Swedish Companies and Nanotechnology

Perception of Nanotechnology Health and Environmental Risks

Master of Science Thesis in Management and Economics of Innovation

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Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2010
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Abstract

VINNOVA (The Swedish Governmental Agency for Innovation Systems), has been assigned the task of leading the development of a Swedish nanotechnology strategy; a strategy which stresses the importance of acknowledging both the possibilities and risks of nanotechnology to successfully create value. In connection with this development work, this thesis aims to analyze how Swedish companies working with nanotechnology perceive and respond to the potential health and environmental risks of the technology.

The core part of the thesis is made up of an interview study where representatives from ten Swedish companies, of different sizes and industrial backgrounds, give their view on nanotechnology risks and company actions in relation to these. The analytical framework applied on the data is based on the idea of health and environmental risks as a source of technological, market, and regulatory uncertainties; which in turn can be mitigated with the help of knowledge and information. Additional elements from theory on the company's innovation process, the technological innovation system, and the notion of reflexivity are linked to this duality of uncertainty and knowledge.

The companies' perception of nanotechnology health and environmental risks is one of little worry. There is acknowledgement of hazards pertaining to specific nanomaterials, e.g. carbon nanotubes, and the potential for what could be described as an image problem in the eyes of authorities and public. But as far as the own business is concerned, there is a general view of the nanotechnology usage as safe. Companies act on the knowledge at hand and given what is known about the nanotechnology used, and the type and context of nanomaterials in this particular study, there is currently no contradiction to the companies' claims. Based on this perception there is little company activity directly related to the potential risks of nanotechnology.

Keywords: nanotechnology, health and environmental risk, Sweden, uncertainty, knowledge, innovation process, technological innovation system, reflexivity

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I am most thankful to my supervisor Eugenia Perez for her guidance and valuable advice throughout the writing process; her feedback has improved the quality of this thesis. In addition, I thank my examiner Staffan Jacobsson for his input during the last stage of the thesis work.

Finally, I am truly grateful for the untiring support from friends and family. Thank you.

Carl Arvid Dahlöf
Göteborg, January 2010

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1 Introduction

This first section gives a short background to the topic and serves to show the relevance and purpose of the thesis. Furthermore, the research questions around which the thesis is written are presented, along with the delimitations made and an outline of the report.

1.1 Background and Purpose

With new technologies often follow great hopes of new opportunities; whether the future promises to be brighter, faster, cheaper or simply unimaginable. However, progress is accompanied by uncertainties about what negative effects might come from the very same technologies; either because of unforeseen effects or through intentionally harmful use. It may take years or even decades before the negative sides begin to show clearly, but when they do, they can turn out to be just as significant as the benefits. History contains numerous discoveries and innovations praised at first, but left with a tainted reputation as the negative effects gradually revealed themselves and damage had already been done; asbestos fibers and DDT being two of the more striking examples (Kulinowski, 2004).

Nanotechnology is potentially the next major technological breakthrough, with an impact as deep and wide as that of the IT and biotechnology revolutions (Bhushan, 2004). A nanometer is equal to one billionth of a meter so anything on the nanoscale is beyond small, but it is not just smaller, it is completely different. The buzz about nanotechnology comes from the entirely new material characteristics only displayed at this minuscule level; characteristics whose impact on humans and the environment remain largely unknown. Although the subject of risks still represents a small share of the nanotechnology-related research, there is a growing concern of what hazards could follow as nanotechnology finds its way into nearly all branches of science and daily life.

This thesis is commissioned by VINNOVA (The Swedish Governmental Agency for Innovation Systems), a state authority aiming to promote growth and prosperity in Sweden by funding needs-driven research and strengthening the networks needed for innovation. VINNOVA has been assigned to lead the work of developing a nanotechnology strategy for Sweden. Various forms of such strategies, some addressing risks, exist in several of the major industrialized countries. An important aspect of the Swedish strategy is the interlinking of nanotechnology's possibilities with its potential risks. Nanotechnology should be used to create value through innovation, but it must be done with risks in mind so that innovative progress does not jeopardize human health or environment (VINNOVA, 2010).

The purpose of this thesis is ultimately to function as support in the implementation of the Swedish nanotechnology strategy suggested by VINNOVA. During the period of writing, the thesis work has also provided continuous input to the ongoing process of strategy formulation. The thesis focuses on one particular group of actors possibly affected by the strategy, namely companies involved in nanotechnology to a greater or less extent. "Involved" is used in the sense that the companies make use of nanotechnology in their business, i.e. some aspect of the technology is relevant to their products. In accordance with the strategy's overall theme of acknowledging possibilities as well as risks of nanotechnology in the value creation, the companies' relation to health and environmental risks is taken as the point of departure.

1.2 Research question

The purpose and thesis focus are concretized by posing the following research questions:

- How do the companies *perceive* the potential health and environmental risks of nanotechnology?
    - How do they *respond* to this perception?
    - What are the *implications* for policy regarding sustainable development of nanotechnology?

Here, a company's perception concerns what the company thinks of the risks as such, their relevance and their impact for the company, e.g. if they constitute a threat to the business. The response then implies some kind of action taken, or not taken, given the perception. Simply what companies do and whether the measures are connected to nanotechnology risks. Lastly, relating to the focus on possibilities and risks in the strategy, what policy issues follow from a given risk perception?

1.3 Delimitations

In this thesis the potential risks of nanotechnology primarily refer to risks connected to environmental and health aspects, but societal risks[1] are mentioned for the sake of their impact on public debate. The focus is on the perception among companies; no further analysis of the risks is performed and there are no recommendations on how risks "should" be handled within the industry. The results and analysis sections contain commentary on companies' environmental work in general, and nanotechnology in particular where applicable. However, the thesis has no intent of elaborating on the topic of companies' organizational structure and internal relationships.

The actual study also has some limitations, most of which are due to the limited amount of time available. As stated in the purpose above, the focus is on Swedish companies and although the included companies were chosen with an aim to represent different branches of industry, not all areas are covered. The number of companies and interviews were limited for practical reasons, and while a sample of ten companies is considered enough to mirror different opinions, the thesis makes no claims of being all-embracing. More detailed information on how the sampling process was conducted, what choices were made and their implications for the thesis as a whole is given in the Method section below.

1.4 Confidentiality

Names of the companies and respondents included in the study are withheld in the official version of the report. Anonymity is granted due to respondents discussing topics related to company research and development, and because of the potentially sensitive topic of risks and product safety.

1.5 Disposition of the report

After this introductory section follows section 2, Method, where the analytical framework is presented along with how the data collection was carried out and reflections on the research quality. In section 3, Thesis context, a background to nanotechnology with both its possibilities and risks is given, as well as brief description of the Swedish context. Section 4, Theoretical framework, provides the reader with an explanation of the theory used to understand and analyze the data presented in

[1] Potential societal risks include unfair distribution of the technology's benefits and ethically questionable usage.

section 5, Results from the interview study. The analysis is carried out in section 6, and the conclusions drawn from this, pertaining to the research question, are presented in section 7. Finally the thesis is concluded with section 8, Discussion, where some closing thoughts are given.

2 Method

First, this section discusses the way the thesis was carried out in different stages, and what theory was applied in order to understand the topic and analyze the results. Second, the methods for data collection are discussed with particular focus on the sampling process employed to find interviewees. Lastly, the issue of research quality is discussed.

2.1 Research design and process

The research design provides a framework for the collection and analysis of data; not to be confused with the choice of research method which just describes the technique employed to collect data (Bryman & Bell, 2007). This thesis relies on a multiple-case study research design for its core part, where Swedish companies involved in nanotechnology constitute the units of analysis. A qualitative approach was chosen over a quantitative one since this was deemed more suitable for the task of gathering the companies' own accounts of their attitude and perception.

The input to the thesis comes from the three distinct parts outlined below, each of which is explained in more detail in section 2.3, Data collection.

Project preceding the thesis

The author was introduced to the topic of nanotechnology in general, and Swedish nanotechnology in particular, working for VINNOVA in a project on the mapping of actors and activities related to nanotechnology within Swedish academia, industry and public funding.[2]

Literature study

Nanotechnology is, like few other technologies, hailed by many as a source of limitless possibilities, but is also at its current development stage subject to many uncertainties. An understanding of the underlying characteristics is necessary to grasp these various sides of the technology.

Upon starting the thesis, literature was researched to build on the initial insight gained from the project work. Therefore, the thesis work is to a large extent a literature study with the initial aim to identify a variety of issues linked to health and environmental risks, topics that were not the main focus of the preceding project. Literature provides information on many levels; not only what risks have been identified for which substances, but also the inherent difficulties of assessing and classifying risks in nanotechnology. Furthermore, the literature study raises the level of consciousness about the different ideological standpoints and suggestions of appropriate policy response that exist within academia.

Interview study

Arguably the most important part of the thesis work is the gathering of empirical information from ten Swedish companies. It is this information that largely constitutes the answers to the research

[2] Through this project the author was given basic knowledge of nanotechnology and was familiarized with relevant terms and concepts. The project provided insights into the diffusion of nanotechnology in different branches of Swedish industry, revealing the difficulties of classifying the contents of nanotechnology and its relevance to a particular company.

questions. The interview links to the project work since much of the company data used to select suitable interview objects was gathered in the mapping of the industry. More details about selection criteria and the study as such can be found in the section on Primary data, below.

2.2 Analytical framework

The analytical framework serves as explanation to what theory is included, why it is included, and how it can be used for answering the research question.

The section on *thesis context* is an effort to capture the distinct features of nanotechnology and to provide the frame of reference necessary when choosing how to go about the analysis. The idea is to highlight the characteristics that are most important for the research question; first and foremost the high level of uncertainty present in many areas of nanotechnology. By establishing the context in which the research question is posed, the choice of theory for the analytical framework is rooted.

The concept of *uncertainty* and its relation to *knowledge* and *information* is chosen as the center around which understanding and analysis of the study results are built. Companies in general and start-ups in particular face uncertainty in their daily business, not least when business involves new technology. The idea is that nanotechnology's potential health and environmental risks also can be related to different elements of uncertainties. Thus, companies' perception of such risks could be connected to what other uncertainties come into play and with how companies prioritize between them. Knowledge on the other hand relates to perception and response by being a remedy for uncertainty. The subsequent theory elements of the analytical framework are included because of their bearing on either uncertainty, knowledge or both.

Companies do not operate in isolation, but in a context of other actors and networks. Functions of this *innovation system* are included in the analytical framework for two reasons. First, they have implications for both uncertainty and knowledge and are thus related to companies' risk perception and response. Second, they form the strongest connection to policy and are necessary in order to understand what policy implications could be deduced from the study results.

Models of the *innovation process* focus more on the individual company and the internal progression from idea to product. The purpose of including the innovation process in the analytical framework is to illustrate the flow of feedback between different stages as well as the link to knowledge and research. Also, when analyzing what response follows the companies' risk perception, it is the implications on the innovation process that will be of most interest.

The idea of a *reflexive system of innovation* has much in common with the theme of the proposed Swedish nanotechnology strategy, i.e. effective innovation with consciousness of the risks. In the analysis, reflexivity is taken from the systemic level and applied on a company level to characterize the perception and response to risks in innovation. For a company, reflexivity could translate to an innovation process with continuous input from processes concerned with risk identification and evaluation, e.g. an environmental department, thus resembling the flow of knowledge pictured in the innovation process.

2.3 Data collection

This section describes in further detail what kind of data comes from the parts described in the research process above. Furthermore, some aspects pertaining to the different kinds of data and how the data is obtained are discussed.

2.3.1 Primary data

The primary data of the study consists of information extracted from interviews with representatives of Swedish companies involved in nanotechnology. The choice of interviews over self-completing questionnaires as research method has several reasons. While self-completing questionnaires offer the possibility of large quantity distribution and convenience for respondents, there are also drawbacks as pointed out by Bryman and Bell (2007). The one considered most significant for this particular study was the lack of probing possibility, i.e. letting respondents elaborate on an answer. Given the open nature of the questions asked the respondents and initial uncertainty over what answers could be expected, the opportunity to ask for clarification was deemed necessary.

In qualitative research the two major types of interviews are the *unstructured interview* and the *semi-structured interview* (Bryman & Bell, 2007). Throughout this study, the latter of the two types is used, mainly because of the flexibility it offers concerning order of questions and addition of questions in order to probe, while covering fairly specific topics at the same time. Compared to the unstructured style, the semi-structured interview grants a higher level of similarity between different interviewing occasions (Bryman & Bell, 2007). Since this thesis aims to possibly discern tendencies within groups of companies and relate observed differences to company characteristics, there should be a certain degree of comparability between interviews present.

The interviews conducted for the purpose of this thesis were based on an interview guide comprising questions grouped into sets relating to various aspects of the main topic. With the exception of some minor changes, the interview guide was kept consistent throughout the study. However, at times questions were left out or given less priority depending on the interviewees' area of expertise, or because of answers given at an early stage ruling out further probing of the subject. Some questions proved to be consistently difficult to get answered in a satisfactory way. The interview guide can be found in Appendix 1.

In the choice between telephone interviews or interviewing in person, there are several advantages with the former. Telephone interviews are quicker to administer, there is no time-consuming traveling involved, and interviewees' responses are less likely to be influenced by characteristics of the interviewer (Bryman & Bell, 2007). However, it is also frequently suggested that it is important for the interviewer to establish rapport with the respondent. Quickly forming a relationship supposedly encourages the respondent to participate in and persist with the interview (Bryman & Bell, 2007). Partly for this reason, personal interviews were conducted whenever possible, and telephone interviews used when motivated by too great a geographic distance.

Regardless of whether the interview is done in person or over the telephone, there are issues to be aware of with regards to how the interviewee responds. Bryman and Bell (2007) describe *social desirability* as the phenomenon of respondents adjusting their answers to be more in line with what they perceive as socially desirable. In this thesis some of the questions asked in interviews concern companies' risk awareness, product safety, and environmental work. These subjects could potentially induce an amount of social desirability where company representatives intentionally, or unintentionally, portray their company or themselves as “good”. When the interviewer lacks in-depth knowledge about materials, applications et cetera, such flattering descriptions can be difficult to see through. Even so, the potential influence is important to bear in mind when analyzing the data.

All interviews were recorded with the help of a digital recorder after receiving the respondent’s permission to do so. Recording the interviews ensured that the single interviewer could focus on the conversation instead of note taking, while still capturing important details. Bryman and Bell (2007) claim that in qualitative research, it is not only interesting what people say, but also the way they say it. If a complete account of the interview is available, such aspects can more easily be considered in the analysis. For this thesis the recordings were not transcribed word-by-word, but in a summarizing manner. Each interview lasted approximately 45 minutes.

2.3.2 Sampling process

Considering the thesis’s focus on the processes and characteristics of individual companies, the way the investigated companies and their representatives were selected deserves to be highlighted. The type of sampling process affects what generalizations can be done (Bryman & Bell, 2007), and thereby also the importance of the conclusions drawn in the thesis. The sampling process is part of the delimitations in the thesis as this process effectively excludes some of the companies that potentially could be included.

Company selection

The thesis’s focus on Swedish companies involved in nanotechnology set the basic limitation of the population from which the sample could be selected. In this context a “Swedish company” implies a company conducting some amount of research and development in Sweden; sales or marketing activities alone is not sufficient. The company itself may be international or part of an international company group.

