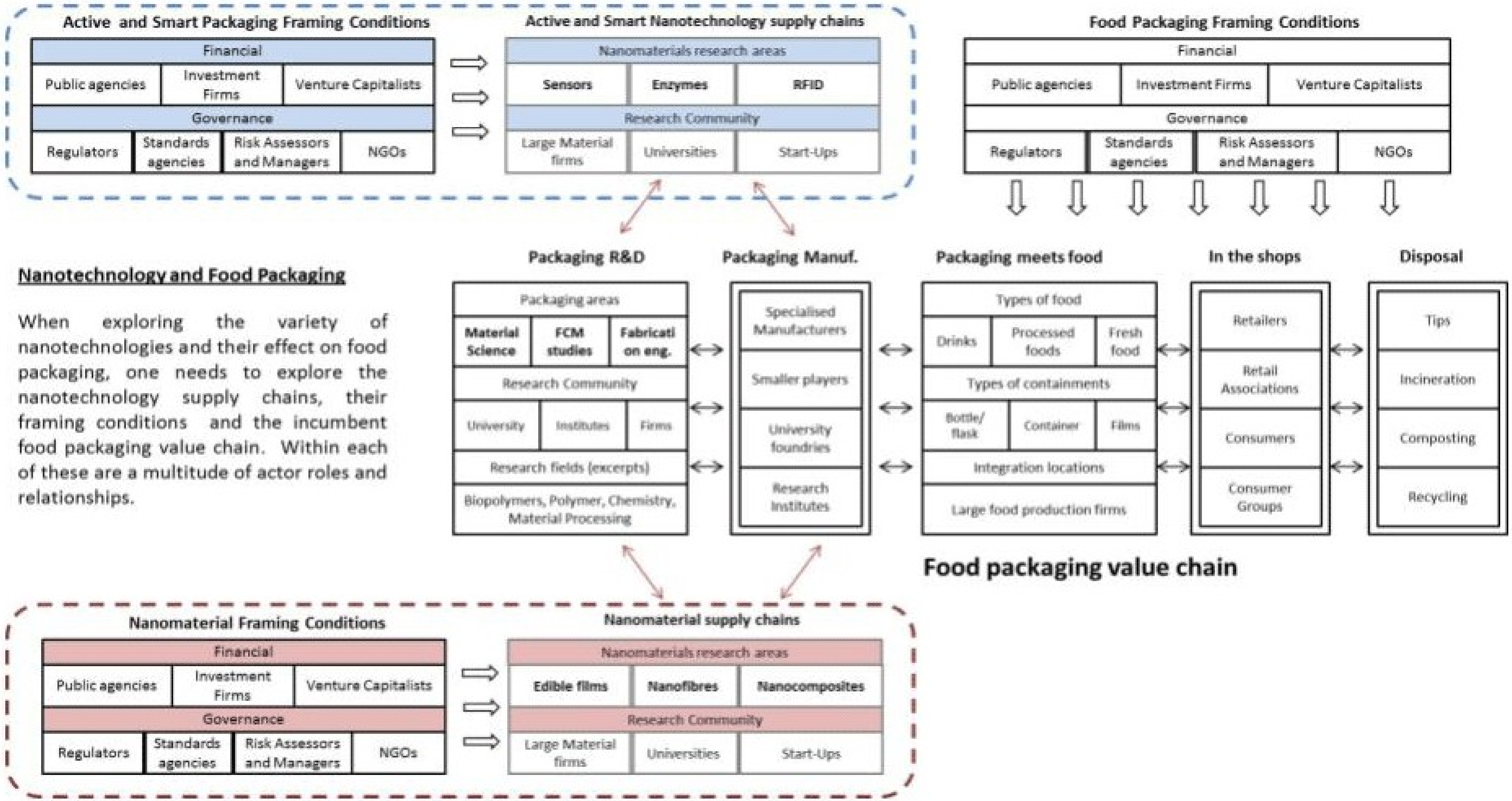

Figure 2: The food packaging chain and its framing conditions along with two nano-related value chains.

3. Nanotechnology R&D Trajectories as technoscientific promises [9]

3.1 Promising nanotechnologies.

This section reviews R&D in nanotechnology options for the food sector. It is broad and deep to give the reader (1) an account of the actual ongoing activities in R&D laboratories, (2) to reveal the scope and variety of activities which makes regulation and governance enormously challenging (because of the diversity of types of technologies and the array of potential uses in food packaging and elsewhere).

3.1.1 Advanced barrier packaging

Nanocomposites are the most mature of three nanomaterial options for the food sector. Nanocomposite materials employed or being developed for use in the food packaging industry contain a polymer and a nano-additive. Mostly nanoclay particulates are used, however, other composites containing nanoparticles, nanotubes or nanofibres are also being developed. [10] We can broadly divide the types of polymers into petrochemical based and bio-based polymers in the following way. Most polymer composite materials are based on fossil fuel derivatives. Polyamides, nylons, polyolefins, polystyrene, ethylene-vinylacetate copolymer, epoxy resins, polyurethane, polyimides and polyethylene terephthalate. Research into bioplastics (sourced from wood and crop waste) is offering biodegradable alternatives. Such biopolymers include: Polysaccharides (such as cellulose and chitosan), proteins, lipids and their composites. They have other advantages since biopolymers are excellent vehicles for incorporating a wide variety of additives. On their own biopolymers have poor mechanical properties (e.g. lipids) or poor water vapour barrier properties (e.g. polysaccharides), which explains the little uptake in industry. However, addition of nano may help here. [11]

The promise of nanocomposites is that they offer improved functionality over traditional composites and polymers in terms of barrier properties, strength, elasticity and optical clarity. Nanocomposites may be functionalised to include other characteristics, for example, antimicrobial activities, visual indicators of food freshness, means of identification and possibilities which augment the ease of tracking. Another desirable property is sustainability. Most polymer composite materials are based on fossil fuel derivatives; however research into biopolymers (sourced from wood and crop waste) is offering biodegradable alternatives. The inherent drawbacks of pure biopolymers (dependent on type, can include poor barrier properties or poor mechanical properties) can be mitigated by the inclusion of nanotechnology to form nano-enabled biocomposites (bionanocomposites). Most nanocomposite materials employed, or being developed for use, in the food packaging industry contain nanoclay particulates, however other composites containing nanoparticles, nanotubes or nanofibres of metals, metal oxides, biopolymers (Kriegel et al. 2008, Torres-Giner et al. 2008, Matthews et al. 2002) other carbon-based materials are also being developed.

For the grand societal challenge, three overlapping of families will be described in the remainder of this section: (1) bionanocomposites, (2) bio-based nanofibres and (3) edible films. There is technological overlap between these three sub-groups; however, there are clear distinctions between the three when you begin to look at applications, the manufacturing process and the environmental, health and safety aspects.

3.1.2 Biodegradable recyclable or edible packaging

For many plastics recycling is made difficult as a result of the different components involved, which means that the item cannot be processed in a single step, but needs to be dismantled and component plastics separated. A promising approach would be to biodegrade (or compost) the plastic rather than recycle. Such biodegradable plastics would come from proteins or sugars which could be derived from animal or plant origin (Robinson and Morrison 2010). Fat (lipid) films are also potentially applicable too and could lend themselves to directly coat and protect foodstuffs.

Polylactic Acid (PLA) is widely expected to be the biopolymer with the highest potential for commercialisation, mainly due to its ease of production from carbohydrate feedstock such as maize, whey, wheat or molasses (Zhao et al. 2008). Polyhydroxybutyrate is another interesting biopolymer for industrial applications; it is highly crystalline and low water permeability. However, in its pure form is has an unfavourable ageing process. Both of these promising biopolymers have limitations due to some deficient functional properties. When biopolymers (such as cellulose) are mixed with nanoclay particles, the resultant nanocomposites exhibit improved barrier properties compared with the pure polymer, and after their useful life can be composted and returned to the soil (Zhao et al. 2008). Other nanomaterials can be used including metal oxide nanoparticles, and carbon nanofibres and nanotubes. Other biopolymers that have been combined with nanoclays include chitosan, starch, casein, whey, and gelatine (Marsh and Bugusu 2007). Soy protein also has been of garnering interest because of its biodegradability characteristics and its thermoplastic properties. Limitations include brittleness and poor moisture barrier properties and thus plasticizers and reinforcements need to be added. The potential applications vary from stand-alone barrier films to coatings on other polymers and paper based packaging, to direct coating of foodstuffs. Such biodegradable nanocomposites could be of great use in other agrifood application areas, such as the plastics used in agriculture (wrapping for feed, wrapping for hay, etc) that are either disposed of into landfill or burned by farmers (estimated to be on the order of 6.5 million tonnes per annum, (Robertson 2006). Instead of incineration, they could be composted and returned to the soil.

3.1.3 Bio-based nanofibres

A number of biopolymers including chitosan, cellulose, collagen and zein (derived from corn) have been synthesised as nanofibres using high electrostatic potentials from various biopolymers via the electrospinning technique (Frenot and Chronakis 2003, Ramakrishna et al. 2006, Li and Xia 2004). In some cases these have superior properties to the traditionally cast polymer, including increased heat resistance (Huang et al. 2003), and in addition, mats of such nanofibres possess a highly nanoporous structure and can be used as support matrixes for additional functionality. Zein is a promising biopolymer for packaging purposes due to its strong hydrophobic characteristics, or in other terms water resistance. In addition zein has good mechanical properties in nanofibre form via electrospinning of zein (Torres-Giner et al. 2008, Yao et al. 2007).Zein has also been widely studied for toxicity, and its non-toxic characteristics have enabled its uptake as a coating material in the pharmaceutical industry (Corradini et al. 2006)

An interesting approach of electrospinning blends of zein and chitosan has been reported (de Azeredo 2009). These blends are reported to have great potential for application in active and bioactive packaging, antimicrobial and antimycotic food coatings and in the biomedical and pharmaceutical areas. However, one issue at the time of writing is that chitosan still has to have regulatory approval as a food contact material [12], and thus as chitosan processing and research is expanding, commercial development remains in the production area of the material, mainly for R&D purposes.

3.1.4 Edible films and coatings

Novel properties of bio-based materials are being harnessed to create edible and biodegradable films in a move to prolong shelf life, provide beneficial properties via advanced packaging solutions and to create a more sustainable industrialised society through reducing packaging waste. However, harnessing these advantageous functionalities is complicated because of a number of limitations such as poor barrier properties (gas and moisture permeability), brittleness and cost (Tharanathan 2003, Azizi Samir et al. 2005, Dalmas et al. 2007). Edible films are layers of digestible material used to coat food (edible coatings) or as a barrier between food and other materials or environments (edible films). Food can be coated by dipping into solution, by spraying or by application with brushes or sponges. Films are created separately and then applied to the food packaging system.

Polysaccharides, such as chitosan, starch and cellulose, proteins such a zein and collagen, and lipids such as triglycerides and fatty acids, can be used as edible film-forming materials. The table below shows some of the possible benefits of using bio-based polymers for packaging purposes. Bionanocomposites created from vegetable and fruit puree and cellulose nanowhiskers have been described in a recent review by de Azeredo (2009) Proteins that can be used include casein, whey, collagen, egg white and fish derived protein. Soya bean, corn and wheat protein also are candidates for edible films producing proteins.

However, there are considerable differences between the types of biopolymer that can actually be used. For instance polysaccharide films are low cost but exhibit low moisture barrier properties. Protein films have advantageous functional properties such as plasticity and elasticity and good oxygen barrier properties (similar to polysaccharide) and poor water barrier properties (similar to polysaccharides). Lipid films have good moisture barrier properties but poor oxygen barrier properties and poor mechanical properties. Research and development of bionanocomposites for edible film applications is expected to grow in the next 10 years (de Moura et al. 2009) and the application of bionanocomposites promises to expand the use of edible and biodegradable films in the agrifood sector (Lagaron et al. 2005, Ray and Bousmina 2005).

3.1.5 Active interaction with the internal environment of the packaging

Active (or Smart) packaging responds to its environment either to regulate an external effect or to produce a visual readout of a change. It includes materials that can regulate the internal environment of packaged foodstuffs to maintain food quality (e.g. through the release or absorption of substances), sensors that provide an indication of the storage history of the product and whether it is still fresh, and materials which can repair minor damage (Yam et al 2005, Brody et al. 2008). A recent report shows that the current active packaging segment is dominated by oxygen scavengers, moisture absorbers and barrier packing product, accounting for 80% of the market. Bakery and meat products have attracted most nano-enabled packaging technology to date (iRAP 2009).

The most rudimentary form of regulation is the control of the temperature of the foodstuff. Manufacturers of chilled or fresh foods want to ensure that their produce reaches the consumer in good condition. However there are inevitable breaks in the cold chain, for example due to transfer between different transport systems. If these occur in high ambient temperatures, food quality can quickly deteriorate. Ideally, it would be useful to have a protective material, which is cheap, recyclable or re-usable and does not add significantly to package weight or volume. Traditional insulating materials (such as polystyrene) are bulky and inappropriate for this use, as they would add significantly to transport costs. In contrast, nanostructured foams, which are considerably thinner than conventional materials for the same thermal properties, could be an alternative, if available at low enough cost (at present these are used more for building insulation). An alternative system based on low cost materials, has been developed by researchers in New Zealand. This system based on nanoporous calcium silicate is loaded with a phase change material (such as paraffin wax) that can mitigate the effects of an increase in external temperature over a short period of time (five hours), while having similar dimensions to bubble wrap (Johnston et al 2007).

Self-heating or cooling systems are an attractive option for consumers. Essentially the chemistry is simple. Exothermic reactions are used for self-heating (e.g. mixing water and calcium oxide) while evaporation of a refrigerant (e.g. water or carbon dioxide) is used for self-cooling. There are several examples of self-heating systems on the market, and at least one for self-cooling. It is unclear whether nanomaterials would offer significant improvements to self-heating efficiencies, however they may provide increased efficiencies for self-cooling, and there is at least one patent, based on fullerenes, for this purpose [13]. In the longer-term, completely different platforms such as combination thin-film photovoltaic and thermoelectric systems could be used (to harness solar power to drive the cooling effect of thermoelectric materials, in much the same way as solid-state coolers).

Gas scavenging or absorbing systems are also of interest for food packaging. There are several on the market using conventional technologies, such as the AGELESS system from Mitsubishi Gas Chemical Co. which contains iron salts and vitamin C, and absorbs oxygen within a sealed package [14]. Research using nanostructured materials may offer enhancements by: increasing the surface area of the active component (through nanoparticles, or loading of a nanoporous material such as silica, with active material). For example, preliminary work with polymer nanocomposites containing titanium dioxide, shows that these exhibit similar oxygen scavenging properties, in the presence of UV, as conventional iron and polymer based materials (Mills et al.2006).

Other research themes have looked at the active release of compounds, to help maintain food quality. Mostly these are based on conventional technologies to release preserving compounds such as carbon dioxide or ethanol, however the last few years has seen the development of systems based on nanomaterials. Research patented from South Western Research Institute provides a means for the release of antimicrobial agents (such as chlorine dioxide) inside packaging to inhibit microbial growth. This uses nanoscale capsules which release chlorine dioxide upon exposure to moisture [15] or nanoparticles of materials such as titanium dioxide to photo-catalyse the production of such gases from inert reactants [16]. This research is now developed by the Microactive Corporation.

3.1.6 Enzyme immobilization systems

Enzymes are widely used by the food industry for many types of processes. Immobilised enzymes act as bioactive materials, in this case they catalyse a reaction, and are promising to provide innovative solutions to the food sector through breaking down undesired elements within a food product or catalyzing the production of useful substances beneficial for the health of the consumer (Kandimalla et al. 2006, Lopez-Rubio et al. 2006, Torres-Giner et al. 2009, Kriegel et al. 2008). Enzymes are very sensitive, and thus key challenges in their application include managing and maintaining appropriate processing conditions. In addition, to maximize the life time of such immobilized enzymes, they must not come into contact with compounds which will affect their activity in a negative way (pH is a particularly relevant) (Fernandez et al. 2009, Kandimalla et al. 2006).

For food packaging, enzymes such as cholesterol reductase have been used and we observe increased activity in R&D for packaging applications (Appendini and Hotchkiss 1997, Soares and Hotchkiss 1998, Fernandez et al. 2008). The advantages of nanotechnology based systems relate to the larger surface area made possible by topographic surface modifications at the nanoscale. Sensor technologies for packaging should provide a visible indicator to the supplier or consumer that foodstuffs are still fresh, or whether the packaging has been breached, kept at the appropriate temperatures throughout the supply chain, or has spoiled. Key factors in their use are cost, robustness, and compatibility with different packaging materials. Nanosensors to detect contamination, product tampering, for spoilage and pathogen detection are been actively developed with some already commercially available.