A database of such companies was generated during the mapping project and was used as the primary source of company information. The database contains company details such as branch of industry, type of product/service, number of employees, financial data et cetera. Below follows a presentation of the criteria on which companies were chosen.

Prior contact: Priority was given to companies where a personal connection had already been established during the mapping project. Since most companies approached during the project had been willing to share information, they were assumed to be open to the idea of a more thorough interview.

Importance of nanotechnology[3]*:* In the database a distinction is made between companies built around nanotechnology, and companies with nanotechnology as just a part of their business. The sample includes companies of both kinds.

*Industrial sector***:** Given the interdisciplinary character of nanotechnology, companies representing a cross-section of industries were selected for the sample. There was some influence on VINNOVA’s part to include companies of a specific sector.

[3] Just as the importance of nanotechnology varies, so does the degree to which the companies are involved in the different niches of nanotechnology, e.g. nanomaterials. This is discussed further in connection with health and environmental risks.

Spin-off/non spin-off: By including both "regular" companies and those characterized as spin-offs from universities the aim was to catch companies in different stages of maturity, and with stronger or weaker links to the scientific community.

Position in the value chain: The samples include companies belonging to different categories of the LuxResearch[4] value chain model (OECD, 2009):

1. *Producers of raw materials*
2. *Developers of intermediate products with nanoscale features from nanotech raw materials*
3. *Larger companies with nano-enabled end products based on intermediates*
4. *Instrumentation companies*

The purpose of this selection is to cover different types of relationships to customers and suppliers, and companies at different distances from the consumer market.

Size: The size of the company, measured in number of employees, was determined to be an important factor. By including companies with just a few employees as well as larger ones, the idea was to cover different organizational schemes.

Selection of interviewees

The selected companies were approached via e-mail where the purpose of the study was explained along with a request for an interview. If not promptly answered, the e-mail was followed up by telephone contact. In some cases the request was forwarded within the company or contact details to better suited respondents provided. Thus, part of the interviewee selection was done by the companies. Of the 12 companies approached, 10 agreed to be interviewed. The interviewees were typically managers connected to product development, or had knowledge of it in their position as CEO or company founder. In one case the interviewee had explicit connections to the company's environmental department.

The sampling methods used to find suitable companies and interviewees can be classified as non-probability sampling. These have in common that some units in the population are more likely to be selected than others because of human judgment affecting the selection process (Bryman & Bell, 2007). The method with which the companies were selected represents so-called convenience sampling. Bryman and Bell (2007) describe a convenience sample as sample based on its accessibility to the researcher. While simple to employ it also comes with an important drawback; since there is no telling what population the sample represents, the findings are impossible to generalize. Yet so, convenience sampling plays a prominent role, at least in the field of business and management research (Bryman & Bell, 2007). Another method, closely related to convenience sampling, is the so-called snowball sampling. With this method contact is first made with a small group of people considered relevant to the research topic. Then the researcher uses this group is to establish contact with other people (Bryman & Bell, 2007). In this thesis some interviewees were found either via the academic supervisor, through VINNOVA, or through referral within companies; all examples of snowball sampling. The problems with generalizing apply to this method as well.

[4] LuxResearch is a research and advisory firm providing strategic advice and ongoing intelligence for emerging technologies, e.g. nanotechnology.

2.3.3 Secondary data

Information from secondary data is used to form a backdrop for the topic; to present the context in which the thesis belongs and to frame the research question. This information covers the essentials of nanotechnology: its past, present and future developments, including the possible good and bad impact of proliferating applications. While journal articles constitute the absolute majority of the secondary data sources, books, official reports, PhD theses, and newspaper articles have also been used.

With the help of library databases the topic was approached using a number of keywords. Moving from an initially wide spectrum, the keywords were gradually refined to narrow down the amount of literature. The interdisciplinary character of nanotechnology resulted in a variety of sources, ranging from nanoscience/technology focused to those with a primarily environmental or law/ethical approach. Bibliographies and lists of references served as guidance to other relevant literature; occasionally providing a new take on certain issues. Some references were cited more frequently, and those authors and articles were assumed to be important for how the scientific discussion has been shaped.

Bryman and Bell (2007) suggests taking a journal's reputation as measurement of an article's quality; a better known journal supposedly warrants higher quality. This has been applied to the extent the researched journals have been familiar to the author of this thesis. The number of citations is another yardstick that was used from time to time.

Given the relative novelty of nanotechnology as a discipline and the fact that it is in many aspects still a developing area, special attention was paid to what year articles were published. Especially within risk research attention has grown in recent years, resulting in new findings continuously being published. Thus the relevance of older articles was considered, although in many cases it was a matter of new findings giving support to older results.

The preceding mapping project which the thesis author was involved in provided some data that could be characterized as primary data since it involved direct contact with some company representatives. However, for most part it involved secondary data obtained from universities' and companies' web pages and official reports.

2.4 Method critique

In assessing business and management research one usually applies the three criteria of *reliability*, whether the results of the study are repeatable; *replicability*, if it is possible to perform the study over again; and *validity*, the most important criterion and concerned with the integrity of the conclusions (Bryman & Bell, 2007). This section focus on the validity criterion, more specifically external validity, as this relates to what can be said about the study results beyond the immediate research context.

Because of the importance given to the information obtained from interviewing company representatives, the implications of the present and any alternative sample of companies should be scrutinized. As pointed out above, with convenience sampling follows that no generalizing can be done. LeCompte and Goetz (Bryman & Bell, 2007) recognize that external validity general represents a problem in qualitative research because of the tendency to employ case studies and small samples. With a larger sample more, and perhaps different, information could have been obtained, providing more input for analysis. However, due to the sampling method the results would still have been impossible to generalize.

Other choices pertaining to the population could have been made that would possibly have generated a different outcome. For example, by focusing solely on small companies, university spin-offs, or companies within the same branch of industry, one can presumably make a stronger argument for that specific niche. Even so, the premise for the thesis is to review a number of companies representing a wider spectrum of Swedish industry. Time permitting one would research with depth and breadth.

In most cases, only one representative from each company was interviewed, something that naturally must be kept in mind when drawing conclusions from the responses. There is the issue of whether interviewees state personal opinions or those of the company. A certain amount of bias could probably be traced to the respondent's hierarchical position or divisional belonging as well. Bryman and Bell (2007) argue that, while convenient, it is unwise to rely on a single respondent to know everything about the organization. Respondents interviewed in this thesis were approached because of their assumingly relevant knowledge, but could of course still be subject to the type of bias mentioned above. As for including company representatives with an explicitly environmental perspective, such people turned out to be scarce, especially in smaller companies.

Given what types of nanomaterials have been associated with health risks so far, a selection of companies relying on free nanoparticles for their business would perhaps have generated different responses and lead to other conclusions been drawn. However, based on what the Swedish context looks like, with few such companies, the current selection better represents the dominating types of nanotechnology in Sweden today. Either way it is important to remember that the conclusions first and foremost apply to the study at hand.

Method

3 Thesis context

This section serves to place the thesis in a wider context and to frame the subject. It starts out with a brief description of nanotechnology, mainly focusing on the possibilities offered by the technology. It then moves on to present where the science on health and environmental risks linked to nanotechnology stands today. Last, given the thesis's focus on Swedish companies, some characteristics of the Swedish context are presented.

3.1 Fundamentals of nanotechnology

The first part is meant to provide the reader with basic knowledge of nanotechnology as a subject, including important definitions, characteristics, and areas of applications. The intention is to show the width of the topic and the heterogeneity of the different areas that constitute nanotechnology. These are important aspects to be aware of once focus is shifted from the technology as such to the companies building their business fully or in part on nanotechnology.

3.1.1 History and definition

In 1959, theoretical physicist and Nobel laureate-to-be Richard Feynman gave a speech entitled "There is plenty of room at the bottom", saying: "Ultimately – in the great future – we can arrange the atoms the way we want; the very atoms, all the way down!" Even though not using the word himself – "nanotechnology" was first coined by Japanese scientist Taniguchi Nori in 1974 – Feynman is generally considered to be the father of nanotechnology. Two decades would pass before his predictions could be realized in practice. When scanning tunnel microscopy was invented by IBM scientists in 1981, followed by atomic force microscopy in 1986, the instruments needed for atom-level manipulation became available to scientists. From then on nanotechnology was not just for visionaries and it gradually found a larger audience. The launch of "The National Nanoinitiative" in the USA, in 2000, has come to mark the breakthrough of a wider commitment to nanotechnology (Karhi, 2006).

Defining nanotechnology

The prefix "nano-" comes from the Greek word *νᾶνος* (nanos) which means "dwarf". Nano- signifies multiplication with 10^{-9}, i.e. one billionth; thus a nanometer is one billionth of a meter. For comparison, a human hair measures 50, 000 nanometers across while ten hydrogen atoms in a line make up one nanometer. Even though the nano-definition is straightforward, *nanotechnology* is not as easily defined.

The difficulties of giving a precise, unequivocal definition of what nanotechnology really comprises is a recurring observation in much of the topic-related literature (Karhi, 2006). While the examples of usage of nanotechnology as such are abound, the difficulty lies in the diverse range of scientific disciplines and applications that all can be seen as relying on nanoscale phenomena to greater or less extent.

Nanotechnology is often referred to as being a so-called *enabling technology*[5] (OECD, 2009), i.e. a technology that alone or in combination with associated technologies, provides the means to generate giant leaps in performance and capability. In the case of nanotechnology, a technology that

[5] Definition of "enabling technology" from Business Dictionary (2009).
Retrieved December 7, 2009, from http://www.businessdictionary.com/definition/enabling-technology.html

has found its way into most branches of science; from chemistry and physics to biology, engineering and medicine. Further testament of this interdisciplinary nature is given by Porter and Youtie (2009). Researching the Science Citation Index, a database containing information on approximately 6,650 journals in most fields of science, they found papers on nanotechnology published in 151 of the database's 175 listed subject categories during the period of January–July 2008.

Evidently, the areas of nanotechnology application can be found within many fields of science, which in turn is related to the technology's evolutionary background. In a way, the investigation of matter at gradually smaller size scales, eventually down to nanometer level, that has come about through scientific progress within each field is what makes up "nanotechnology" (Royal Society, 2004). The sharing of knowledge, tools, and techniques between researchers of different background is considered by many as a prerequisite for the evolution of nanotechnology (Karhi, 2006).

This network of interconnecting disciplines leads some to question if nanotechnology should be viewed as a technology in its own right. "The term 'nanotechnology' is now commonly used, but the degree to which it describes a new scientific and technological area or merely re-labels existing research agendas, is still debated" (OECD, 2009, p. 18). On the same note, nanoscale as a way to describe component architecture has been an important concept within the semiconductor industry since before the nanotechnology hype caught on. Karhi (2006) mentions the relation between nano- and microtechnology as an example where boundaries are somewhat fuzzy. Although "micro" implies a larger scale than "nano", the concepts are sometimes used interchangeably and nanotechnology is considered by some to also comprise microstructures to a certain extent.

The difficulty in demarcating "nanotechnology-land" notwithstanding, efforts to create a common ground have been made, as suggested by the various definitions proposed in national and international contexts. In the US National Nanoinitiative the following definition is given:

> *Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale.* (OECD, 2009)

In its often cited report of 2004, the Royal Society and Royal Academy of Engineering states:

> *Nanotechnologies are the design, characterisation, production and application of structures, devices and systems by controlling shape and size at nanometre scale.* (Royal Society, 2004)

Different definitions essentially convey the same meaning although there are slight variations in how they stress certain aspects. However, in short it involves purposeful control or manipulation of matter at a scale around 100nm and below in order to enable novel applications (OECD, 2009). This definition largely covers the nanotechnology element of the companies included in the thesis, thus qualifying them as nanotechnology companies. However, in the Risks section the discussion primarily concerns various nanomaterials; a more narrow focus that has greater relevance for some companies than others since they are not all directly involved in nanomaterials. The next section will explain why the scale is important and present methods for control and manipulation.

3.1.2 Nanoscale phenomena and fabrication

In nanotechnology, the small scale itself is just part of the phenomena; the most important aspect is the effects that come with the miniaturization. Those are the effects that do not appear on size levels above the nanometer threshold.

Nanoscale typically implies a size span starting at 100nm going down to atomic level, which is approximately 0.2nm. Within this range, a material can have strikingly different or enhanced properties compared to those exhibited by the same material at a larger size scale (Royal Society, 2004). This change in properties has two main reasons. First, nanoscale materials generally have a large surface area per unit mass ratio. The greater ratio increases the chemical reactivity for a given mass of the material; a useful feature for e.g. catalytic or adsorptive purposes. With a large specific surface area the intermolecular forces supersede forces like gravitation; a phenomenon utilized by e.g. geckos climbing almost any surface with their nanofiber covered feet (KemI, 2007). Second, as the size of a material approaches the nanoscale, the rules of Newtonian physics give way to those of quantum physics. This can radically change significant characteristics such as the material's optical, magnetic, and electrical properties. A trivial, but common, example is the color of nanoscale gold particles that look red, blue or greenish. In conclusion, by controlling the processes that create nanoscale versions of materials it is possible to control the materials' properties (Ratner & Ratner, 2003).

The methods for fabricating nanostructures are commonly divided into two main types that are essentially opposite in their approach to fabrication. In the first one, *top-down*, production starts out with a larger piece of material which is successively reduced, yielding smaller and smaller structures until reaching the nanoscale. Examples of techniques used for this include electron beam lithography, ion beam lithography, and etching. Particularly in the semi-conductor industry, improvements in lithography have played an important role for the continued miniaturization of components. The second type of method is known as *bottom-up*. Here the nanostructures are created by individual atoms or molecules put together like building bricks forming larger structures. Compared to top-down techniques, bottom-up fabrication is still in its infancy (Karhi, 2006; Matsuura, 2006). A third approach to nanofabrication is so called *self-assembly*. The idea is to have atoms or molecules aligning themselves into particular positions and form bonds. Once fully developed, this technique would reduce the amount of necessary work, allowing for larger sets of nanostructures to be formed (Ratner & Ratner, 2006).

3.1.3 Classification of nanomaterials

Given the great number of nanomaterials and their many areas of application, and as preparation before moving on to risks, a structured overview is helpful. Without a frame of reference everything "nano" is easily viewed as a single entity, opening up for sweeping conclusions about a topic that is already complicated; a worry confirmed by companies in the study.

Hansen (2009) has developed a procedure for dividing nanomaterials into subcategories in order to facilitate hazard identification and to focus the risk assessment procedures (see Figure 1). The categorization is based on the location of the nanoscale in the system[6]; in this framework there are

[6] Categorization of nanomaterials is commonly based on the number dimensions in which the material exhibit nanoscale (see e.g. KemI, 2007). In this thesis Hansen's framework is chosen because the categories resemble how nanomaterials appear in products.

three main categories of nanomaterials, and each of these categories can be specified in further detail.

The materials in category 1 are nanostructured in the *bulk*; in **1a** the system consists of only one type of material whereas in **1b** there are two or more types. Category 2, materials that have nanostructure on the *surface*, is divided into three subcategories; **2a** where surface and bulk consist of same material, **2b** are un-patterned films of nanoscale thickness on a substrate of a different material, and **2c** are patterned films on substrates, where the film is either nanoscale in thickness, or the pattern has nanoscale dimensions along the surface.

The last category is made up of materials that contain nanostructured *particles*. In **3a** the nanoparticles are bound to the surface of another solid structure, **3b** contains nanoparticles suspended in a liquid, **3c** is nanoparticles suspended in solids, and **3d** contains airborne nanoparticles.

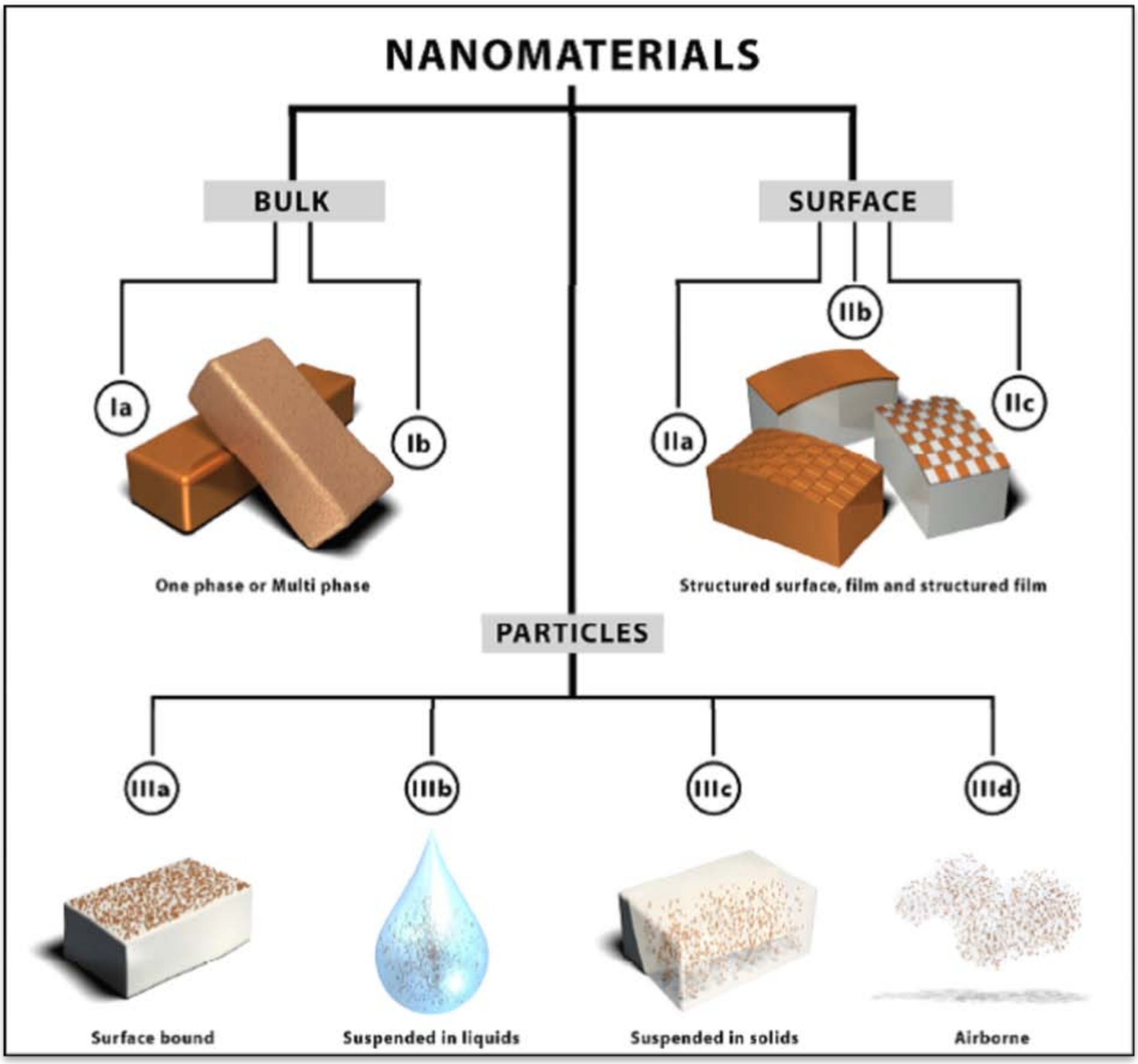

Figure 1 Framework for classification of nanomaterials (Hansen, 2009).

In order to not further complicate a topic like nanotechnology with its many different connotations, a clarification of terminology is in place. First, nanotechnology is more than nanomaterials and companies in this thesis are interviewed about their perception of nanotechnology risks. However, as detailed in the next section, these risks are primarily associated with materials. Thus, in practice most companies comment on their perception of nanomaterials in general and particles in particular. Second, when talking about nanoparticles it is *engineered* particles that are of interest here. Nanoparticles can be created unintentionally, e.g. soot particles from combustion, or exist naturally e.g. in soil (KemI, 2007). However, in this thesis the particles of interest are intentionally manufactured ones. In Hansen's (2009) framework a definition of particles as free structures that are nanosized in at least two dimensions. This includes particles like those listed in Table 1 e.g. fullerenes, nanotubes and nanowires.

3.1.4 Nanotechnology applications and products

Nanotechnology is frequently referred to as the new "General Purpose Technology"[7] of the 21st century with the potential to provide long-term productivity increase and economic growth (OECD, 2009). It is forecasted to impact on $3.1 trillion worth of products in 2015 (LuxResearch, 2009). Proponents of nanotechnology see it as the answer to challenges as grand and varying as provision of clean energy, reducing environmental pollution, curing cancer, and the continued relevance of Moore's Law of computing power (Kulinowski, 2004). These truly disruptive applications of nanotechnology still lie in the future; some within years while others, if ever realized, are decades away.

Even so, nanotechnology has already found its way into people's everyday life, not least through the nanomaterials present in a variety of goods. In the "Nanotechnology Consumer Products Inventory" maintained by the Project on Emerging Nanotechnologies (2009) there are currently 1,015 nanotechnology-based products registered, all available on the market. Examples of products are sporting goods reinforced with carbon nanotubes, anti-bacterial clothes with silver particles, and protective coatings enhanced with titanium- or silicon dioxide. Since there is no labeling of "nanocontent" and product information can be unclear, there are most certainly more products than listed in the inventory. A selection of nanomaterials and their area of application are presented in Table 1.

Type of nanomaterial	Examples of applications
Carbon nanotubes	Reinforcement in other materials, solar cells
Nanowires	Semiconductors, LEDs
Metal oxides	Solar cells, protective coating, sun lotion
Silicon dioxide	Protective coating
Fullerenes	Catalysts, drug delivery
Silver nanoparticles	Anti-bacterial properties in clothes

Table 1 Areas of application for a number of different nanomaterials (Fernholm, et al., 2007; KemI, 2009a)

3.1.5 Key points of nanotechnology and nanomaterials

The key points of nanotechnology to have in mind are as follows:

- Nanotechnology is a complex field owing to its dependency on various scientific disciplines, research/engineering approaches and advanced instrumentation.
- The new phenomena that arise at the nanoscale make the real difference.
- Nanotechnology may play an important role for both traditional industries, and for the growth of new companies and industries.
- There is a wide variety of nanomaterials and applications.

The complexity and wide impact of nanotechnology are contributing factors to the on-going development of knowledge and the differences between companies; two themes further developed in the analysis.

[7] Wikipedia (2009) defines general purpose technologies as "technologies that can affect an entire economy and have the potential to drastically alter societies through their impact on pre-existing economic and social structures". Retrieved December 7, 2009, from http://en.wikipedia.org/wiki/General_purpose_technology

3.2 Risks with nanotechnology

As seen in the previous section, materials at the nanoscale have properties substantially different from those of materials at a larger scale. But with potential benefits also come potential risks; a physical or chemical property useful in one context can be detrimental in another. This section gives a snapshot of current research on nanotechnology-related health and environmental risks. Also, to show the width of nanotechnology's impact, the issue of societal risk is briefly touched upon.

3.2.1 Health and environmental risks

In the previous categorization, nanomaterials appear in a variety of shapes and contexts, circumstances that likely influence what materials have which effects on humans and environment. According to the Royal Society and Royal Academy of Engineering, "Many nanotechnologies pose no new risks to health and almost all the concerns relate to the potential impacts of deliberately manufactured nanoparticles and nanotubes that are free rather than fixed to or within a material" (Royal Society, 2004, p. 8). Thus, according to current knowledge, it seems that there is a limited set of nanomaterials, mainly free particles, which have the potential to cause harm. Furthermore, exposure to this set may be limited as well; in Hansen's (2009) study of consumer goods, most of the nanoparticles present were suspended in liquid, compared to the absolute minority of them being airborne.

Humans can be exposed to nanomaterials in many different situations, also unknowingly. It can be through work, e.g. a scientist handling nanoparticles in a laboratory; or when repairing, dismantling or recycling products containing nanomaterials. For the greater public, chances are that exposure comes via consumer goods, e.g. sun lotion containing titanium dioxide or zinc oxide nanoparticles, or from the environment itself which already contains nanomaterials brought there by air and water emissions from production sites and sewage treatment works. In the future the levels may multiply as nanoparticles could be deliberately released into the environment as a way to treat contaminated water or soil (KemI, 2007).

Possible ways for nanomaterials to enter the human body include inhalation, ingestion, and through the skin. Out of these, inhalation of nanoparticles is considered to be the most important way of entry and a majority of the research efforts have been focused to this area. Nanoparticles have also been proven to possibly cross the blood-brain barrier. The impact from ingestion is likely to be less serious than respiratory exposure, and also less of a concern than dermal (skin) exposure (Clift, 2006; KemI, 2007, 2009b).

The most severe signs of negative impact come from the combination of nanomaterials in the shape of free particles and a respiratory exposure route. Carbon nanotubes are presumably the nanomaterial that has attracted the most attention so far, and is commonly referred to in literature on nanotechnology risks. The negative publicity comes from results of animal studies indicating effects on lung tissue similar to those of asbestos fibers; fibrosis and cancer being the most severe (KemI, 2009b). Other nanomaterials suspected of negative impacts include e.g. metal particles; in early 2009, the Swedish Medical Products Agency banned sun lotions containing nanoparticles of zinc oxide (Kleja, 2009).

Research on potentially negative health and environmental impact of nanotechnology is still a work in progress. Necessary information on nanomaterials to determine the health risks, as well as information on the effects of long-time exposure, is still lacking (KemI, 2009b). This is due both to risk research not having received attention (Kulinowski, 2004) and the difficulties posed by the subject as such. Nanomaterials are essentially “new” materials compared to their macroscopic counterparts. The toolbox of test methods currently used to determine toxicity is not entirely applicable under the new circumstances. This includes, for example, how to characterize physical and chemical properties in nanomaterials, how to trace nanoparticles in the environment and human body, and how to measure level of exposure. Projects within international organizations like the European Union, the International Organization for Standardization (ISO), and OECD aim to adapt current methods to the nano context or, when not possible, develop entirely new ones. It is an ongoing work that will take years to complete. (KemI, 2007, 2009b)

3.2.2 Societal risks

A technology as potentially disruptive as nanotechnology does not only carry risks from a health or environmental perspective, but also has implications in the way it can affect society. First, like for most new technologies, there is the question of who will benefit from the advances and get access to them; on a global level it concerns whether the gap between developed and developing nations will be increased (Kulinowski, 2004; Theodore & Kunz, 2005).

Second, technology that can do good can usually also be used for harm. With nanotechnology allowing for miniscule constructions, there is the issue of protection of personal privacy from e.g. nearly invisible cameras, microphones and tracking devices. Furthermore, nanotechnology may also be used for weaponry which leaves questions of how to handle military nanotechnology research (Mnyusiwalla, et al., 2003).

3.2.3 Key points of nanotechnology risks

The key points of nanotechnology risks to have in mind are as follows:

- Nanomaterials are a heterogenous group – limited set of substances that have shown signs of negative impact.
- Likelihood of exposure to free nanoparticles is small.
- Many uncertainties – about the materials as such, toxicity assessment, level of exposure, and long-term effects.
- Some risks are linked to potential societal impacts.

The first two points in particular are important for understanding the results of the interview study since these points are related to a company’s branch of industry. The uncertainties aspect is an important component for the analysis.

3.3 Swedish context

This section details the current what situation of nanotechnology in academia and industry looks like and the legislative circumstances for nanotechnology in Sweden.

3.3.1 Nanotechnology in academia, industry and society today

Today, nanotechnology-related research is carried out at approximately 20 Swedish universities, but the great majority of both scientists and projects are linked to one of the following universities: Chalmers University of Technology, Linköping University, Lund University, Royal Institute of Technology, or Uppsala University. A number of centers and initiatives built specifically around nanotechnology exist, e.g. the Nanometer Structure Consortium at Lund University, and the Chalmers Nano-Initiative (VINNOVA, 2010).

A look at the industry gives that nanotechnology is utilized in 100+ companies representing more than ten different branches of industry, with most companies sorting under either life science or electronics. Many of the companies are concentrated to the same geographical locations as the most prominent universities (VINNOVA, 2010).

According to research on public perception, the public usually has little or no knowledge about nanotechnology, but they often have a favorable impression of it. Most people consider the benefits to outweigh the risks; it is viewed positively due to its potential applications (Macnaghten, 2008a; Sylvester, et al., 2008). This seems to apply for the Swedish context as well, where the public show no signs of worry (Wallerius, 2009). Compared to the situation in some of the other countries with nanotechnology research and industry, there is not much of a public discussion in Sweden; ”Political and societal debates on nanotechnology are virtually non-existent” (Fogelberg & Sandén, 2008, p. 66).

3.3.2 Legislative situation

Current as well as prospective legislation sets limits to how nanomaterials may be handled and is likely shaping the companies’ perception of nanotechnology risks, and is an influencing factor on their response and proactive work.

REACH, short for **R**egistration, **E**valuation, **A**uthorisation and Restriction of **Ch**emical substances, is a European Community Regulation on chemicals and their safe use that has been in force since 2007 (European Commission, 2009). REACH oblige manufacturers and importers to register all chemical substances produced or imported in quantities exceeding one metric ton per year, with the European Chemicals Agency. Failing to do so, a company is no longer allowed to manufacture or import the substance in question. Registration requires companies to obtain relevant information on their substances and to use that data to manage them safely (European Commission, 2007a).

REACH is built around the so-called *precautionary principle* (European Commission, 2007b). In short it is a “better safe than sorry” attitude when it comes to risks, meaning that something should be proven safe before treated as safe. In practice this translates to a variety of measures. As an example, in its 2004 report on nanotechnology, The Royal Society and Royal Academy of Engineering recommended manufactured nanoparticles to be treated as hazardous and that the release of free nanoparticles into the environment should be avoided (Royal Society, 2004).

In 2008 the European Commission presented a recommendation of a “Code of conduct for responsible nanosciences and nanotechnologies research” (European Commission, 2008) offering principles and guidelines for actions carried out by stakeholders in nanoscience and nanotechnology. The precautionary principle is a salient feature of this code of conduct, as can be seen in this excerpt:

> *“Given the deficit of knowledge of the environmental and health impacts of nano-objects, Member States should apply the precautionary principle in order to protect not only researchers, who will be the first to be in contact with nano-objects, but also professionals, consumers, citizens and the environment in the course of N&N research activities.”*

Proponents of the precautionary principle regard it as a reasonably conservative approach to regulation given the highly uncertain circumstances, but the principle is also the target of critique, not least regarding its perceived effect on technology development. Matsuura (2006) argues that the precautionary principle poses a significant threat to the development of emerging technologies and to overall innovation. Used in the wrong way, all new technology may be harmful, and Matsuura fears that if applied to nanotechnology now, the precautionary principle will result in future regulation delaying commercial use of all emerging technologies. This way society could potentially lose access to beneficial applications of new technology; an optional cost considered too high by Matsuura (2006).