3.1.7 Oxygen sensors

During food storage, aerobic microbes may proliferate if given access to oxygen. The ability to detect the presence of oxygen within packages of, for example, fresh meat, at an early stage could alert the (aware) consumer that the packaging has been compromised, even if there are no visual indications to suggest this. Such systems for the purpose of food packaging rely on changes in the colour of dyes in the presence or absence of oxygen. A key challenge is to develop such sensors/indicators which are non-toxic and irreversible (if there is oxygen present (even briefly) in the lifetime of a packaged food (Gutièrrez-Tauste et al. 2007), it is important to maintain the record and not have the indicator return to signalling 'safe' when oxygen is removed).

One commercialised, microtechnology product is 'Ageless Eye' [17] which is pink in the absence of oxygen and blue in its presence. Advances using nanoparticles are expected to produce more sensitive systems that respond faster and produce stronger colour changes. For example, researchers at the University of Strathclyde have produced a hydroxyethyl cellulose polymer film oxygen sensor, containing titanium dioxide nanoparticles and the blue dye, indigo-tetrasulphonate. Following incorporation in the packaging, the sensor is exposed to UV light, the dye is photobleached (a reaction catalysed by the titanium dioxide) and remains so until exposed to atmospheric oxygen levels, when it rapidly (within three minutes) returns to a deep blue colour (even in the dark) (Lee et al. 2005, Mills et al. 2008, Mills et al. 2009). Recently nanocrystalline Tin Oxide (SnO2)_ has been used as an oxygen (O2) indicator combining glycerol with a redox dye and hydroxyethyl cellulose. This system is photoactivated through exposure to UVB light and remains bleached until exposed to O2, whereupon it turns blue (Robinson and Morrison 2009).

3.1.8 Time-Temperature Indicators

While there is much research in the area of self-healing polymers, as described above, it is unlikely in the near future to be used in food-packaging. Packaging would therefore benefit from the presence of materials which would indicate that barrier properties have been compromised, through heat or mechanical stress. In some cases this can be achieved using oxygen sensor technologies, which indirectly indicate a break in the packaging.

Time temperature indicators (Fanini 1996) allow suppliers to confirm that processed foods requiring refrigeration have been kept at the appropriate temperatures throughout the supply chain. They fall into two categories: one relies on the migration of a dye through a porous material, which is temperature and time dependent , the other makes use of a chemical reaction (initiated when the label is applied to the packaging) which results in a colour change, the rate of which is temperature dependent. These have limitations in that they require multiple components (dyes, reactants, porous layers), which can affect accuracy under some circumstances, and so a single component system would be an improvement. Timestrip plc has developed a colloidal gold based system (iStrip) [18] which is red in colour at temperatures above freezing. Freezing leads to the irreversible agglomeration of the gold nanoparticles resulting in a clear solution, a useful indicator to detect the accidental freezing of chilled goods.

3.1.9 RFID tags and tracking

Radio Frequency Identification (RFID) tags have been in use for a number of years now, but manly utilised for high value items such as clothing and electronics (Finkenzeller 1999). They typically consist of two modules, one responsible for processing and information storage, the second (an antenna) responsible for transmitting and receiving information. A second device, the reader, is used to obtain information from the tag, and depending on the radio frequency used, this can be at distance of several tens of metres. RFID tags for the packaging industry are passive, they have no associated power source, and gain energy to transmit information from the incoming radio waves from the reader.

Their value is that multiple items can be monitored at every stage in the supply chain without the need for line of sight; therefore potentially increasing the speed and efficiency of distribution. This is a critical factor in modern supply chains where large amounts of raw materials may be coming from different global regions to be processed in one site, then distributed to consumers (in many different global regions). It is widely envisioned that RFID tags are expected to replace barcodes (Subramaniam et al. 2005).

RFID tags at present are largely based on silicon semiconductor technologies, however recent research could change this, allowing cheaper and easier production on a number of different materials. Printable electronics (using conducting polymers, such as pentacene and oligothiophene, and metallic inks, including copper, silver and gold nanoparticles) are being developed by a number of institutes and companies around the globe (Tentzeris 2008). While at present most are based on desktop ink-jet printing, other forms more suited to high production levels (as already used in the printing industry) could be developed. In Interestingly, there is some research into combining RFID tags with chemical sensing functions. One group has produced a prototype for ethylene sensing (for fruit ripeness), while another has demonstrated the potential of this technology by constructing a moisture sensor (Jedermann et al. 2006, Potyrailo et al. 2008). While these are both microelectronic systems, the potential for nanotechnology to enhance such systems is clear.

3.2 Nanotechnology supply chains.

The variety of nanotechnologies given above can be grouped broadly into two supply chains for nano-enabled food packaging:

Nanomaterial enabled packaging incorporating nanomaterials to improve packaging properties such as temperature and moisture stability, flexibility, improved barrier properties, also biodegradable [19] recyclable or edible packaging materials. [20]

Active and Smart packaging to control and monitor the internal environment of the food packaging: oxygen sensors, ammonium sensors, time-temperature indicators, RFID for trace and track.

These are illustrated in Figure 2. But how are these supply chains emerging? A large share of advanced nanomaterials are stemming from public R&D laboratories and enter value chains through up-valuing through either licensing or spin-off. Exceptions with regards to food packaging relate to petrochemical based nanocomposites which have already entered the market including Imperm® for CO2 release reduction (Nanocor® Inc) [21], Aegis® OX a barrier nylon resin for oxygen scavenging (Honeywell) [22] Cloisite and Nanofil from Southern Clay Products Inc. [23] and Durethan® KU2-2601 (Bayer AG). [24]

Innovia films has developed and patented a compostable nanoparticle coated packaging for foodstuffs with improved gas barrier properties using nanoparticles of starch and synthetic polymers [25]. The Paraloid BPM-500 (Carrado et al. 2009) particle is used by Rohm and Haas mixed with a biopolymer (PLA). Other nanoclay-polyner nanocomposite barrier products have been reported to be commercially available (Greiner 2009): such as NycoNanoTM (NYCOA, USA), NanoblendTM (PolyOne, USA), NanomideTM (Nanopolymer Composites Corporation, Taiwan), Systemer (Showa Denko, Japan), Ecobesta® (Ube Industries Ltd., Japan). Robinson and Morrison (2010) reported that companies such as Nanograde GmbH market polymer composites containing nanoparticles of silver and calcium phosphate that demonstrate microbicidal activity also some companies are including nanoparticles in food container products include Sharper Image®, US; A-DO Global, China, BlueMoonGoods, US, Everin, UK, JR Nanotech Plc., UK).

Up-valuing promising techno-scientific knowledge relies on financial and managerial support, whether resource provision in a large firm for a new development line, or supporting a technostarter/spin-off. A key challenge observed here from interviews and workshops in the nanomaterials sector is venture capital related to scale up. One success story here is Nanobiomatters. A medium sized firm based in Valencia and the greater Valencia region. Over the past six years Nanobiomatters has developed R&D and production capabilities for nanoclay powder (Commercial Additive Plant of 2500t/year) and polymer-clay nanocomposite production (Commercial Extrusion Plant of 4000t/year). Commercial products are currently available, and with €4 million invested in the development of its manufacturing facilities, and a diverse portfolio of nanobioplastics (including antimicrobial and gas scavenging functionalities), Nanobiomatters is rapidly becoming a major player in the field of biodegradable packaging. So there are activities in this arena, though the strategy is to have a diverse portfolio, such as that of Nanobiomatters which aims at food, medical and pharmaceutical sectors. NanoBioTer® (gained regulatory approval) and Degradal® (in development).

DuPont are marketing a titanium dioxide nanoparticulate (Light Stabilizer 210) to block UV light and provide a longer shelf-life for food (this is currently before the US regulatory authorities for use in non-contact food packaging materials); and Rohm and Haas are marketing acrylic nanoparticles (Paraloid BPM-500) to increase the strength of polylactic acid, a biodegradable polymer.

One of the key issues is of scale up and scale out with regards to novel material production. To compete with incumbent supply chains, large amounts of the new material need to be able to be provided along with a regular/standard quality. Often this is where there is a challenge. Attracting investment for radically new materials requires convincing the packaging firms in the packaging value chain - who themselves can only truly assess whether to rearrange supply chains to accommodate the new entrant when it is in place and already running and providing quantities of material that it needs and at a guaranteed quality. This means new entrants have to be smart in their expansion strategy, to show the capability of scale up on demand - a large challenge in deed (though Nanobiomatters provides an example of such a strategy in place).