In the case of REACH and nanotechnology, the critique is of a different kind and is related to how regulation accommodates the inherent properties of nanomaterials. REACH does not take into consideration the possibility that a substance may exist in more than one form, e.g. in bulk and on nanoscale (KemI, 2007). This has implications for how the regulation is applied on nanomaterials since these are not viewed as separate substances although their properties may differ from those of the form covered by the regulation. Hassellöv et al. (2009) already see several problems with the new regulation in that it does not take enough consideration of the specific properties displayed on the nanoscale. First, basing the demand of information about a substance on the quantity produce or imported means that many nanomaterials only produced in small quantities are not covered. Furthermore, due to their nature even a small weight of nanoparticles can contain a large number of particles with a large combined surface area. Second, since an adequate and agreed upon terminology to describe many nanoscale properties is still lacking, it is problematic to clearly define substances, which is necessary to evaluate their environmental or health risks. Third, the conventional criteria used to describe how chemicals behave in the environment are largely irrelevant for nanomaterials. In summary, what is needed is new set of nano-adapted descriptors to adequately describe the toxicity and eco-toxicity of nanomaterials (Hassellöv, et al., 2009).

4 Theoretical framework

This section presents the theory that is used to understand and interpret the results, and to perform the subsequent analysis which leads to the conclusions about the research questions. The point of departure and main theme is the duality of uncertainty and knowledge. Given that companies face uncertainties, having or lacking knowledge is thought of as influencing their response. Subsequent sections are concerned with innovation from an external and internal company perspective.

4.1 Uncertainty

Before going deeper into theory, a clarification of concepts is in place. Both *risk* and *uncertainty* have sliding definitions and are sometimes used interchangeably, especially in everyday situations. The simplest explanation gives that uncertainty[8] is the lack of complete certainty, the existence of more than one possibility. Risk on the other hand has more nuances; Hansson (2007)suggests risk to be (1) an *unwanted event* which may or may not occur, (2) the *cause* of an unwanted event which may or may not occur, or (3) the *probability* of an unwanted event which may or may not occur. When talking about health and environmental risks of nanotechnology it is first and foremost the two former meanings that are implied.

Uncertainty then means that the number of outcomes can vary from a few possible ones to a potentially limitless range (Dorf & Byers, 2008). Connecting this to innovation and technology, the degree of uncertainty is not only strongly correlated with how big an advance the innovation represents, but also depends on the state of the underlying science and relevant engineering knowledge (Kline & Rosenberg, 1986). The link to innovation and technology, together with the indications of knowledge "blind spots" in nanotechnology, makes approaching the subject from an uncertainty perspective appear suitable. Thinking in terms of uncertainties is taken as a relevant basis for developing an understanding of companies' perception and actions.

4.1.1 Different types of uncertainty

In their reasoning, Dorf and Byers (2008) primarily view uncertainties from the perspective of entrepreneurship and (new) technology ventures. However, the points made and uncertainties discussed should be valid for business in general, albeit with different degrees of relevance. Furthermore, although debated, nanotechnology and its applications are considered new in many respects, regardless of the type of company commercializing the ideas.

Dorf and Byers (2008) present five sources of uncertainty and their contributing parts. *Market uncertainties* are rooted in e.g. customer behavior and market size; *organization and management uncertainties* concern company specifics such as internal capabilities, financial strength, and strategies; *product and process uncertainties* relate to technology, materials, design et cetera; *regulation and legal uncertainties* such as government regulation, but also industry-specific standards; *financial uncertainties* are cost and availability of capital, and expected return on investment. Grant (2008) also acknowledges the uncertainties faced by emerging industries and points out market uncertainty, in the same sense as Dorf and Byers (2008), and *technological uncertainty* as the two main sources. Here, technological uncertainty relates to the inherent

[8] Definition of "uncertainty" from Merriam-Webster Online Dictionary (2009).
Retrieved December 4, 2009, from http://www.merriam-webster.com/dictionary/uncertainty

unpredictability of technological evolution and the ways industries will evolve; as well as the complex dynamics at play when standards and so called dominant designs emerge (Grant, 2008).

Matsuura (2006) views regulatory uncertainty in a complementary way to that of Dorf and Byers (2008), focusing on two aspects of it. First, there is the scope of regulation. Here, uncertainty concerns whether a particular activity is covered, or in the case of emerging technologies, will be covered by certain legislation. Second, there is uncertainty about the exact regulatory requirements once legislation is applied.

Another division of uncertainty, presented by Johannesson (1998), is between uncertainty related to science and uncertainty related to non-scientific issues. Ethical aspects are given as an example belonging to the latter category. For questions relating to a set of values, experts cannot provide a more definite answer than can laymen or politicians. However, when there are elements of both scientific and non-scientific character involved, a scientist could help draw the line between the two (Johannesson, 1998).

4.1.2 Uncertainties pertaining to nanotechnology

In previous sections it has been established that several aspects of nanotechnology remain uncertain; being a science in development the definitions, analytical methods, areas of application, and attitudes are developing concurrently.

For companies involved in nanotechnology, the main reason for the uncertainties they could potentially face trace back to working with a developing technology. This thesis addresses a particular aspect of nanotechnology; the health and environmental risks. Among the abovementioned uncertainties there are probably several affected by if, how, and to what extent nanomaterials pose a danger to humans and the environment. However, focus will lie on three of them: technological, market, and regulatory uncertainty (see Figure 2).

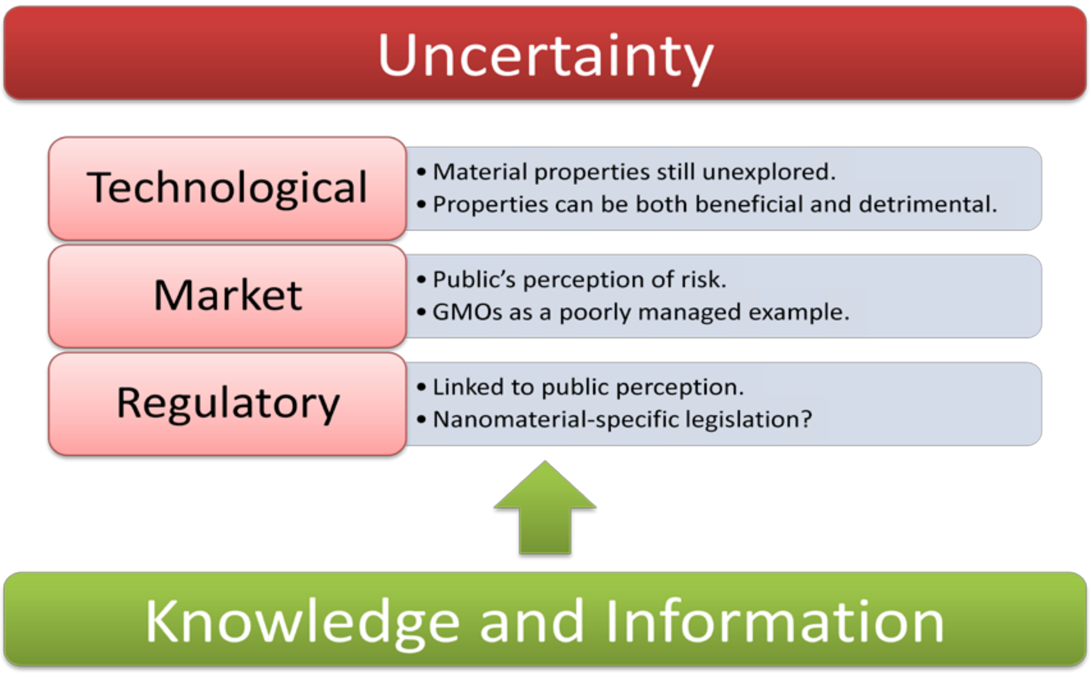

Figure 2 Examples of how health and environmental risks relate to technological, market, and regulatory uncertainty.

There is an uncertainty over the potential areas of use since it is in many ways still an immature technology with future applications to come. The possibility of some of these applications having detrimental side-effects directly related to aspects of the technology itself, constitute a technological uncertainty.

Market actors, e.g. end consumers and companies sensitive to public opinion, may react negatively to the mere possibility of nanotechnology-related hazards. Awaiting more definite answers on health and environmental risks, customers may hesitate to buy nanotechnology enabled products or reject them completely. Thus, in this sense nanotechnology is subject to market uncertainties as well.

Lastly, much of legislation, including industrial standards and regulations, is still not adapted to accommodate nanomaterials specifically; how and when that will be done is another uncertainty companies most manage. The development in legislation and policy, e.g. concerning scope and severity, following publication of research findings, or affected by public opinion, constitute regulatory uncertainties.

4.1.3 Managing uncertainty through information

According to Dorf and Byers (2008) "information is essentially the negative of uncertainty". Thus, by acquiring information and knowledge organizations usually have the possibility to reduce uncertainty (illustrated in Figure 2), improving the chances of adaptation and performance. In the case of emerging technologies uncertainty is implied by the technology's novelty, but the novelty factor also means that uncertainty declines as the "newness" declines over time (Dorf and Byers, 2008). Here, with nanotechnology health and environmental risks as sources of uncertainty, it is knowledge about the very same issues that is thought of as a mitigating factor.

However, according to Johannesson (1998) there can also be a downside to increased knowledge. If new results contradicts or raise questions about earlier assessment, or reveal previously unknown facts that have not been taken into account, uncertainty may actually increase along with the amount of knowledge. The case of genetically modified organisms is a prime example of how knowledge alone is not always enough to manage uncertainties (see Box 1).

The connection between impacts of nanotechnology-related uncertainties on companies and management of uncertainty through knowledge, as displayed through companies' actions, constitute the basis of the Analysis section.

Cautionary tale of the GMOs

Biotechnology, more specifically the sub-topic of GMOs (genetically modified organisms), is a common example in literature of a promising new technology losing credibility in the eyes of the public (Sandler & Kay, 2006). Proponents of genetic modification envisioned sturdier crops and better foods; possibly offering a way to combat world famine. However, the European, and later US, public was averse to what was viewed by many as something "unnatural" and ethically questionable. This influenced governments and lead to regulations on GMO. The EU-wide law on labeling of modified foodstuff introduced in the mid 1990s had severe effects on the possibilities for producers to introduce their products to the European market (Sylvester, et al., 2008).

Even though there is strong scientific evidence that GMOs pose little risk, the global public is still largely anti-GMO (Sylvester et al., 2008). The mere suspicion of negative impact appears to have as an important influence as would real proof of danger. The fear of nanotechnology following the same trajectory, evolving into a worst case scenario of public relations, is a recurring theme (Sylvester, et al., 2008).

While scholars acknowledge the apparent lessons to be learned from the GMO backlash, not everyone agrees it makes for the best comparison to nanotechnology. Branding it as the next GMO has been done rather "lazily" and often the wrong lessons are identified (Einsiedel & Goldenberg, 2004; Wilsdon, 2004). Sandler and Kay (2006) refer to the inherent differences between the technologies that, in their view, leave nanotechnology less exposed to public resistance than GMOs. First, the latter is closely connected to food that, apart from being meant to go into the human body, also is surrounded by social, cultural and religious connotations. Second, there is a "sanctity of life" aspect on genetic modification, an objection to what some people see as "playing God". According to the authors, concerns like these do not apply for technologies already considered artificial, thus rendering most objections to GMOs invalid in the case of nanotechnology.

Box 1 The GMO backlash and the links to nanotechnology.

4.2 Companies' external and internal innovation contexts

Maintaining the link to uncertainty and knowledge, this section first presents theory on the innovation system[9], which is the context in which companies exist, and second a model of the company's innovation process. Lastly, the concept of reflexivity is presented as a way to combine innovation with risk awareness.

4.2.1 The company as a part of the innovation system

The concept of innovation system is a way to illustrate how actors, e.g. the companies in this study and universities; networks, such as standardization networks and university-industry links; and institutions in the shape of culture, norms, and regulation interact and contribute to the development, diffusion, and utilization of new products and processes (Bergek, Jacobsson, Carlsson, et al., 2008). Since it is primarily an analytical tool for illustrating and understanding system dynamics and performance, the system as such does not necessarily exist in reality or can be lacking certain components.

[9] A comprehensive account of the Swedish nanotechnology innovation system is given by Perez and Sandgren (2007). In the thesis at hand, selected functions are related specifically to observations made in the study.

Bergek, Jacobsson, Carlsson et al. (2008) focus on what they call *technological innovation systems*, or TIS. In this version the aspects of development, diffusion, and application mentioned above, concern a particular technology. Nanotechnology, including both the knowledge per se, and the products enabled by it, is an example of such a technology.

A TIS does not start as a complete system but evolves over time. In order to analyze the dynamics of a TIS Bergek, Jacobsson, Carlsson et al. (2008) suggest looking at a number of sub-processes, or functions, that influence the buildup of system structures. While the authors list a total of seven such functions, this section will focus on the three deemed to be of greatest relevance for the uncertainties and knowledge linked to health and environmental risks. First, *knowledge development and diffusion* ties to the fact that nanotechnology still is not a fully researched area. Second, *legitimation* relates to how a new technology is received by actors in the innovation system. Third, *influence on the direction of search* springs from the expectations, knowledge et cetera present in the innovation system. The chosen functions may be partly or wholly induced or hindered by R&D policy (Bergek, Jacobsson, Carlsson, et al., 2008) and are thereby linked to the policy issues that may arise.

Knowledge development and diffusion

This function is central to the TIS and concerns the system's knowledge base, i.e. how wide and deep the knowledge is and how it diffuses and changes over time. Knowledge comes in different types such as scientific, technological, and market knowledge et cetera; and from different sources such as R&D, production, and through learning from new applications (Bergek, Jacobsson, Carlsson, et al., 2008).

Given the relative novelty of nanotechnology with on-going build-up of knowledge concerning both benefits and risks, this function of the TIS is particularly interesting. It relates to what knowledge finds its way to the companies, where it comes from, and how this information helps manage uncertainty. Policy measures can facilitate development and diffusion of knowledge, or promote development in certain areas of the knowledge base.

Legitimation

Legitimacy is a measure of social acceptance and compliance with relevant institutions. For a new technology this implies that the use and development must be considered appropriate and be desired by certain actors. Without legitimacy there will be no mobilization of resources needed, no demand of the technology will form, and the actors of the emerging TIS will not be able to acquire any political strength (Bergek, Jacobsson, & Sandén, 2008). Legitimacy is gained through the process of legitimation, where individuals and organizations try to overcome the competition put up by proponents of existing innovation systems and institutional frameworks. Strategies include manipulating or adapting to existing frameworks, or creating new ones (Bergek, Jacobsson, Carlsson, et al., 2008).

The possibility of public aversion towards nanotechnology could impact on the legitimacy of the technology in terms of social acceptance. As for compliance with institutions, the uncertainty about how to determine risks with e.g. nanomaterials could impact on the regulatory framework and slow down legitimation. Conversely, from the policy perspective it is possible to influence the legitimation process, at least partly, by passing the laws and regulations with which companies must comply.