4. Regulation and risk issues where nano supply chains meet the packaging sector

It is beyond the scope of this paper to review all the regulatory and governance issues of nanomaterials (this is covered elsewhere in this special issue). There are three different elements here, (1) nanomaterial regulation and risk issues themselves, (2) regulation of nanomaterial based packaging, (3) nano-involved active and intelligent packaging.

However it is an important element of the nano-food packaging situation and thus I include an indication of three broad areas which are affecting the food packaging innovation system: Environmental, Health and Safety issues (EHS), Occupational Health and Safety (OHS) concerns.

4.1 Nanomaterials

Nanomaterial standards, regulations and occupational health issues are still in flux (Chaudhry et al. 2007). It is an extremely complex issue because of the wide variety of materials and properties at the nanoscale, the limited knowledge of toxicity of nanomaterials on living systems and their transport in living and environmental systems, the lack of harmonised standards or guidance for nanomaterial production. In Europe, where the precautionary principle is prominent, this lack of clarity is currently seen as the biggest bottleneck to nano-enabled solutions to the Grand Societal Challenge of food packaging management.

There are some indications emerging for nano regulation and food packaging which is making the situation a little less nebulous. For example, the Plastic Implementation Measure (PIM) - 14262/10, a regulation on plastic materials and articles intended to come into contact with food, came into force May 2011. It will affect the use of nano-based food packaging in the EU as it states clearly that plastics that use nanomaterials should be assessed on a case-by-case basis until more information is known about potential risks they present. However, in Europe, a review of the Novel Foods Regulation collapsed recently (29 March 2011). [26] The aim of the collapsed amendment to the current Novel Foods Regulation that dates back to May 1997 was to 'allow for safe and innovative foods to reach the European market faster' and to 'encourage the development of new types of foods and food production techniques (such as nanotechnologies)'. While the collapse of this amendment is not related to the provisions for nanotechnologies (it was related to genetically modified livestock), the impact of this recent development is that nano-foods remain unregulated and are not subject to European labelling requirements for the time being. Food manufacturers are left with no clarity on what is allowed and not allowed in Europe. Since there is a general move towards the precautionary principle in European Legislation on foodstuffs, the question asked by food packaging material developers is how precautionary should we be?

Another important regulation for nanotechnology and the food packaging sector is the European Commission chemicals regulation (EC 1907/2006). *The Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH)*, requires registration of all substances that are produced or marketed in the European Union that are produced at a level of more than 1 tonne per year.

For occupational health and workers safety, the majority of activities are focused on adapting the existing risk management approaches, and to develop appropriate guidance for the handling and disposal of engineered nanoparticles/nanomaterials. Reference documents have been produced by the *National Institute for Occupational Safety and Health* (NIOSH) in USA, *the German Chemical Industry Association* (VCI), the *Federal Office of Public Health* (FOPH) in Switzerland, the *Institut de recherche Robert-Sauvè en santè et en sècuritè du travail* (IRSST) in Canada (Mantovani et al. 2009). One major lacuna is the lack of suitable measurement and monitoring tools, and increasingly recognized as a major stumbling block, information on hazards and exposure levels with regards to the use of nanomaterials.

4.2 Regulation and legislation regarding nanomaterials in packaging

Regarding nanotechnologies, EFSA [27] set up an expert working group in 2007 [28], involving people from national food safety authorities. the group launched in early 2008 a - Call for Scientific Data on Applications of Nanotechnology and Nanomaterials used in Food and Feed - to collect data on the safety of nanomaterials used in foods and feeds, in particular information related to risk assessment procedures used for nanomaterials. Following this initiative, EFSA published first a draft and then, in February 2009, a final scientific opinion on the potential risks related to the application of nanotechnologies in food and feed safety and the environment (EFSA 2009). The result was that their use in Europe is in principle sufficiently [29] regulated by the *Regulation EC/1935/2004* [30] that covers all materials come into contact with foodstuffs. Although the European Commission (EC) concluded that current regulations suffice for nanotechnologies, mandatory labelling of nanomaterials in cosmetics came into force in early 2010. Although in a different sector, it sets a precedent and could spread to other sectors. The nano-labelling however only indicates that there are nanomaterials in the product and does not give an indication of the degree of safety (of risks or benefits) of the nanomaterials. As Throne-Holst et al. have described in detail, it isn't clear how the labelling will benefit the governance system

According to this regulation the EC or individual Member States may ask the European Food Safety Authority (EFSA) to conduct a safety evaluation of food contact materials. This did indeed occur, for example following requests by the European Commission, EFSA reviewed existing data on an use of nanomaterials in the food packaging industry and concluded that there are no toxicological issues with regards to the use of titanium nitride nanoparticles in plastic drinks bottles. Also in November 2009, the EC requested that EFSA produce guidance on how risks associated with engineered nanomaterials could be assessed in applications in food, feed, food supplements, and food contact materials (Mantovani et al 2009).

In a report to the European Commission in March 2009, the European Parliament asked for amendments in the regulation for foods including: which would include the introduction of a specific definition of nanomaterials, nanolabelling, stricter requirements for risk assessment of products containing nanomaterials. Only amendments with regards to labelling of foodstuffs was retained (March 2010). [31] Food contact plastics are subject to additional measures regulated by the Regulation (EC) 282/2008 on recycled plastic materials and articles [32] and by the Regulation (EC) No 450/2009 which sets down additional requirements to Regulation (EC) No 1935/2004 for active and intelligent materials and articles. [33] (Plastic Implementation Measure (PIM) - 14262/10)

The regulation on plastic materials and articles intended to come into contact with food, came into force May 2011. It will affect the use of nano-based food packaging in the EU as it states clearly that plastics that use nanomaterials should be assessed on a case-by-case basis until more information is known about potential risks they present. Since biodegradable packaging is still in its initial stage of market development, regulation and standardisation play an important role for the future direction. At the European level all biodegradable packages (packaging films) have to fulfil the European composting norm EN 13432:2000, and also in the US they have to be certified to the American standard

ASTM6400. Although there are no stimulatory measures towards broader use of biodegradable packaging at the European level, at the national level Germany has already introduced legislation that privilege certified biodegradable plastics packaging against conventional plastics packaging. [34]

4.3 Regulation of nano-involved active packaging

This is an emerging field with regards to nanotechnology enabled active packaging. Active and Smart packaging responds to its environment either to regulate an external effect or to produce a visual/audio readout of a change. It includes the release or absorption of substances and sensors that indicate the transportation and storage history of the product and/or whether the food stuff is fresh or ripe.

The promise of active and smart packaging has been in circulation for a long while especially with regards to oxygen scavengers and moisture absorbers. A recent report shows that the current active packaging segment is dominated by oxygen scavengers, moisture absorbers and barrier packing product, accounting for 80% of the market. Bakery and meat products have attracted most nano-enabled packaging technology to date (iRAP 2009).

Very little has entered the market yet, but there are some representative commercial products on available. BIOSWITCH, by TNO Life Sciences, is an encapsulation and release technology which locks functional ingredients into a polymer matrix. The ingredients are released by an external stimulus, such as pH change or contact/interaction with skin or microbes (Kampers 2011, Robinson and Morrison 2011). OnVu is a time-temperature system that uses a visual indication on the food package to show the time-temperature chronology of the product (Kampers 2011).

4.4 Regulation

Active and smart packaging introduces new perspectives for food packaging, for example the goal of intentional migration of substances from the package into the food or beverage. These include preservatives, antioxidants, aroma and colour enhancers.. This causes some complications with regards to food packaging legislation as active and smart packaging needs to consider other elements of food legislation - for example issues such as which legislation is relevant for the intentional migration of substances into food? Is it food packaging legislation or another specific legislation?

In addition to the *EU Directive (89/109/EEC)*, legislation on flavourings, food additives, safety and hygiene should be taken into account with regards to some types of active packaging. The EU directive on plastic materials ((90/128/EEC) has set a general limit on the maximum, overall migration substances from packaging materials at 60 mg/kg. What is unclear hear is the effect of this legislation on composite materials that are designed to *intentionally*release substances. The EC project ACTIPAK came up with recommendations which were taken up in the drafting of the amendments to 89/109/EEC - which resulted in the adoption of a the framework (1935/2004/EC) where the use of active and intelligent packaging systems are included.