Influence on the direction of search

This function represents the incentives and pressures needed to convince firms and organizations to enter a developing TIS. It also represents the mechanisms of influence within the TIS concerning e.g. different competing technologies, applications, and business models. The amount of influence exerted is the combined result of: visions, expectations and beliefs in growth potential; actor's perceptions of the relevance of different types and sources of knowledge; actors' assessments of the present and future technological opportunities; and articulation of demand from leading customers (Bergek, Jacobsson, Carlsson, et al., 2008).

The direction of search is closely linked to the legitimation process; legitimacy is important for attracting companies to an innovation system. As seen from the influencing factors there are elements of both knowledge and regulation involved which makes direction of search relevant for the topic of uncertainties and how these are mitigated by companies. While policy is listed as one of the factors in itself it could also be a tool that acts upon the others. Thus, relating companies' situation to the direction of search could reveal policy issues.

4.2.2 A company's innovation process

Investigating how companies respond, following a certain perception, also includes determining when in time that response comes. For this purpose the idea of an innovation process is useful to structure the different activities within a company. Kline and Rosenberg (1986, p. 275) describe the innovation process as "an exercise in the management and reduction of uncertainty". Thus, with the amount of uncertainty pertaining to nanotechnology, the innovation process should be a relevant place to look for impact from the companies' perception of health and environmental risks.

In some cases the company is developing alongside the progressing innovation process. When the business idea is revolving around commercialization of university research for example, the company's existence is linked to a single or a limited number of initial applications. The company is more or less synonymous with its idea. There may be several potential areas of use on the horizon, but in many cases a proof of concept within a specific area is needed as a starting point before branching out. Established companies also need to be innovative in order to stay competitive, but are perhaps not as dependent on one specific technology or product. Below, two different models of how the innovative work is conducted in a company are presented.

Linear model of the innovation process

The linear model is a traditional, simple model of the innovation. This model exists in several variations with different numbers and names of steps; Figure 3 shows one of these models. Kline and Rosenberg (1986) use it as a cautionary example of how not to illustrate the innovation process. The authors' main critique is aimed at the lack of feedback paths within the development processes. They claim this feedback to be essential for performance evaluation, determining how to progress, and assessing one's competitive position.

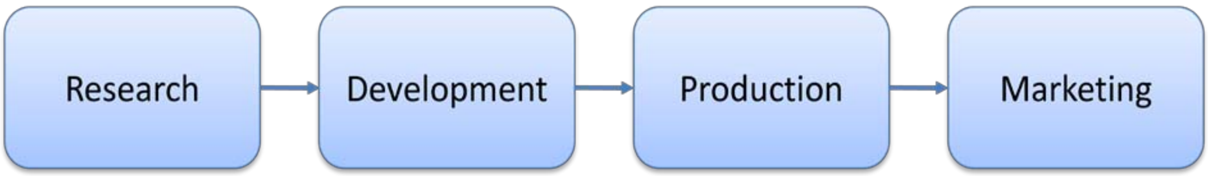

Figure 3 The linear model of the innovation process (Kline & Rosenberg, 1986).

Chain-linked model of the innovation process

Instead of a linear model, Kline and Rosenberg (1986) suggest a "chain-linked model" to describe the connection between research, invention, innovation, and production. Unlike the linear model there is not one, but five paths of activity (see Figure 4).

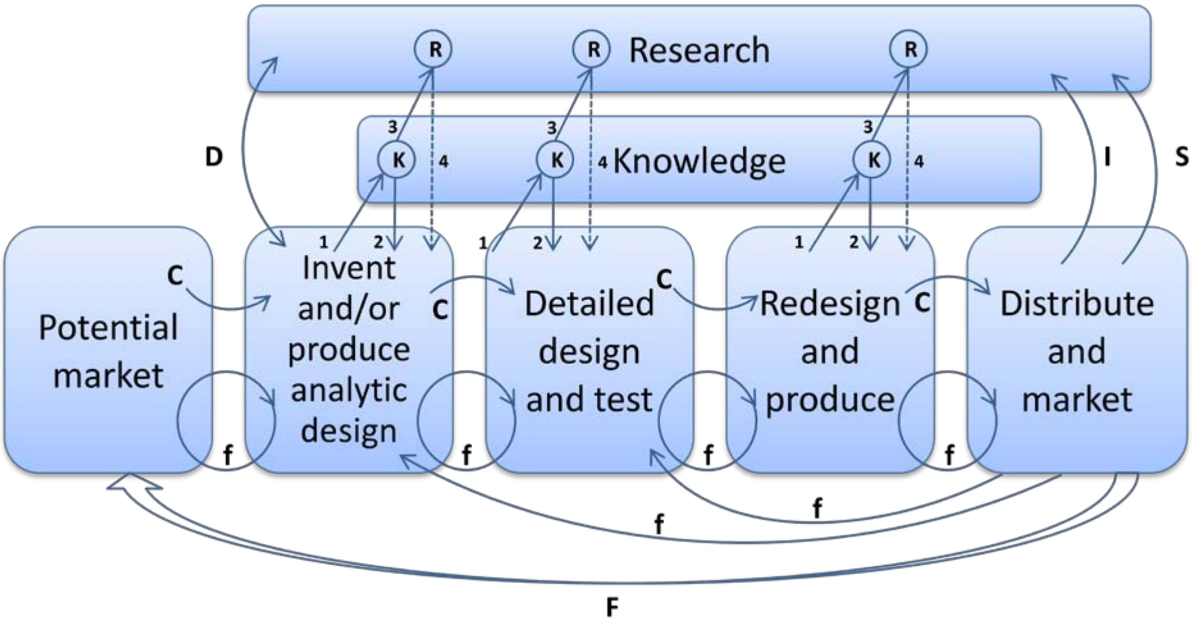

Figure 4 The chain-linked model of the innovation process (Kline & Rosenberg, 1986).

First, there is the central-chain-of-innovation (**C**) that much like a linear model runs continuously through all the steps in consecutive order. Iterating the steps of this first path, the second path is comprised by feedback loops (**f** and **F**, the latter indicating particular importance). This path signifies the importance of feedback as part of the cooperation between the stages of the model. The name of the model is given by the third path, the "chain-link" between the central-chain-of-innovation and research (**D** and **K-R**). Here the linkage from innovation to research, or science, is considered to extend through the whole process, it is not just for the beginning. The authors view the use of science as occurring in two stages. If a problem is not solved by stored science, knowledge, the link to research is activated. However, the return from research is problematic, hence the dashed line in Figure 4. The fourth path (also **D**) represents the rare occurrence of new science enabling radical innovations that can create completely new industries. The fifth and last path (**I**) illustrates the feedback from products of innovation to science, e.g. the scanning tunnel microscopy making nanotechnology possible. The arrow **S** represents support of research in sciences underlying product area to gain information directly and by monitoring outside work.

While not specifically discussing neither nanotechnology nor health and environmental risks of new innovations, Kline and Rosenberg (1986) do relate their model to the uncertainties of the innovation process. "The chain-linked model of innovation shows clearly that there are many points at which the uncertainty of the end product and processes of production and marketing can be reduced" (Kline & Rosenberg, 1986, p. 294). As mentioned above, the presence of feedback loops is an essential feature of the model, so also when it comes to uncertainties: "In short, there is room for reduction of uncertainty at every step and in every feedback link..." (Kline & Rosenberg, 1986, p. 295).

In conclusion, it appears that referring to a model of the innovation process will be useful in analyzing how companies respond, or do not respond, to uncertainty-related issues as it connects the influence of knowledge and research feedback to the innovation activities.

4.2.3 Reflexivity

Sociologist Ulrich Beck (1992) regards innovation itself as the main producer of risk in modern societies. Arguably this applies for nanotechnology as well, considering the expected possibilities of the technology, but also the signs of detrimental effects elaborated on in the risk section above. In VINNOVA's proposal for a nanotechnology strategy the vision expressed speaks of risks becoming an integrated part in the value creation process. Innovation and risk should be closely linked by continuous feedback. The goal is a *reflexive force of innovation*. (VINNOVA, 2010, author's translation).

In a system producing both benefit and risk, Fogelberg and Sandén (2008) recognize there is a need for the actors to handle the duality at a system level. Their suggestion, inspired by sociology and economics of innovation, is a "reflexive system of innovation". Here, reflexivity implies ability for the system of innovation, in this case built around nanotechnology, to "identify needs and avoid risks"(Fogelberg, 2008). Reflexive systems of innovation are presumably preferable to systems characterized by more "closed and linear" processes (Fogelberg, 2008).

Much like the case of innovation process models where Kline and Rosenberg (1986) advocate the presence of feedback loops over a simple linear model, a reflexive system of innovation is also characterized by feedback. In a "traditional", linear model of innovation and risk, results from science are transformed into technology and products by industry, while regulators use scientific findings to develop constraints and guidelines (Fogelberg & Sandén, 2008). By contrast, a reflexive system of innovation is a dynamic system producing innovations, but is at the same time evolving in parallel with the technology that is innovated. In the reflexive system there is what Fogelberg and Sandén (2008) denote as "self-regulating feedback". Effective innovation is paired with a built-in sensitivity; growth is fueled by positive feedback, but it is also guided with the help of anticipatory negative and positive feedback.

Although Fogelberg and Sandén (2008) discuss reflexivity on a system level, the same characteristics can be translated to apply on a company level as well. Thus, given that a reflexive system of innovation is an objective of the nanotechnology strategy, the concept of reflexivity is relevant to have in mind when analyzing how companies perceive and respond to risks. The feedback loops and reduction of uncertainty in every step of the innovation process that Kline and Rosenberg (1986) speak of are examples of how reflexivity could be manifested.

As mentioned in the section on risks, the fraction of nanotechnology research focused on potential environmental, health and social risks is considered inadequate by most scholars. Even so, those issues do receive some attention. Several of the national nanotechnology initiatives adopted throughout Europe and in the US contain elements of research on potential negative effects from technological development (Fogelberg, 2008). National initiatives appear to be an important step forward in dealing with risks and the course of innovation, but the question remains to what extent they will be able to generate reflexive innovation in the case of nanotechnology (Fogelberg & Sandén, 2008).

5 Results from the interview study

The outcome of the interview study represents the core of the thesis since the overall research questions are directly linked to the nanotechnology perceptions held by Swedish companies and the effect this has on their actions. This section is an account of the information provided by company representatives during the interviews, including a thematic structure based on perceived similarities in actions and company characteristics.

5.1 Companies in the study

This section consists of information about the companies given by the respective representatives interviewed. For each company the results are grouped under sub-headings for clarity and easier comparison between companies. Basic company characteristics are presented in Table 2, but some of these divisions are somewhat floating. For example, all the small companies have connections to a university, but some respondents did not classify their companies as spin-offs. Regarding the value chain position, it is difficult to clearly delimit since several companies have a broad business activity. The company size division is based on the number of employees in Sweden.

Company	Spin-off	Size			Lux Value Chain[10]				Industry sector
		0-49	50-249	250+	1	2	3	4	
Alpha	x	x			x	x			Life science
Beta		x			x	x			Life science
Gamma				x	x				Chemicals
Delta				x		x			Chemicals
Epsilon		x						x	Electronics
Zeta	x	x					x		Electronics
Eta	x	x					x		Electronics
Theta				x			x		Automotive
Iota			x		x	x	x		Metalworking
Kappa				x			x		Metalworking

Table 2 Characteristics of companies in the study.

5.1.1 Company Alpha

Alpha is a university spin-off made up of different divisions, all of which regard nanotechnology as essential to them. The company representative interviewed is CEO of the materials development unit with a small number of employees.

Nanotechnology type and application

Alpha is a materials development company and their product is a silicon based nanoporous material with many possible applications. The technology platform is used by customers and subsidiaries in a number of industries, e.g. pharmaceuticals.

Perception of nanotechnology risks

Alpha's representative points out that even though nanotechnology has really come into focus in the last couple of years, nanostructured materials exist naturally and have been around for a long time. There is no concern about the nanomaterials the company is using to today, since they have a

[10] (1) Producers of raw materials
(2) Developers of intermediate products with nanoscale features from nanotech raw materials
(3) Larger companies with nano-enabled end products based on intermediates
(4) Instrumentation companies

nanoporous structure while the constituent particles themselves are micrometer sized. When smaller particles are handled, and there is a possibility of these being released into the air, the work is conducted in special labs. The base material, silica, is classified as a food additive and not subject to any particularly strict legislation.

Concerning other types of nanoparticles, e.g. carbon nanotubes, the respondent claims he “would not be comfortable having them in the lab” (Alpha, 2009, author’s translation). Furthermore, he acknowledges that there are many questions that remain to be answered in the future as science moves towards nanomedicine, even for a material considered to be safe like Alpha’s. In addition, relating to the potential benefits, there is the question of what risks can be motivated without knowing everything beforehand.

Environmental work and its influence on the innovation process
Alpha has access to certain environmental competence through cooperation with one of the research institutes, but the knowledge about potential risks is embedded in the company. Since Alpha has chosen to aim for clients in the pharmaceutical industry the company has been subjected to the industry’s strict regulatory demands and bureaucracy. The choice to start out in a “difficult” branch of industry is something the respondent believes will prove beneficial when the company enters less regulated industries.

The assessment and handling of potential health risks come into the innovation process from the very beginning. Alpha’s representative describes the risk management as “totally integrated” in the innovation process, there is no saying where one process ends and the other begins (Alpha, 2009, author’s translation).

Influence and knowledge from external sources
According to the respondent, Alpha spends a substantial amount of time and money on participation in projects that generate valuable information. Alpha is involved in projects on standardization, and tries to keep up with legislation as it develops.

The company maintains two-way communication with potential customers who give feedback on the “portfolio of materials” that Alpha presents to them. Customers are involved in the development process, especially if there would be toxicity issues.

Regulations and standards concerning the properties of laboratories limit what a small company can manage to fulfill. This is why Alpha choose to remain in a university environment and make use of available facilities.

5.1.2 Company Beta

Beta is a small company with close links to university research, although not defined by the respondents, two of the original founders, as a spin-off company. Its main product is still not on the market, so the company could be characterized as being in a start-up phase. The use of nanotechnology is central to the business.

Nanotechnology type and application

Beta synthesizes a material that exists naturally in the human body and is meant to be used in combination with implants. The material is applied as a thin film on implants in order to increase the bone-implant adhesion. A completely separate use for the material is as coating on sensors.

Perception of nanotechnology risks

Beta considers its product to be generally safe. Nanoparticles of ground bone have been in use for a long time and Beta's synthetic version is bioresorbable, i.e. it can be broken down by the body. Also, in this specific application the nanoparticles are surrounded by liquid and thus are not "free" in the sense of being airborne. There have been no doubts regarding the product's safety expressed from legislative quarters and a similar, competing product has been approved for the US market by the FDA (Food and Drugs Administration).

However, the Beta representatives acknowledge that there is a big difference between their product compared to nanoparticles of e.g. silver, or carbon nanotubes, that may pose greater risks. The respondents are aware of other researchers experimenting with carbon-nanotube coatings for implants, but receiving an approval for that would be "a whole different ball game" (Beta, 2009, author's translation). A statement they consider true for all materials that are not biodegradable.

Moreover, the Beta representatives view public perception as a potentially important factor. "The greatest risk is that people or companies view nanoparticles as a package and that there suddenly would be a warning about the dangers of nanoparticles. In the debate, nanoparticles have been grouped together, both all types of particles as such, and how one comes into contact with them" (Beta, 2009, author's translation).