For nanotechnologies, the recently amended Plastic Implementation Measure (PIM) - 14262/10 will play a role. Also the Active and Intelligent Packaging amendment which came into force in August 2009 and provides a much anticipated platform for active and intelligent packaging (both with nanomaterials and more broadly). *Regulation (EC) No 596/2009*

5. Governance issues when packaging and food meet the consumer

The food packaging value chain is the incumbent arrangement of actors that transform the raw material and add value up until the consumer receives the package as part of a food product. The previous two supply chains have given some insights into those elements 'early' in the value chain. What has not been described in the supply chain examples is the actors' involved when the packaging meets the food value chain, the retailers and the consumers. Regulation related to nano has been covered to a large extent by the previous section. However one group of actors which clearly deserve a mention are the consumers, non-governmental organisations (NGOs) and civil society organisations (CSOs).

When the packaging material meets the food value chain itself, it begins to be exposed to different actors and a number of additional issues and concerns. The product (food substance and the food packaging) is combined and delivered to retailers and then sold to the consumer. During this period of the value chain, we must consider issues such as those elements described in the often quoted speech of President Kennedy, which was later transformed into The Consumer Bill of Rights. (Lampman 1988) This speech outlined four broad rights for consumers:

1. The right to safety: to be protected against the marketing of goods which are hazardous to health or life.
2. The right to be informed: to be protected against fraudulent, deceitful, or grossly misleading information, advertising, labelling, or other practices, and to be given the facts he needs to make an informed choice.

3.The right to choose: to be assured, wherever possible, access to a variety of products and services at competitive prices; and in those industries in which competition is not workable and Government regulation is substituted, an assurance of satisfactory quality and service at fair prices.
4.The right to be heard: to be assured that consumer interests will receive full and sympathetic consideration in the formulation of Government policy, and fair and expeditious treatment in its administrative tribunals.

I will use these as an entrance point to consider some of the issues relating to the food packaging value chain with regards to nanotechnologies and the consumer.

5.1 Right to safety

Siegrist et al. (2011) studied the situation of EHS issues of nanofood in general. They produced a nanoparticle flow diagram showing the different entrance points of nanomaterials into the environment and into humans. Figure 3 gives an adapted version of the diagram highlighting two flows specific for food packaging (labelled as routes 1 & 2).

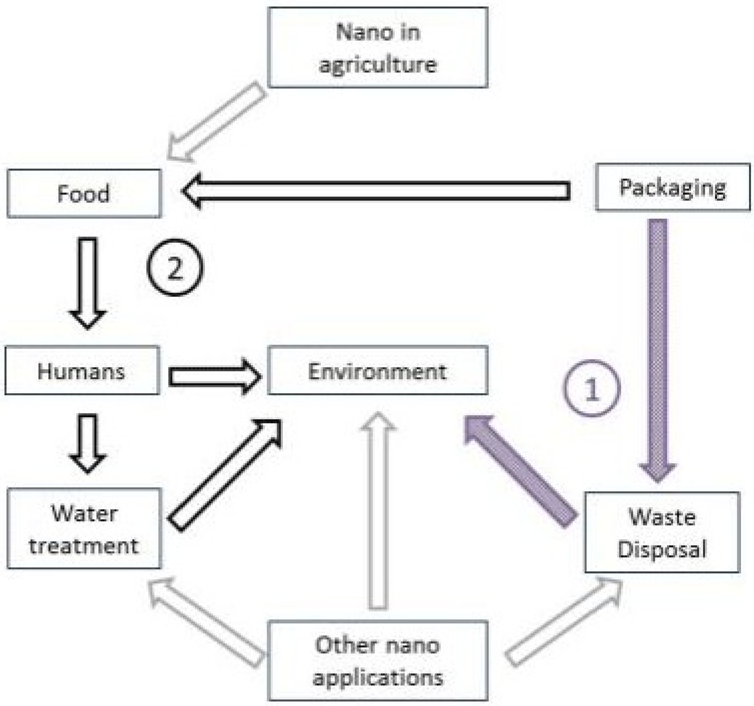

Figure 3: Nanoparticle flows between food, humans and environment. Adapted from Siegrist et al. 2011 showing two main nanoparticle flows that can be related to nano food packaging.

Recent research highlights that there are insufficiently reliable analytical methods for the detection and characterization of nanoparticles and their properties in substances to which humans and ecosystems are exposed, including air, soil and water as well as food products and packaging themselves.

Regarding waste disposal, there is an issue of the lifecycle of the nanomaterials when the consumer has finished with them. They degradation process, the accumulation of nanomaterials in the environment, and their environmental effects are not clear, though alarm bells have been heard ringing with reports on toxicity of nanoparticles in

One group which is raising concerns of nanomaterials in food packaging (as well as agrochemicals) is the organic foods industry, currently a niche area but which has seen growth in recent years prior to the global economic crisis. For example, the British Soil Association [35] put forward a ban in 2008 on nanomaterials due to conflicts with its principles of clear accountability, their systems approach to agriculture (including awareness of the life cycle of products) and the lack of knowledge of toxicity.

In addition to toxicity studies and environmental, various uptake paths have to be studied, (see flow 2 in the figure 3) regarding ingestion of particles from food packaging that have migrated into the packaged food. [36] A review of 155 pages by Buzea et al. (2007) was published to create a common foundation document for both researchers, industry and risk assessors on the variety of nanoparticles, activity in these areas and biological toxicity. They compare engineered nanoparticles with naturally occurring ones and describe how various systems of the human body are equipped to interact with nanoparticles. What is clear from this review and those since, is that the toxicokinetics of these nanomaterials are important and the risk assessment community have called for improved understanding of both toxicity and accumulation of the nanomaterials including dermal, oral and intestinal, as well as nanoparticle accumulation and potential long-term effects (Robinson 2009b). This has been echoed elsewhere. For example, Chaudhry et al (2011) point out that whilst there has been an ever increasing amount of studies in to the inhalation toxicity of engineered nanomaterials, a very limited number of studies have been carried on the translocation and distribution of nanoparticles to various organs and tissues after oral intake. The effects of such distribution is dependent on a number of variables such as size, surface charge (Szentkuti 1997) and surface topography and chemical make-up (Lai et al. 2007)

These concerns by both consumer orgs, environmental organisations and the risk assessment community translate into the request for action in four specific areas (authors synthesis):

1. Detecting and characterising nanomaterials (Nanotoxicology)
2. Understanding potential uptake paths (Nanotoxico-dynamics)
3. Standard methodologies to facilitate interpretation of data
4. Lifecycle analysis - exposure scenarios from production and use of nanomaterials in food and exposure as waste

5.2 Right to be informed and the right to choose

Here labelling is a going concern and there are calls for labelling by consumer organisations and other NGOs. For example, in June 2009 at the at a conference in organised by the Transatlantic Consumer Dialogue (TACD), which is a forum of 80 European and US consumer organizations, there was a clear indication that there should be labelling of nanotechnology in foods. With the lack of specific nanotechnology regulation, they argue that the consumer must have the opportunity to choose between nanofoods and other options. Hence access to information and clear labelling is another strategy for responsible governance. The European Parliament has also recently argued for the clear labelling of nanofoods, however, this is not a case of merely slapping a 'nano-inside' label on the product, as a representative of a nanotechnology industry association meeting pointed out in the TACD meeting. The amount of information on the label, the degree in which consumers can interpret the data and the specificity of the information are all areas that must be resolved, otherwise nanotechnology enabled products may be unfairly singled out and misrepresented. They went on to argue that what is needed is a labelling system which allows consumers to make an informed choice.

As outlined in the sub-section above on the nanomaterial supply chain, nano labelling has emerged in the cosmetic products only - but this sets a precedent and a transfer into other sectors is increasingly more probable. Throne-Holst et al. (forthcoming) has argued that labelling in itself is not straightforward, there are issues of distribution of responsibility - the consumer/citizen has the responsibility to make a choice on whether to buy a product with nanomaterials included but evidence shows that there is a low level of knowledge about nanotechnology by the general public (Throne-Holst et al. forthcoming). There have been many studies of the public perception of nanotechnology, and there is reasonable data that public awareness of nanotechnology is limited at best (Waldron et al. 2006, Gaskell et al. 2005, Cobb and Macoubrie 2004) thus it is difficult to predict how consumers will react to labelling.

5.3 Right to be heard

Another element is the interaction between consumers and the food sector itself. For nano and food this began in the early 2000s in response to the growing concerns of nanotoxicity, coupled with the rapid development of nanotechnology, a number of nano-engagement exercises were initiated. On broad issues, an example was the engagement activity created by the Cambridge Nanoscience Centre, in collaboration with the University of Newcastle, Greenpeace and the Guardian Newspaper who organized Nano Jury UK in the summer of 2005. This was a citizens' jury on nanotechnology over a period of six weeks in Halifax, North of England. Following this, the British Government launched its 'Programme for Public Engagement on Nanotechnologies'.

Elsewhere, the European project, Nanologue, an 18-month European Commission-funded project designed to support dialogue on the social, ethical and legal implications of nanoscience and nanotechnologies. Although having different remits, targeted at different publics, and leading to different forms of outcomes, the projects did receive some attention but it is unclear how they have affected nanotechnology policy.

Other actors than governments and nanotechnology developers began to initiate exploration and engagement exercises. For example the IG DHS professional association of Swiss Retailers explored the regulation gap in nano and the food sector as well as issues of consumer confidence. The developed a code of conduct with the assistance of the Innovation Society (a risk management consultancy).

In a meeting run by The Innovation Society, Swiss Re (a re-insurance firm) proposed risk dialogue and self-regulation as the solution with adaptation of governmental laws only desirable for longer term issues. Organisations such as Greenpeace UK were analysing and producing reports on the potential impacts of nanotechnology. There were calls for moratoria from ETC group and from Friends of the Earth (the latter on commercial release of Nanomaterials in personal care products and cosmetics). [37] The British Soil Association is another example of a group which has argued that specific values and codes must be part of the nanofood debate - here the argument is on the organic food production paradigm as an alternative to the current chemical-industrial based paradigm.

Government lead engagement exercises, anticipating on public concerns have been proliferating. More recently the British Food Standards Agency published a report of consumers' views on the use of nanotechnology in food and food packaging. It reported on a number of focus groups in the UK which explored a number of nano applications in the food sector. What was very visible was the relative acceptance of food packaging as opposed to other areas of nano and the food sector such as functional foods, flavourings etc. (Bhattachary et al. 2011). This was echoed in Switzerland in a study of public attitudes towards nanotechnology reported by Siegrist et al (2008) and Burri et al. (2008) which describe the public positions as pragmatic, demonstrating a focus on transparency and a preference towards nano in food packaging when compared with other nanofood applications. What is clear, is that consumer perspectives are and will play a strong role with regards to the commercial development of nanofoods. Engagement exercises stimulated by public agencies and other organisations are an important part of the nanofood landscape and the forms and functions of these interactions will play a strong role in the emergence and societal embedment/rejection of nanofood options.

6. Arenas of nanotechnology development and selection: a tool for future-oriented socio-technical analyses

The focus on the value chain is important for those wishing to develop strategies for managing nanotechnology emergence. Those developing innovation strategies (be they governments, technology developers, industry or civil society) face the general challenge of being able to prospect possible technology trajectories and are also are challenged to prospect the changing environments and framing conditions that will determine whether an innovation will move from a hopeful proof-of-principle to a product well embedded in our society. This means a broadening of the techno-centric focus on promising nanotechnologies, and also a move away from speculation of potential applications/products, towards a focus on new/transforming value chains - where stakeholders are visible and already anticipating and acting with regards to nanotechnology in a variety of sectors.

When speaking of management and governance of nanotechnology and food packaging more broadly, as well as particular product lines, one should therefore add the layer of value chains, supply chains, industrial and R&D networks that interlock and shape the value creation process.

There are three-layers of dynamics

1. A macro-layer of societal goals, national and international policies and agendas.
2. A meso-layer of value chains, supply chains, industrial and R&D networks.
3. A micro-layer of product development lines and innovation trajectories.

This type of multi-level or multi-layer perspective has been applied elsewhere in nanotechnology. In Rip and van Amerom's study of Risk Governance in Nanotechnologies (Rip and van Amerom), in Robinson 2009 on soft and hard law of nanotechnologies and foresight (Robinson 2009) and by te Kulve 2010 with particular regards to entrepreneurs lining up the three-layers. Robinson et al. 2011 proposed an innovation chain model which is located at the micro-layer but which combines dynamics and actors from the mesa and macro layers, in order to locate arenas for innovation and selection mechanisms.

6.1 Arenas of innovation, interaction, engagement and options selection

Sections 2, 4 and 5 have provided insights into the macro-level and meso-level of nano-involved food packaging. For the micro-level, Section 3 has provided a review of activities in science and technology research along with some first translation of this knowledge into commercially available products. When evaluating the potential impacts of a promising emerging technology, focus is usually technocentric - that is taking the technology as the central point to the evaluation and seeing how it will emerge and impact markets and society more broadly. But emergence of a technology option is part of a chain of choices, of interactions and selections based on many different factors stemming from the macro, meso and micro-level. Thus any analysis of potential emergence of nanotechnology options in the food packaging sector would not only have to consider the technical feasibility of the R&D but also the various factors outlined in Sections 2, 4 and 5.

For a (broadened) technocentric perspective on factors that will shape the emergence of potential nano-involved food packaging solutions, one can apply the Innovation-Chain+ approach (IC+) to locate the arenas of innovation activity where choices are made, and value created, connecting technoscientific promises with multi-actor perspectives. The IC+ diagram given in figure 4 (a reduced version) illustrates the point that there is more at play than the 'supply-side visions' of technology developers. There are interlinked arenas of innovation and selection which an innovation has to navigate through sequentially (although not necessarily linearly to become embedded in society). Moving from left to right in Figure 4, emerging innovation in packaging materials pass through different arenas of action being (represented by the bubbles and annotated briefly in the boxes above) being influenced by a variety of selection forces from within this arena, as well as coming from the framing conditions (see box at the bottom of the diagram).

In the figure 4 I have placed six numbers (1) - (6), at positions in the IC+ to give an illustration of the arenas that will shape the emergence of a nanotechnology option for food packaging. It is not an exhaustive account, but is intended to demonstrate that if the manager/policy maker wishes to locate challenges/opportunities that may occur during emergence, the data from Sections 2, 3, 4 and 5 can be collocated in this perspective to frame issues and locate interventions (including multi-actor engagement processes or interventions).

1.The packaging R&D arena. Here there are many nanotechnology possibilities from nanofibres, to nanofilms and nanocomposites etc. The driver here is to understand material properties and develop production technologies. A key challenge at this point of the IC+ is the choice of R&D lines, which are vast, and how to connect them with needs further down the line. Historically there have been a few attempts at such coordination, for example the EC funded SUSTAINPACK and NAFISPACK projects where large consortia of European research institutes collaborated with the food packaging industry to develop applications based on nanofibres and natural antimicrobial packaging respectively. A particular challenge is agenda setting in this arena to provide directly transferable knowledge to the next arena is. Figure 2 (the value chain diagram) positions some of the key actors that will be important for making decisions here (the framing conditions of the supply chains).

2.Here, up-valuing promising techno-scientific knowledge relies on financial and managerial support, whether resource provision in a large firm for a new development line, or supporting a technostarter/spin-off. A key challenge observed here from interviews and workshops in the nanomaterials sector is venture capital related to scale up. Still techno-centric, actors here attempt to chart multiple pathways from their enabling technology into a diverse array of sectors, to try to mobilise resources. Illustrative here is the company, Nanobiomatters, a medium sized firm based in Valencia and the greater Valencia region. Over the past six years Nanobiomatters has developed R&D and production capabilities for nanoclay powder (Commercial Additive Plant of 2500t/year) and polymer-clay nanocomposite production (Commercial Extrusion Plant of 4000t/year).