Environmental work and its influence on innovation process

Among the employees at Beta there is no one assigned to specifically review the risk situation; the material is considered well tested. While demands of testing are not as strict as for pharmaceuticals, a number of pre-clinical trials have been performed; animal studies were first performed about one year into the development process. Although health risks were not the main focus of the studies, issues like tissue reaction were investigated. Tests are performed to verify different stages of the development when questions arise.

Influence and knowledge from external sources

Beta maintains close ties to academia; one of the respondents is an active university researcher and is involved in a bigger project where nanotechnology regulation is one of the topics. The company itself is active in a couple of projects and networks, mostly to get noticed by potential customers.

5.1.3 Company Gamma

Gamma is a company of more than 1000 employees in the chemicals industry. The company is divided into a number of units, but is also part of a larger business group. Nanotechnology is present in some of the units, although not always communicated in external marketing.

Results from the interview study

Nanotechnology type and application
The unit of Gamma in focus for this study manufactures a product based on silica particles dispersed in water. Buyers of the product represent a variety of industries; there are currently applications in areas ranging from surface treatment to food-stuffs.

Perception of nanotechnology risks
The material has been in production since the 1950s, at Gamma since the 1980s. It is not marketed specifically as a nanoparticle and has a "good profile from a risk perspective" (Gamma, 2009, author's translation). As far as the respondent knows there are no documented risks, and the material has never given cause for alert in the studies performed. The respondent is aware of the discussion on effects of carbon nanotubes, but nothing like that has been spotted for Gamma' materials. However, the respondent also says that it can be difficult for Gamma to know what applications the product is eventually used for, as the end product can be several steps away in the value chain.

On the topic of legislation, the company representative fears that if one does not consider that the potential negative effects are material dependent, regulation may err in two directions: "There is a risk that legislation will be unnecessarily strict for harmless products, while giving a "discount" to the more dangerous ones if they are all lumped together" (Gamma, 2009, author's translation).

Environmental work and its influence on innovation process
No individuals have all the necessary environmental competence, but every function needed is represented within the company, according to the respondent. Through its parent company Gamma has access to toxicologists, and the parent company also has a special group focused on life cycle analysis. Locally, at the production site, there is a council that evaluates whether new chemicals may be used in production and risk assessment is performed on chemicals in new product development. As products are scaled up during development, from prototypes to production, a risk assessment is performed with input from technology and production specialists.

Influence and knowledge from external sources
In connection with REACH the respondent asserts that "a great amount of work is done to describe materials and what studies need to be done" (Gamma, 2009, author's translation). Gamma is part of different consortia, some concerning REACH, and it is possible for the company to initiate studies based on what is discussed in relation to REACH.

As for external signals affecting the innovation process, the respondent describes it as interaction between customer demands and the company's ideas for applications. There is a certain amount of coverage on the company's part of what goes on within science and the patenting area.

5.1.4 Company Delta

Delta is a large chemicals company with approximately 20 business units. Until recently there has been a centralized focus on nanotechnology, but that is no longer the case. Instead nanotechnology now appears in different contexts in the decentralized company.

Nanotechnology type and application

The Delta representative interviewed for this study has links to the company's most important business area, coating. Silica-based nanoparticles are used to improve product characteristics, e.g. surface hardness.

Perception of nanotechnology risks

"The main risk is a decline in share value, even if this is sometimes expressed in terms of environmental concern". This is imprinted all the way down to the laboratories; "there must not be a new asbestos situation". Delta uses silica particles and if those would prove dangerous; "industry would be a small problem compared to sandy beaches" (Delta, 2009, author's translation).

"It is important to be clear on how nanoparticles are used, both in production and in products. Free particles are unpleasant and are surely a problem if inhaled" (Delta, 2009, author's translation). There is a company-wide policy to not handle free nanoparticles and it is almost non-occurring. The particles used by Delta must be dispersed to be useful; they are delivered in that state by the suppliers and stay like that all the way to the end customer. "Once the particles are dispersed, the process cannot be reversed to produce free particles again" (Delta, 2009, author's translation).

The respondent believes some people may oppose to nanotechnology just like they may oppose to technological development in general; such a mentality is hard to challenge. "People may be frightened just because it is new, but there are much more hazardous chemicals" (Delta, 2009, author's translation).

Environmental work and its influence on innovation process

Environmental knowledge comes with the people located in each division of the company and there is an intention to have people with nanotechnology risk knowledge in every business unit. Chemicals can be looked up for toxicity in a database and there are toxicology resources as well as animal test laboratories. However, according to the respondent, the influence exerted by the environmental department on the innovation process is weak. "There is a consciousness within R&D to avoid certain chemicals and one knows to look it up" (Delta, 2009, author's translation). The environmental department has no insight into the innovation process.

The respondent believes that there may sometimes exist a will within R&D to show proof of principle regardless of toxicity and cost, but that such attitudes are about to change. "People are pressured to finalize their projects and present a product. Compared to ten years ago, there is less of doing research and then discover it is not sustainable" (Delta, 2009, author's translation).

Even so, the respondent admits that it is somewhat of a gamble, conditions may change during the project. In projects the respondent has personally been involved in, there has sometimes been a deliberately "skeptical" person or group of people working in parallel with the project group, questioning the development work to spot problems, although not specifically environmental risks. There have been "grand initiatives on business group level to renew the R&D process but nothing has been realized yet" (Delta, 2009, author's translation).

Influence and knowledge from external sources

Delta is not actively involved in any projects concerning nanotechnology, but has been discussing the issue with one of the research institutes. Although standards and regulations have been important for other areas; it is less clear within nanotechnology. Most focus is on REACH so if nanoparticles would become a group of their own within that framework, the respondent thinks "work would get under way" (Delta, 2009, author's translation) concerning nanoparticles as well.

5.1.5 Company Epsilon

Epsilon was formed around university research, but the respondent, one of the founders, does not think of it as a true spin-off. Even so, the company maintains a close cooperation with the university. The business idea is essentially a process alternative to photolithography for use in e.g. semiconductor industry. Epsilon is currently in a proof of concept phase and has yet to sell their first products.

Nanotechnology type and application

According to the Epsilon representative there is a fine line between micro- and nanotechnology, but usually microtechnology is used for describing the technology in e.g. computer processors. However, at the same time the so-called half-pitch value of processors, i.e. half the distance between memory cells on a chip, is measured in nanometers. "The microelectronics industry is driven by nanoscale innovations. It is all nanotechnology in a sense, but then there are specific applications like nanomaterials, and that is not really what we do" (Epsilon, 2009, author's translation).

Perception of nanotechnology risks

The respondent points to the fact that the type of nanotechnology found in electronics components has been well known for quite some time; transistors have been manufactured since the 1960s. The technology started on a large scale and has then shrunk successively, the aim being to reduce the line width on chips in order to cram more function into less space. Thus, it is not about manufacturing new materials, an area admittedly much less understood. Taken together this means that for Epsilon, the fact that it is nanotechnology does not constitute any environmental risk in itself. Instead, the respondent claims that risks are mainly financial due to big investments and long developing times.

Environmental work and its influence on innovation process

At Epsilon there is no one appointed as responsible for handling environmental concerns, and nobody is specifically in charge of monitoring the regulatory demands. The university laboratory the company uses has certain regulations concerning what chemicals can be brought in, and the laboratory monitors emissions et cetera. The electronics industry has had to adapt its processes to certain environmental regulations, e.g. lead is no longer allowed in solder. The possibility of such changes should be kept in mind says the respondent. Customers specify what materials they allow so adaption is necessary.

The Epsilon representative argues that for a company in an early stage of development, there is no point in focusing on environmental risks because it is barely a company yet. If neglecting the risks stops the company from entering the market, then it should be considered when the company is about to take that step. Before that there are other concerns. "When you first of all have to show proof of concept you probably do not worry about other demands" (Epsilon, 2009, author's translation).

Influence and knowledge from external sources

Standards are important in the semiconductor industry. Potential customer companies jointly establish so called technology road maps, detailing e.g. what size scale of components is going to be used. Epsilon has taken part, and plans to take part, in a couple of EU-projects on development of components.

5.1.6 Company Zeta

Zeta is a university spin-off started in 2005, currently employing nine people. The company is active in the field of power electronics components, but is still in the process of establishing a product on the market.

Nanotechnology type and application

Zeta does not make use of nanotechnology per se. The respondent explains that some process equipment is the same as when working with nanotechnology, but in Zeta's case the smallest dimensions are 500nm. However, occasionally the scale is somewhat smaller, e.g. the patterns for photolithography that must be adjusted to each other within a 100-200nm margin.

Perception of nanotechnology risks

Given the type of business Zeta is active in, the company is not concerned with any risks related to nanotechnology. The respondent claims that neither the substrate material nor the substances used for doping are harmful.

Environmental work and its influence on innovation process

Most of the environmentally-related issues have to do with the manufacturing process and work environment; some steps of the process require acids or gasses that could pose a health risk. Such matters are regulated in the guidelines of the laboratory where manufacturing is conducted. As for the actual products, customers often know what materials are allowed to be used and can specify this when dealing with Zeta. According to the respondent, the person within Zeta who is product responsible also has the environmental responsibility, but other aspects of the product, e.g. reliability are more important.

Influence and knowledge from external sources

Zeta cooperates with university scientists and with one of the research institutes. The respondent claims that the institute's laboratory is a prerequisite for the company's business. A close cooperation with potential customers is also considered important; in Zeta's case this means specifically targeting parts of the heavy vehicle industry.

5.1.7 Company Eta

The interviewee is CEO for Eta, a company formed a few years ago when research results from a university laboratory were turned into business. Today ETA employs 16 people and is still very much a development company providing consultancy work. The aim however, is to move towards a product oriented business, but it will be a few years. The company is active within the field of small scale electronics and sensors; customers are primarily found in the space and military industry.

Nanotechnology type and application

According to the respondent Eta has no connection to the nanotechnology associated with "carbon fibers and strange molecules" (Eta, 2009, author's translation). The electronic components may include nanoscale elements and the coatings applied by Eta are in the micro-nanometer range. However, nanotechnology is not a salient element in the company's business says the respondent.

Perception of nanotechnology risks

Due to the type of products Eta is involved with, there are no environmental concerns like those sometimes voiced in relation to free particles. In the production process on the other hand, some hazardous chemicals are used.

Environmental work and its influence on innovation process

At Eta one person works internally with work environment-related issues, e.g. the handling of chemicals which is partly regulated by the university laboratory where some of the work is carried out. The rules are clear to follow and it has not affected the production processes, according to the respondent.

The external environment does not receive any special attention and, according to the respondent, the work of building up risk-related knowledge is not very intense either. "It comes down to that there are no obvious risks connected to the finished product" (Eta, 2009, author's translation). So far there have been no demands or requests concerning environmental issues put forward by customers. The respondent speculates that this perhaps will change as the company expands and approaches other branches of industry.

At the moment Eta is not prepared for how to handle issues related to the end-of-life stage of their products, such as waste management and recycling. There is also no worrying about it; "We cannot afford thinking about that now. All our resources are put into development" (Eta, 2009, author's translation). As long as there is no customer demanding the company to take certain environmental aspects into concern, Eta will not engage in that.

Influence and knowledge from external sources

Standards are not that comprehensive within the space industry. Occasionally Eta could influence how standards are shaped but usually standards are dictated among a group of considerably larger companies where Eta has no saying. However, Eta tries to cover all standards and they are not perceived as having any detrimental effects.

As for influence on the company's R&D processes, research is still connected to the university, e.g. through a PhD student financed by VINNOVA. The influence exerted by the customer side has so far been very limited.

5.1.8 Company Theta

Theta is part of a larger company group and serves as both a consultant to other units of the group, and as a research company focusing on applications 10-20 years away. Hence, much of the work performed by Theta still has a long way to go before being commercialized, and nanotechnology often represents only a small part of the technologies involved.

Nanotechnology type and application

While Theta does not manufacture nanomaterials themselves, both surfaces and particles with nanoscale dependent properties are used in the components of the products they research, such as fuel cells and thermoelectric materials.

Perception of nanotechnology risks

Traditionally the nanoparticles of greatest concern have been the non-engineered ones created during combustion. As for the nanoporous surfaces in e.g. fuel cells the company representative says: "That surface will never come in contact with humans or the environment. Once worn out the whole component will be recycled, and the idea of any particles being released and inhaled by humans is incredibly far-fetched" (Theta, 2009, author's translation).

Concerning the company's relations to other actors in the value chain, the respondent acknowledges that since the nanotechnology components are not manufactured by Theta, suppliers are the ones who deal with everyday concerns about work environment. Also, in the other direction, a certain amount of responsibility is put on the end user to not "fiddle with the product" (Theta, 2009, author's translation).

While it has not been an issue with any nanomaterials yet, other materials, e.g. specific metals, have been subject to "political storms" of the kind where there is a temporary ban, and "things are blown out of proportion by someone who does not understand"(Theta, 2009, author's translation).

Environmental work and its influence on innovation process

At Theta, "There is a lot of focus on safety" (Theta, 2009, author's translation). There are lists of what materials may be used in products; lists based on standards developed for the whole business group, and in each laboratory there is a person responsible for the environmental issues related to the laboratory. According to the respondent, Theta does not perform a great deal of risk analysis; instead their task is to provide the client with options to choose from. A product solution is presented and is then evaluated as it moves through the other units of the business group. Risks are assessed at each level, with increasingly stricter demands as the product gets closer to the end user.

Some problems that may afflict the product are related to ageing and will not appear for years; by then the product has moved on from Theta. "We cannot do everything from start to finish, then we would never get done" (Theta, 2009, author's translation). Even so, there is a consciousness within the innovation process. "Anyone who has followed an idea to the end knows it cannot be too extreme. There is an instinct of self-preservation; you do not want your project to be rejected" (Theta, 2009, author's translation).

The respondent believes there is a reason the relationship between innovation process and risk assessment efforts looks the way it does. "It has been done so many times. If the day comes when it does not work anymore, it will change" (Theta, 2009, author's translation).

Influence and knowledge from external sources

Being a research company, Theta takes part in projects together with other companies and university researchers. Some of these projects, e.g. major EU projects, may have an element of risk, although not necessarily linked to nanotechnology risks. Theta does not discuss in terms of "nano" with its suppliers, but take part in the development and can confirm the function of e.g. a certain structure.

5.1.9 Company Iota

Iota is a company in the tooling industry and part of a larger business group. The company serves customers of all sizes worldwide.

Nanotechnology type and application

At Iota, materials play a major role for the products; nanotechnology is represented as structures in bulk materials and as thin surfaces. According to the respondent, production on the nanoscale is not new for the company, but it was not until the analyzing technology had developed sufficiently that it was possible to actually view the structures and the "nano" became relevant to describe them. "One has to go down to that level in order to understand what has been created" (Iota, 2009, author's translation). Before, research and development could generate beneficial material properties but the underlying structure was not fully understood.

Perception of nanotechnology risks

Since the nanostructures are integrated in bulk materials they are not considered a risk factor. Also, the thin surfaces withstand extreme force and will not be simply scraped off the material they are part of. However, there are steps in the manufacturing process that involves nanosized particles that need to be watched.

Potential environmental risks sometimes appear to receive more attention than the possibilities. Especially in connection to project applications there is a sense that thorough investigations of potential risks are demanded and including the word "nano" in project suggestions complicates matters. The respondent acknowledges that free nanoparticles deserve a "warning label", but there is a tendency to group all materials together; the differences sometimes are lost in the discussion. "The risk of nanomaterials may lie in calling it nanomaterials" (Iota, 2009, author's translation). However, as far as the respondent knows, there is no company yet that has been drawing negative attention due to inadequate routines for nanomaterial handling.