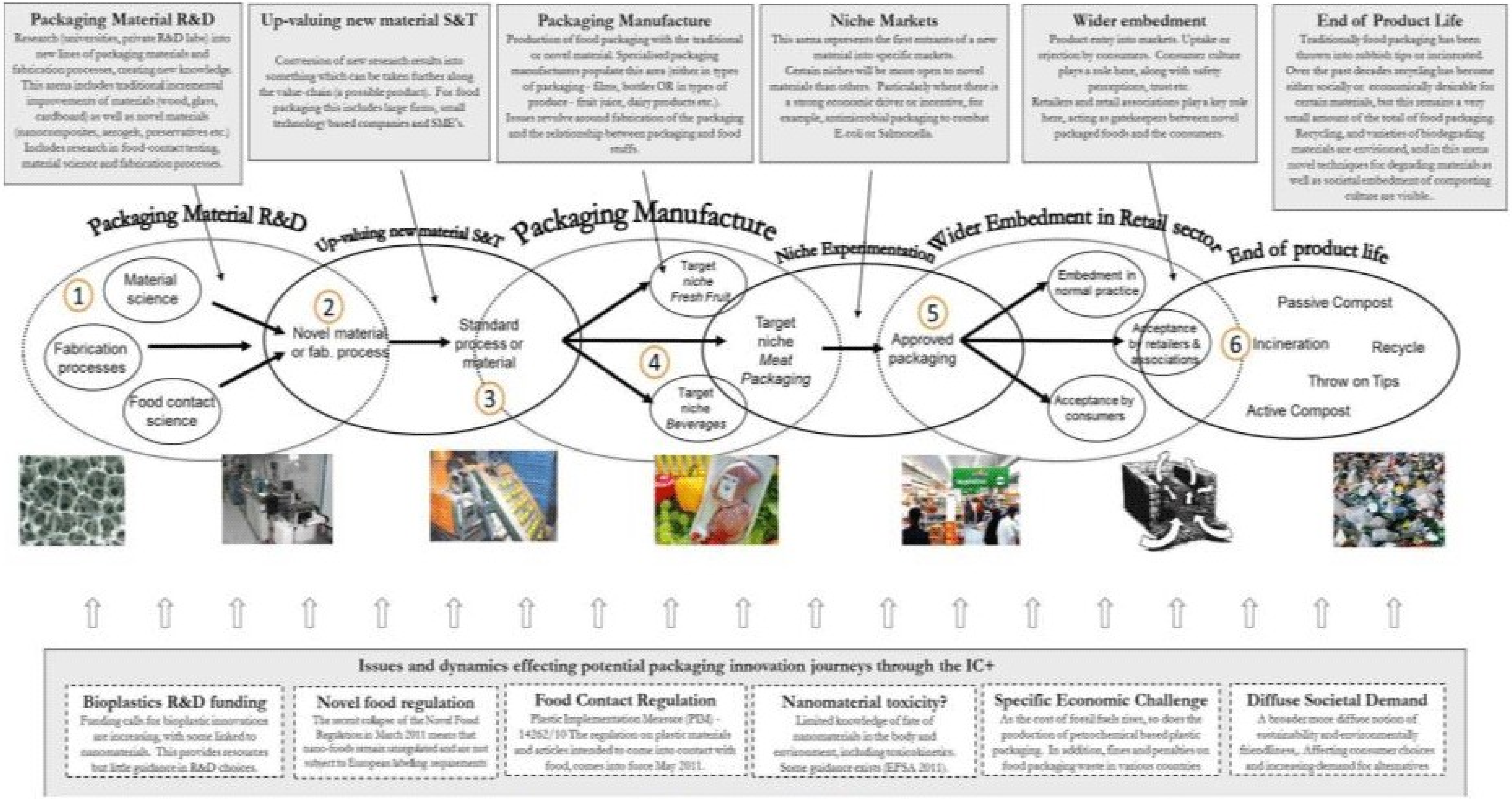

Figure 4: The Innovation-Chain+ perspective

Commercial products are currently available, and with €4 million invested in the development of its manufacturing facilities, and a diverse portfolio of nanobioplastics (including antimicrobial and gas scavenging functionalities), Nanobiomatters is rapidly becoming a major player in the field of biodegradable packaging. So there are activities in this arena, though the strategy is to have a diverse portfolio, such as that of Nanobiomatters which aims at food, medical and pharmaceutical sectors.

3. Nanomaterial standards, regulations and occupational health issues are still in flux. It is an extremely complex issue because of the wide variety of materials and properties at the nanoscale, the limited knowledge of toxicity of nanomaterials on living systems and their transport in living and environmental systems, the lack of harmonised standards or guidance for nanomaterial production. In Europe, where the precautionary principle is prominent, this lack of clarity is currently seen as the biggest bottleneck to nano-enabled solutions to the Grand Societal Challenge of food packaging management. Anticipations of actors in this arena show that without a clearer regulatory landscape calibrated to standards there will be limited incentive to invest. This is, in part, because of liability issues, but also due to being seen as less than cautious by a consumer group which is already suspicious of food technologies (cf. Genetically Modified Organisms). There are some indications emerging for nano regulation and food packaging which is making the situation a little less nebulous (see Section 4). However, in Europe, a review of the Novel Foods Regulation collapsed recently (29 March 2011). [38] The aim of the collapsed amendment to the current Novel Foods Regulation that dates back from May 1997 was to 'allow for safe and innovative foods to reach the European market faster' and to 'encourage the development of new types of foods and food production techniques (such as nanotechnologies)'. While the collapse of this amendment is not related to the provisions for nanotechnologies (it was related to genetically modified livestock), the impact of this recent development is that nano-foods remain unregulated and are not subject to European labelling requirements for the time being. Food manufacturers are left with no clarity on what is allowed and not allowed in Europe. Since there is a general move towards the precautionary principle in European Legislation on foodstuffs, the question asked by food packaging material developers is how precautionary should we be?
4. This is where new materials meet incumbent material processing technological infrastructure and embedded practices. There are key questions such as: How to (and who should) select the new material option which on the one hand provides novel and desirable material properties and which on the other hand can fit the current packaging regime (a view of most incumbent packaging manufacturers) or can provide a substantial return on sunk investments into new processing technologies. Issues such as machinability make a considerable difference in the material selection; however this is less of a priority in the R&D arena.
5. This is where packaging combined with what is packaged (food, drink, nutritional supplement) meets the retail sector. Here there is already interest in greener forms of packaging, there is a market for it and recyclable/recycled cardboard and cellophane can already be seen in high street supermarkets (for example in sandwich packaging). However, the issue of labelling and standards for food packaging is a big question here. Without clear guidelines, retailers will be risking garnering mistrust or rejection of their products by consumers. There is a trade-off and with little clarity on alignment earlier in the IC+ there is little or no incentive for retailers to accept nano-based packaging materials.
6. For nano-packaging aimed at more sustainable packaging waste management, such as biodegradable or edible food packaging options outlined in 3.1.2, figure 4 shows some of the waste management options that are discussed today (DEFRA 2011). Using figures just for the UK: Approximately 10.5 million tonnes of packaging enters the UK waste system every year (DEFRA) more than half of this is related to food and drink. The cost of the raw materials for this is about 4.5 billion Euros per year and this cost does not include disposal and recovery costs or wider social and environmental costs such as the accumulation of plasticizers in underground water, or the production of dioxins by, for example, PVC and paper based packaging materials. This not only mentions a real incentive behind the diffuse grand challenge (a specific economic one, emphasised in the framing conditions in figure 4) but also the size of the waste management problem. The waste management solution (or portfolio of solutions) should be aligned with the food packaging material options (and vice versa). But each waste management option requires a large socio-technical infrastructure requiring perhaps a transition in socio-technical regime (Geels 2002). Incineration and landfill are the major waste management regimes in place to -date. Concerns are raised whether biodegradable packaging options are viable if the composting infrastructure at national levels is not in place, not matched, or not available at the time a biodegradable packaging option is available. In short, these are misaligned windows of opportunity.

6.2 Prospecting futures of nano-involved food packaging: a co-evolution of micro, meso and macro levels.

Above I have given a taster of mapping out the innovation and selection landscape that will shape the emerging nanotechnologies for food packaging. Such a perspective allows the co-location of intelligence from the macro, meso and micro levels. As I have argued in this article, the meso-level of value chains for nanotechnologies entering incumbent sectors, to help locate the issues that broadly effect the industry which nano may become a part, and to locate the framing conditions and societal actors that will play a role with regards to the rejection or acceptance of nano-involved food packaging.

This approaches shows promise in connecting discussions of nanotechnology developments and governance (both regulatory, voluntary codes and citizen/user-based modulation). A key point is about support tools and analyses for governance of nanotechnologies and food. There is an issue of a shift in the types of actors influencing the creation and selection of options. Future-oriented technology analyses should include both an analysis of the incumbent and evolving situation from the side of nanotechnology and the food sector (and I highlight here that value chains are an important factor for this). Another element is what Rip has described as de facto governance in the broader shifts in responsible innovation and distributed governance (Rip 2006). Arenas are opening up for shaping and modulating technology development and societal embedment processes. An investigation into these sorts of shifts (actual or potential) are important (especially with regards to future-oriented technology analyses and strategy/policy making - this will be a target of further work by the author.

7. Conclusions

I have proposed that the incumbent value chain of food packaging should be a location of analysis, with new nanotechnology supply chains linking up with the incumbent. It provides a linking-pin between the vast array of technoscientific promises at the level of R&D and linked to the micro-level of individual research projects (and potential innovation pathways (Robinson et al. 2011)) and the broader and more global (macro-level) issues of governance of nanotechnologies in society. This article has provided a large amount of detail about the technoscientific promises in public and private R&D involving nanotechnology and potential food packaging applications. These promising nanotechnologies for application in the food and beverage packaging sectors have been described as offering potential industrial applications (Sorrentino et al. 2007) however it is far from certain that these technology promises can indeed be realized (let alone whether they will emerge in the ways that are proclaimed in the world of R&D). This is because such promising technology must enter existing industrial sectors (or be part of new ones) and become inserted into value chains which themselves are adapted to both incumbent technologies and regulatory environments and retailer and consumer preference contexts, etc.

Section 2 described some of the broad societal drivers for food packaging both from the side of retailer/consumer demand, policy drivers and the force of environmental and sustainability grand challenges. Section 3 followed this with describing the families of nanotechnology R&D that are promising to have an impact and respond to the elements described in Section 2. Section 3 revealed that there is substantial activity in nanotechnology for food packaging covering novel materials, active release composites, sensor technologies etc. The potential impact of these promising technologies only begins to be relevant when we look at the potential translation of these hopeful technologies into products that will reach the consumer.

The value and supply chain model allows one to locate roles and responsibilities in the translation of R&D into products that reach the consumer, along with the regulatory, financial, political framing conditions that shape decisions within elements of the value chain. [39] Sections 4 and 5 started placing the issues into context by looking at the supply and value chains. For reasons of space, I have restricted myself to illustrative elements of relevant supply chains and value chains -the full study would provide a more exhaustive analysis of elements of the supply and values chains.

Section 6 has outlined that, for foresight and intervention, the linked arena model of IC+ is useful in connecting the meso/macro to the micro level of actual emerging innovations. The chain of development which most technologies will have to go through will face contestation, and the factors that influence whether a technology will transform from a hopeful piece of scientific knowledge into a working technology in society depends not only on the technology itself, but the dynamics, assessment processes, positions of different actors in a complex web of interactions. Reducing the complexity to value chains allows one to locate the origins and arenas of interactions and assessments that will be part and parcel of the evolution of a technology option (in this case nano-involved food packaging).

The article title claims that the value chain is a linking-pin framework for exploring governance and innovation processes for nanotechnologies as they enter sectors. It allows the positioning of technoscientific promises in the context of supply and value chains, plus the framing conditions. In this framework the different actors and their stabilised routines in innovation and selection processes are made clear.

I have presented the IC+ as an example of how the various elements can come together to provide an insight into the state-of-the art of both the R&D activities and also the state of the arenas of development and selection that will influence how nano-involved food packaging will emerge. The value chain model locates actors in terms of specific roles played in the value chain, the IC+ frees up actors and focuses on arenas. Traditionally technology developers and researchers play a strong role in the R&D arenas (left hand side of Figure 4), but increasingly actors from other parts of the value chain are becoming involved in this arena through upstream engagement, discussions of governance of R&D and technology production and in the visioning of potential (desirable and undesirable) future applications of technology options.

As nanotechnology enters various parts of the agrifood sector, the emerging governance arrangements of nanotechnology meet incumbent (and still developing) governance regimes, consumer positions and actor arrangements. This paper has further articulated this claim along with providing an illustration of how such insights could inform approaches for foresighting potential developments in nanotechnology, their impacts and potential frameworks for exploring and modulating nanotechnology governance.

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[2] An 'umbrella term' is a term that covers a wide-ranging subject rather than representing a specific definition. In this way umbrella terms are inherently ambiguous, can combine notions of promises, potential and ongoing activities and communities involved in this umbrella term. Umbrella terms can become a rhetorical denominator for an emerging field - a label to refer to, which demarcates a world of research and development whilst remaining loosely defined.

[3] http://etp.ciaa.eu/documents/SRA_2007_2010.pdf

[4] http://www.fooddrinkeurope.eu/event/fourth-nanotechnology-stakeholder-dialogue-day/

[5] http://www.fooddrinkeurope.eu/industry-in-focus/topic/nanotechnology/what-is-nanotechnology/

[6] This figure was created by the author and first presented in March 2009 in London as a means of describing the scope of a report on Nanotechnologies in the Food Sector (Robinson and Morrison 2009).,

[7] For a quick insight into the technology see http://www.ienica.net/greentech/willemse.pdf

[8] This has been described by industry analysts (Berger 2008) and social scientists (te Kulve 2010, Rip et al. 2007).

[9] By way of a disclaimer, I report on the promises of nanotechnology whilst not necessarily endorsing these promises.

[10] Clay based nanocomposites were developed at the end of 1980s, first placed on the market by Toyota. During the following decade, researchers began to explore the potential of clay nanocomposites as food packaging materials (Alexandre and Dubois 2000, Collister 2002, Ray et al. 2006).

[11] One interesting project in the EU is NanoCelluComp, which is developing bio-based high end nanocomposites from food product waste (www.nanocellucomp.eu)

[12] In European regulation, No. 1935/2004, EFSA must grant its approval before a substance is authorised for use in food contact materials.

[13] World patent number 0073718: Self-cooling beverage and food container using fullerene nanotubes

[14] Mitsubishi Gas Chemical Co. http://www.mgc.co.jp/eng/products/abc/ageless/index.html

[15] US patent number 5922776: Sustained release, transparent biocidal compositions

[16] US patent number 7273567: Energy-activated compositions for controlled sustained release of a gas

[17] Mitsubishi Gas Chemical Co. http://www.mgc.co.jp/eng/products/abc/ageless/eye.html

[18] World patent number 2007148321: Irreversible Coolness Detector. Marketed as iStrip, http://www.timestrip.com/

[19] Biodegradable plastics are defined as biopolymers in which at least one step in the degradation process is done via metabolism by naturally occurring organisms.

[20] There are other packaging innovation drivers which have led to the articulation of other packaging needs such as active packaging (internal environment control including interacting with food contained within); and smart packaging (including functionalities such as trace & track and indication of authenticity).

[21] www.nanocor.com

[22] www51.honeywell.com/sm/aegis/products.html

[23] www.nanoclay.com

[24] www.research.bayer.com/edition_15/15_polyamides.pdfx

[25] World patent number 0240579: Coated films and coating compositions

[26] http://www.euractiv.com/en/cap/novel-foods-review-stumbles-cloning-news-503610

[27] The European Food Safety Authority (EFSA) is an independent source of scientific advice and communication supporting the European Commission, the European Parliament and EU Member States in taking effective and timely risk management decisions on risks associated with the food chain. EFSA's remit covers food and feed safety, nutrition, animal health and welfare, plant protection and plant health.

[28] http://www.efsa.europa.eu/EFSA/efsa_locale-1178620753812_1178678338323.htm

[29] The FSA regulatory review 'A review of potential implications of nanotechnologies for regulations and risk assessment in relation to food' published in August 2008 has not identified any major gaps in regulations relating to the use of nanotechnologies in food.

[30] See http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:338:0004:0017:EN:PDF

[31] www.europarl.europa.eu/news/expert/infopress_page/067-52498-082-03-13-911-20090324IPR52497-23-03-2009-2009-false/default_en.htm

[32] See http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:086:0009:0018:EN:PDF

[33] See http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:135:0003:0011:EN:PDF

[34] For more information see the Ordinance on the Avoidance and Recovery of Packaging Wastes (http://www.bmu.de/files/english/waste_management/downloads/application/pdf/verpackv_3aenderung_en.pdf)

[35] The British Soil Association is currently the main organisation of the organic movement in the UK and certifies about 56% of organic farmers and 70% of the organic food sold in the UK.

[36] An interesting study was reported by Avella et al. looking at the migration of Iron, Magnesium and Silicon from biodegradable starch-nanclay composite films into lettuce and spinach (which were encased in the packaging film). The findings showed negligible migration of iron and magnesium into the vegetables, however silicon migration was observed.

[37] The ETC-Group and Friends of the Earth are active non-governmental organisations in this area. Both have reviewed the R&D and product development activities in nanotechnology and the food sector (indeed both reports have been widely referenced as a review of developments) (IG DHS 2008, ETC-Group 2004).

[38] http://www.euractiv.com/en/cap/novel-foods-review-stumbles-cloning-news-503610

[39] The value chain model is itself a reduction of complexity (in effect a network or system model may be more accurate but perhaps more unwieldy).