Environmental work and its influence on innovation process

At Iota there is an environmental department that performs risk assessments of chemicals used in production. According to the respondent the routines for handling chemicals are well established, but she adds that a working process alone is no guarantee for safety; for some materials, e.g. nanomaterials, risks may not have been thoroughly identified yet.

In every development project an environmental analysis in conducted, not only concerning what ends up in the product but also for the manufacturing process as well as concerning scrapping and recycling of the product. The project leader has the formal responsibility and it is not stated that the environmental department must be involved. However, this is usually the case to make sure the risk analysis is performed in a correct way. Furthermore, there are audits to ensure the quality of the process.

The respondent claims that projects aiming at introducing new products are preceded by a substantial amount of investigative work. The company works with technology platforms from which new products branch out; new projects are not launched until a sufficient knowledge base has been built up. This way projects have a higher success rate at the time of market introduction (Iota, 2009).

Influence and knowledge from external sources

Concerning nanomaterials and their possible dangers, the company relies on readily available information to a great extent. Identification of risks with nanotechnology is not a major focus of the business; it is hard to have knowledge beyond what is stated in guidelines from authorities, says the respondent.

The respondent is unsure of whether Iota has been part of any projects specifically targeting nanotechnology. In general the company does not take part in that many projects, something the respondent attributes to the company’s characteristic of a subcontractor. Instead most project participation comes as an effect of customers participating.

Previously, insights about the hazards of other chemicals have come gradually and it cannot be ruled out that similar insights will be reached about certain nanomaterials. The important thing is to have procedures in place to detect it, concludes the respondent.

5.1.10 Company Kappa

Kappa is one of the divisions within a larger business group in the metal working industry. The division is focused on thin sheet metal. Two respondents contribute with information, one of whom is responsible for product development and the other representing the chemicals group laboratory.

Nanotechnology type and application

While not currently used in any products, nanoparticles have been evaluated on a research stage as one of several possible means to improve the properties of the coating applied to the thin sheet, primarily in regards to its hardness. The coating is not produced by the company itself and the idea of using nanoparticles was presented as an alternative by suppliers. Even though there are currently no plans to implement nanotechnology, it may very well be a future trajectory according to the respondent.

Perception of nanotechnology risks

Kappa’s representative does not mention any risks in particular. He refers to the in-house chemicals group reviewing all new chemicals used in production, and the dialogue maintained with suppliers. As for free particles, a potential danger during handling, the coating (paint) is already prepared when delivered to Kappa. Thus, the risk of free particles escaping into the air is mainly of concern to the suppliers.

Results from the interview study

Environmental work and its influence on innovation process

According to the respondent, suppliers are responsible for much of the work aimed at reducing risks. Kappa assumes that suppliers handle environmental aspects seriously and that they have done their own assessment before recommending a certain product.

Internally, there is a chemicals group that analyses and assesses any new chemicals brought into the production, mainly based on safety data sheets. The group consists of laboratory personnel and people from the environmental department. According to the chemicals group representative, chemicals are assessed regarding their impact on both work environment and external environment. "One has to be somewhat foresighted with regards to where the product will be used" (Kappa, 2009, author's translation).

The work performed in the chemicals group is reliant on people from R&D reporting any new chemicals they want to use, even if it is just in a laboratory environment. In most cases this is done, but not always. However, no projects move on to production without approval from the chemicals group, so there is hardly any point in starting up only to be rejected by the chemicals group afterwards.

According to the respondent, people within product development have a pretty good sense of what chemicals may be used. They sometimes interact with the environmental department during development, but there is no structured cooperation.

Influence and knowledge from external sources

Kappa is involved in EU managed development projects, but nothing specifically geared towards nanotechnology. In connection to REACH the company is currently reviewing what chemicals are being used, and if these chemicals are registered for the area of use in question.

Customers, universities, and research institutes are all possible participants in Kappa's innovation process. The company's main market, construction, is heavily controlled through certificates and standards, so there is no room for sudden changes in products. Kappa takes part in these standardization processes, but it is, in the respondent's words, "slow work filled with politics" (Kappa, 2009, author's translation).

5.2 Observations in the results

This part of the Results section structures some of the observed similarities in the perception and action taken, and company characteristics.

5.2.1 Similarities in responses

Reviewing the answers given by the respondents, some similarities begin to show concerning attitudes and actions. Some of these tendencies are quite easily discernible, while other observations are more sporadic.

Our nanotechnology is safe

Perhaps the most obvious pattern, one exhibited to some extent by all respondents, concerns the companies' attitudes towards potential risks of nanotechnology in general and what relevance these risks carry for the business of each company.

The respondents acknowledge that there are areas within nanotechnology that could present cause for worry; free nanoparticles, especially carbon nanotubes, are the most commonly cited example. Some respondents refer to the alleged likeness to asbestos or just the potential danger of inhaling any particles. However, when focus is shifted to the particular application of nanotechnology within each company, respondents make sure to emphasize the few or non-existing safety issues of that niche. The attitude can be summarized as "There may be risks with nanotechnology, but our nano is safe".

Excluding the companies where nanotechnology is not a central aspect or not connected to particles or materials at all, arguments as to why it is safe mostly revolve around what kind of material is used and its properties. The reasoning follows two paths. First, respondents point to the fact that the material has been used historically with no indications of detrimental effects, and/or that the material resembles a naturally existing substance. This applies for e.g. silicon which is used in different variants by some of the companies. Second, the state and context in which nanoparticles are present plays an important role for how the risks are perceived. Examples given by respondents include the fact that particles are dispersed, thus not "free" and possible to inhale, or that particles are part of a matrix or structured surface from which they will not break loose.

Involvement of upstream and downstream actors

In relation to how companies determine their products to be safe, there are some tendencies of involving other actors, both from upstream and downstream the value chain, and consider them as partly accountable for the safety of the product.

Among the companies that use nanomaterials in their products but do not produce the particles or materials themselves, some express their trust in that suppliers make sure to provide a safe product. The supplier is assumed to have done the necessary testing and evaluation. Also, when products come from the supplier they are delivered in a safe state, e.g. free particles have been dispersed, so any work environment-related risks are mostly of the supplier's concern. This goes for product safety in general and is not limited to nanomaterials.

Even though a product is considered completely safe when leaving the company, the receiving customer may use it in contexts or applications that are difficult to foresee and take account of. For a company manufacturing nanoscale raw materials the product may pass through a number of actors before reaching the end application. Thus, accountability for how nanomaterials and particles are handled and where they end up is to some extent put on actors of the later stages in the value chain.

It is also mentioned that demands put forward by customers sometimes influence the selling company's products, e.g. through specifications of what materials may be used. A customer's explicit demands of certain considerations could be the only incentive for a company to take any measures at all; without the demands no measures taken.

Indications of reflexivity

Judging from how most respondents describe the relationship, interaction in the shape of formalized and recurring input from any environmental department or risk assessment processes to the innovation process is rare. At the same time there is confidence in the way work is currently done and in the ability of R&D people to take environmental aspects into consideration and make the correct judgments on their own.

In those companies where there is an environmental department to consult with, interaction with the more R&D-related processes seems to take place in connection to specific occasions. One typical example is to get approval for new chemicals or materials when these are brought into the research laboratory or production process.

Answers given by the respondents indicate that people in R&D have a feeling of what chemicals may be questionable and in need of additional investigation. Furthermore, there is also a need for R&D departments to complete their projects. There is no point in trying to circumvent initial approval just to find out later that the project cannot be allowed to continue. It is equally futile to push projects forward that will not translate into viable products due to safety issues. However, there are instances where research is solely focused on presenting a proof of concept.

Knowledge exchange in projects

Although topics and scope vary with companies and their line of business, it is not uncommon for companies to come together with other actors in a project context. Looking at the answers given by respondents, the reasons for project participation are almost as many as there are companies. Companies use projects as a mean of acquiring new knowledge about e.g. new regulations; taking development forward by seeking input from potential customers; or giving input on a certain matter such as the establishment of new industry standards, sometimes with prospects of influencing the final outcome. Among the projects mentioned in interviews few are related to nanotechnology, but those that are seem to include the risks of nanotechnology as a part of their topic.

Public perception

On the topic of the public's relationship to nanotechnology, two issues are touched upon by some of the respondents. While no company in the study expresses it has suffered from the public sentiment, the tendency seems to be a slight worry this could change. First, the general aversion towards any new technology presumably harbored by parts of the public could also afflict nanotechnology. Second, ignorance and misconceptions about nanotechnology, e.g. not separating different areas of applications or associating all nanoparticles with carbon nanotubes, could have implications on both public and the regulatory response.

However, there is no mentioning of engaging in public dialogues or of any particular measures taken by the companies to counter unwanted developments, e.g. a perception of all nanotechnology as a homogenous phenomenon.

5.2.2 Similaritites related to company characteristics

This section is an effort to establish the presence of patterns pertaining to company characteristics. Similarities may tend to be expected and not very surprising; small start-up companies rarely operate in the same manner as divisions of global business groups for example, but nonetheless there is a point in clarifying these patterns, not least in consideration of the conclusions to be drawn.

Size related properties

The size and characteristics of a company have a two-way relationship; size seems to be both an explanatory cause of some company properties and the resulting effect of some others. In this study, company size can be related to the resources available for environmental risk assessment, the maturity of the company, and its relationship to academia.

First, what seems to be a result of size is that none of the companies classified as “small”, i.e. less than 50 employees, in the study have a separate environmental department. However, there are examples of individuals appointed with product responsibility or to look after the work environment. Second, the small companies in the study, all with connections to academia, maintain close ties to one or more universities and also to the research institutes in some cases. The majority of these companies’ development and business are largely dependent on the opportunity to utilize the resources and facilities, like laboratories and clean-rooms, provided by those actors.

Then there are some company characteristics that represent causes rather than results of company size. Companies in a start-up phase, regarding how far along development of the company’s product has advanced, and the expected time left to market introduction, are all founded relatively recently and are consequently still small companies. Given that the start-ups are originally university spin-offs or at least companies closely linked to university research that has been commercialized, there is a link between company background and current size.

Industry-related properties

Companies belonging to different branches of industry employ different areas of nanotechnology in their business and for completely different applications. Thus it can also be expected of them to have different views on other nanotechnology-related matters as well.

For the companies involved in life science or in the chemical industry, nanotechnology is present in the shape that it is most often associated with. The companies utilize particles, structures and other materials, where the small scale permits properties that constitute the core for the companies’ products.

In the companies focusing on electronic components nanotechnology, the role of nanotechnology is different, if acknowledged as a constituent part of the business at all. There are no particles or surfaces here, instead nanotechnology is represented by measurements to signal product performance, and potentially in methods used in the manufacturing processes.

While there is a tendency among companies to regard their respective application of nanotechnology as safe, the industrial background and prospective market for each company entail certain differences in what type and amount of testing products are subjected to. For example, products that will ultimately end up in the human body also seem to get tested for what health impact might come with such application. In the study there are two examples of such products; in the first case the testing is done in response to demands of the target market, in the second case testing for negative impact is a “side effect” when researching other effects in the interaction between product and body.

Having identified the commonalities between companies in their attitude towards nanotechnology risks, and the impact on their business, the succeeding section will apply the analytical framework to these findings.

6 Analysis

The purpose of the Analysis section is to apply relevant theory in an effort to offer explanations to the results presented in the previous section. Given the way companies reason about nanotechnology risks, focus for the analysis shifts somewhat from dealing only with companies' responses, to explaining the reasons behind the perception as well.

The analysis returns to the theory of technological, market, and regulatory uncertainties and carries on the idea of how these may be resolved through information and knowledge. The observations from the Results section are viewed in terms of uncertainties in an effort to explain the impact that uncertainties have on companies. Then the knowledge side is applied to understand the companies' actions. The second part of analysis deals with how the TIS functions relate to the observations, and what the related policy issues can be.

6.1 Uncertainty and knowledge perspective on observations

The analysis first focuses on what appears to be most well-founded observation, the one concerning the companies' perception of risks with nanotechnology. It then moves on to reflexivity and investigates the indications that can be found on a company level. For the last part, public perception is highlighted since this is the only real risk issue expressed by companies.

6.1.1 Perception of nanotechnology risks

As stated in the results section, the most common observation is the strong belief expressed by respondents in the safety of the own company's particular use of nanotechnology. Below, some of the other attitudes and activities observed are offered as support and explanation to this concordance.

As far technological uncertainties regarding health and environmental risks are concerned, companies do not seem to be troubled. Looking at the current knowledge base of the innovation system in which the studied companies operate, their attitude towards nanotechnology risks is understandable. So far, the materials in question have not been shown to pose any danger and therefore do not cause the companies to worry; a noteworthy exception is the policy regarding free nanoparticles at Delta. Relating to Hansen's (2009) classification, nanomaterials in this study come from all the three main groups: bulk, surface, and particles. As for the nanoparticles, in this study there are no examples of companies using particles in an airborne state.

Reliance on knowledge at hand

The indications of negative impact on human health and the environment that do exist come from research focused on a limited set of substances (Lubick, 2008). Carbon nanotubes and the infamous link to asbestos are somewhat of a poster child for the dangers of nanotechnology. Along with metal oxides and a few others they have received the most prominent attention. As the interviews show, these dangers are indeed acknowledged by several respondents, most referencing to carbon nanotubes, so there is no denial of potential risks within some applications of nanotechnology. However, the respondents make sure to distinguish these nanomaterials from those that their respective company uses.

As seen in the interviews, companies support the safety claims by referring to the substance in use as being natural, e.g. the link between silicon and sand, or by pointing to the product's track record. If the substance has been in use for a longer period of time, perhaps decades, without any indications of harmful effects, companies reason it will stay that way. This can be compared to the duality of new and old in nanotechnology, as discussed in the report from OECD (2009). While applications in many cases may be new, much of nanotechnology traces back to products that have been in use for quite some time.

In addition to using a reliable substance, at least two of the companies have tests, even tests on animals, to back their claims of a safe product. Thus, the companies cannot be accused of taking a chance; the odds are stacked in their favor for most materials. However, as the knowledge base expands with new methods of evaluating nanomaterials and a wider focus of risk research, some claims may have to be revaluated. It would not be the first time for a transition from safe to harmful.

Kline and Rosenberg (1986) distinguish between knowledge and research, where the link from the innovation process to research is not activated unless the available knowledge is proven to be insufficient. This is also a valid description of how companies' view nanotechnology risks. A company's attitude is based on the knowledge at hand, information above and beyond that must come from further research. However, companies in general do not conduct much risk research themselves (e.g. Iota); instead they rely on the findings produced by academic research and knowledge embodied in data sheets, routines, and experience.

The question is when knowledge is insufficient and must be supplemented with more research. If the potential hazards of a particular substance have not been researched at all, then there probably is insufficient knowledge. It is more complicated when current knowledge already has determined a substance to be safe; there is presumably a lack of incentives to further investigate "sufficiently" researched areas.

Sharing the responsibility in the value chain

By leaving some product responsibility to other actors, as expressed in interviews (e.g. Gamma, Theta), a company also leaves them with resolving of some of the uncertainty, which in turn probably affects the perception of risk. The immediate concern of potential risks is transferred to other actors. This is the case not just for nanotechnology, it goes for product safety in general.

A majority of the companies in the study occupy such positions of the value chain that they depend on actors both upstream and downstream for their business. Upstream actors can be suppliers of nano "raw material" or intermediate products, while downstream there are customers, although not end users, that integrate the company's products with their own, further refining and adding value.

In their model, Kline and Rosenberg (1986) stress the importance of iterative feedback loops in the innovation process; it is part of the cooperation between the product specification, production processes, and marketing. These feedback loops connect sub-sequent steps in the innovation process, but also activities further apart. This model can be expanded by letting upstream and downstream actors represent the activities.

Companies can be seen as not only having an internal innovation process to manage, but also as playing a part in what could be likened to a high-level innovation process, represented by the nanomaterials' flow through the value chain. In this process there is research on new materials conducted in one end and final applications marketed in the other, but activities are split on different companies.

While not a perfect model, this wider interpretation of the innovation process still works as a metaphor that might be useful in explaining the companies' tendency to assign some of the accountability to others. If not in control of the whole process, a company has little choice but to rely on the safety of their suppliers' products and leave some responsibility to customers. Relating to the relationship between knowledge and research in Kline and Rosenberg's (1986) model, one can view involving other actors as a way to negotiate uncertainties by making use of other parties' knowledge instead of researching everything oneself.

Reliance on customers is supported by Pandza and Holt (2007), whose findings show that enthusiastic lead customers can be important for a company since these customers can bear some of the uncertainty that comes with nanotechnology products.

Influence of company characteristics

Both the perception of nanotechnology risks and how companies choose to act upon those notions are in part dependent on the size and maturity of the company, as well as the branch of industry in which a company operates.

Two of the companies still in the start-up phase, Epsilon and Eta, reason it is too early to worry about the health and environmental consequences of a product before the product is actually ready for the market. Their reasoning is understandable, customers may eventually ask for certain considerations and specifications to minimize negative impact, but without a proof of concept to start with potential customers will not ask for the product in the first place.

This perception of technological uncertainties, as having more to do with proving the functionality of a technology than clarifying environmental consequences, is probably common in growing companies. It is also most likely a reflection of the fact small companies usually are closely tied to a specific application of technology. In an early phase the knowledge base and the research to expand it are very specialized and geared towards taking an idea all the way to a working concept. This is not to say that hazardous applications flourish in start-up companies, but it serves as part of the explanation to the lack of functions dedicated to environmental issues within these companies.

Belonging to a certain industry reinforces certain sides of uncertainties and the impact they have, which in turn entails demands for certain knowledge. When it comes to health and environmental risks, these are simply more of an issue within some industries. As in life science for example, even if the material is perceived as safe, Alpha's representative acknowledges that testing procedures for a substance that will be used with pharmaceuticals are extensive.

Project participation

Judging from what type of projects companies claim to take part in, they do so to mitigate all three kinds of uncertainties mentioned in the thesis. However, with the exception of projects related to the REACH legislation, indicating at least some connection to nanotechnology risks, aspects linked to health and environmental impact are not the main focus. Instead, the central theme of many projects seem to be product applications, probably reflecting what companies consider to be the most important feature of technological and market uncertainty.

Continuing the line of reasoning with knowledge and information as remedies for uncertainty, participating in projects is one way for companies to expand their knowledge base. In projects, different actors of the innovation system can come together to share their own experience and expertise, while at the same time get in touch with potential customers, partners, or representatives of legislative authorities. Although not that influential on risk perception, project participation is still a contributing source of knowledge base expansion for companies.

6.1.2 Indications of company level reflexivity

As exemplified in the study, companies thought of as involved in nanotechnology do not necessarily work with nanoparticles or even with nanomaterials in general. Combined with the predominant view of nanotechnology as safe, finding reflexivity emanating from health and environmental risk awareness is challenging. Even with a broadened approach, including more than specifically nanotechnology risks, at first glance, there is little indication of the "self-regulating feedback" that Fogelberg and Sandén (2008) elaborate on.

In most instances where companies have some kind of environmental department, respondents describe its influence on the innovation process as weak, or limited to routine approval of substances. However, with altered demands on what constitute reflexivity there are traces to be found. Reflexivity on a company level could be taken as implying continuous input to the innovation process from other processes concerned with some form of risk assessment. In that sense, the companies may not appear very reflexive, but if one acknowledges that important input can come from other sources the case is stronger.

Reflexivity does not necessarily have to involve the environmental department or depend on the influence from other processes; reflexivity could originate from the innovation process itself. As stated by some respondents, the people involved in R&D consider themselves to have the adequate knowledge and abilities to make judgments on their own. Thus, not involving other processes is not necessarily a sign of ignorance of risks, but could be evidence of embedded reflexive capabilities.

A certain degree of reflexivity can also be said to follow indirectly as a response to technological, market and even regulatory uncertainties. As mentioned by representatives of Delta and Theta there is an element of "survival instinct" involved in the innovation process. In a business environment, the goal of development is a marketable product, a goal which automatically sets some boundaries. If there are elements of the product that could obviously result in danger to humans or the environment, there is usually no point in running the full course since the end product will be uninteresting to the market or, in worst case, banned. However, it is still a question of companies acting on the information at hand; there may be unforeseeable effects that eventually halt development anyway.

6.1.3 Public perception

The possibility of nanotechnology health and environmental risks holding back the public's enthusiasm is a quite straightforward case of market uncertainty and perhaps the easiest link to understand. Public opinion could also influence legislative authorities thus contributing to the regulatory uncertainty.

However, the topic of public perception is also perplexing because of the differences between how companies understand the situation on one hand, and what the situation actually looks like on the other. As noted earlier, various studies show that companies within the nanotechnology business are concerned about what the publics' perception and reaction could develop into, with the GMO debacle as the low-water mark to compare with.

The situation is similar for the companies in this study with all but one of the companies involved in nanomaterials expressing a fear that a few “bad apples” could taint the safety reputation of all substances. Important to point out though is that most companies spoke in general terms, not claiming to have suffered themselves from any misconception about nanomaterials. Similar indications are given in Pandza and Holt’s (2007) study where social acceptability ranked low as a source of obstruction to the realization of nanomanufacturing.

While mentioned as a potential roadblock by some respondents, public opinion on nanotechnology probably has a comparatively small impact on the industry in the current Swedish context. Sweden should not be remarkably different from other countries where the public either does not have any knowledge about nanotechnology or approval dominates over skepticism (Macnaghten, 2008b). Also, as far as Sweden is concerned there are claims of an almost non-existing nanotechnology debate (Fogelberg and Sandén, 2008). Thus, it appears to be a difference between reality and the companies’ perception, but companies may relate more to what they see as the authorities’ attitude rather than that of the consumers.

6.2 Innovation system and policy issues

This part of the analysis revolves around the three functions of the technological innovation system presented in the theory section. The intention is to discuss these functions in relation to the observations and also to highlight a number of function-linked policy issues that are of interest.

6.2.1 Knowledge development and diffusion

Following the analytical framework adopted, relying on the uncertainty/knowledge duality for explanation and the comparatively early stage that nanotechnology is in, the function of knowledge development and diffusion is prominent when viewing the observations from an innovation system perspective.

The relationship between knowledge and research as described by Kline and Rosenberg (1986) has already been discussed from an innovation process point of view. In the TIS, a similar relationship can be established by acknowledging that research is essentially development of knowledge, whether carried out by companies themselves or other system actors like universities and research institutes.

As hinted in the discussion above on project involvement, companies coming together this way and discussing different aspects of technology is an example of how knowledge diffuses among actors throughout the innovation system. Some level of diffusion is also likely taking place between upstream and downstream actors; presuming their relationship is not merely one of division of product responsibility.

Diffusion of knowledge does not only take place between companies and researchers in the innovation system. The public perception and the attitude from authorities are also influenced by the level of knowledge and understanding held by the respective actors. Here it is not mainly development of new knowledge that is needed, but rather paths for spreading the existing information.

Reflexivity also depends more on the diffusion of existing knowledge between people involved in assessing risks and those with understanding of the innovation process, than on the creation of new knowledge. However, as most of the reflexivity elements are considered on a company level in this thesis, there is perhaps not much direct influence from other actors in the innovation system.

Policy issues
There are a number of policy issues that arise in connection to knowledge development and diffusion in the nanotechnology TIS. First, if there is a wish or expectation of the TIS to accommodate certain aspects, e.g. health and environmental risks, the question of what knowledge is developed becomes important. In the case of nanotechnology, companies interviewed and the projects they participate in have little focus on risks for the most part.

Linked to the desired type of research is the equally important second issue of which actor/actors should conduct the research and what incentives policy can provide. As seen in the interviews, e.g. with Theta and Iota, companies do little risk research themselves. Judging from this study, companies generally rely on external information, even though it may appear in the form of internalized knowledge such as data bases, company policy et cetera.

Adequate knowledge development alone will not help the TIS to develop, thus the third issue relates to how well knowledge diffuses in the innovation system. For example, there are differences in companies' abilities to assimilate new information; not least because of their size and resources allocated to environmental work. This could prove important given that REACH puts the responsibility on manufacturers to assure the safety of the substances they produce.

6.2.2 Legitimation and Influence on the direction of search

When analyzing how the public and other actors in the TIS perceive nanotechnology and what implications this has on a system level, the legitimation process appears to be the obvious function to address. Also, the close link between legitimation and influence on the direction of search is apparent in the public perception context.

Social acceptance does not only depend on the actual properties; imagined characteristics, fear, and ethical conviction can be equally important. This acceptance could in turn have potential bearing on the direction of search. If certain areas of technology are considered less commercially viable due to skepticism among consumers, they are less attractive to explore. However, the companies in the study do not seem to have suffered from this so far. It is worth underlining that the sense of misconception about different nanomaterials and their relative risks that is brought up in the interviews applies to companies' interactions with authorities rather than consumers.

Based on what was expressed in the interviews, health and environmental risks presently have no influence on the direction of search. Whether nanotechnology is employed as a solution or not is dependent on what performance can be achieved, to what cost, and what the alternatives are.

Projects' importance for knowledge diffusion is discussed above and from this one can link them to the legitimation process. If the "right" set of actors, e.g. those representing institutions, is involved in a project it can possibly support the legitimacy of a technology as companies can get a better understanding of the circumstances they are expected to comply with. Projects also function as an opportunity for companies to showcase their products or technical solutions. In that way projects have relevance for the factors that influence the direction of search in the TIS; new actors may discover and adapt nanotechnology based solutions to their problems.

Policy issues

These two functions also give rise to policy issues. Since part of a technology's legitimacy is determined by its adaption to institutions, those institutions with power over policy can both facilitate and complicate legitimation. Ultimately this may be a balancing act between sufficient precaution of risks and enough freedom for actors to explore new possibilities. This is the kind of balancing that Matsuura (2006) fears is not possible if the precautionary principle is used as the basis for policy.

The legislative matters have links to another issue as well; that of policy's attitude towards public opinion. This includes both whether policy should seek to influence the public opinion for a presumable good of the innovation system, and the degree of influence on policy that the public opinion should be granted.

As stated in the theory section, policy is in itself also one of the factors influencing the direction of search. This includes what policy does to attract or deter actors that are still not part of the TIS and how actors already in the innovation system are guided; if there is an agenda to consciously steer them in one direction or another. The companies in this study rely on nanomaterials perceived as harmless, if depending on materials at all. Such companies could theoretically be favored over those working with less researched and known variants of materials. Or, policy could be formulated to encourage commercialization of ideas incorporating the very same materials.

Analysis

7 Conclusions

Based on the observations from the study and the analysis of those, this section presents what is considered by the thesis author to be the most important conclusions in relation to the purpose of the thesis and the research question.

Research question

"How do Swedish companies perceive the potential health and environmental risks of nanotechnology?"

The companies selected for this study were purposefully chosen to represent different branches of industry, different level of company size and maturity, and different application areas for nanotechnology. This apparent heterogeneity notwithstanding, they all have similar answers, albeit for different reasons, when asked about the health and environmental risks of nanotechnology. The respondents strongly link hazards to inhalation of free nanoparticles and acknowledge that this could be a risk in an early manufacturing stage or in a laboratory environment. However, this type of risk is not considered to be of any major concern to the own company; each respondent describes their respective company's use of nanotechnology as safe, without exception.

Looking at what determines the perceived safety of a company's nanotechnology application there are four main reasons:

- Nanotechnology is present in nanoscale rather than nanomaterials; this applies to the three companies from the electronics industry.
- Current knowledge and experience says that the substance is safe; in the two life science companies this is further supported by own testing.
- The context is safe, i.e. particles are strongly bound to a surface, dispersed in liquid et cetera.
- Trust in suppliers' products and in customers' usage.

The only side of nanotechnology that respondents brought up as a perceived problem related to risk is how others view the technology. Although there are few, if any, signs of companies suffering because of outside misconceptions about nanotechnology, there are worries that risks are discussed without nuances. This could in turn have negative impact for "safe" materials, both from an image perspective and in connection with legislative changes. In some interviews there is a sense that companies feel that risks sometimes attract too much attention, overshadowing the possibilities. Not as to suggest this is an expression of a negligent risk attitude in general, but rather an expression of feeling questioned based on the nanotechnology elements alone.

Follow up question 1:

"How do they respond to this perception? "

At the time of formulating the research questions, the health and environmental risks of nanotechnology were expected to be of much greater significance to the companies than turned out to be the case. While there is a definite awareness of some risks, as proven by the frequent references to carbon nanotubes, the direct impact on business envisioned when starting working on the thesis seems to be absent.

Conclusions

Knowing how the interviewed companies perceive risks, it comes as no surprise that responsive actions to nanotechnology threats are hard to pinpoint. If a company "knows" its product is safe there are few incentives to research the risks further or limit the application areas. However, companies usually have environmental measures in place, e.g. routines for evaluating new substances and work environment directions, but these are general precautions and have not come about as a result of the company utilizing nanotechnology. An exception to this is the company policy at Delta to avoid or at least minimize the handling of free nanoparticles.

Follow up question 2:
"What are the implications for policy regarding sustainable development of nanotechnology?"

The question of what the implications for policy may be is the most difficult one to draw far-reaching conclusion about since the companies' perceptions leave two possibilities; either there are no particular risks or companies think there are no risks. From a policy perspective those are two quite different circumstances to relate to. As has already been detailed in the analysis, the case of nanotechnology as safe is rather convincing in this specific study; against this background there should be little concern to policy makers. On the other hand there will probably be instances when signs of safety are more deceptive and companies relying on external information for assessing risks will be the last to know. In that case it becomes a matter of encouraging development and diffusion of knowledge about risk among companies even though they largely deal with "safe" materials.

The concept of sustainable development suggests a balance akin to that of reflexivity; it is neither full steam ahead nor being in reverse, but safe and controlled progression. In order to maintain sustainability one has to know where the hazards of nanotechnology lie. Judging from the lack of standards and methods for evaluating toxicity, not to mention the fact that most applications still await, there is yet much work to be done.

In order to have development it may be equally important to know where the hazards of nanotechnology do not lie. There are hints in the respondents' answers that risk sometimes gets too much in focus and everything "nano" is viewed with suspicion. Policy must be shaped carefully to target the areas of potential danger while acknowledging that nanotechnology covers a wide array of applications, most of which probably are safe.

8 Discussion

The results show similarities to those obtained by Köhler and Som (2008). Their interviewees were also aware of the health and environmental risks of nanotechnology, but did not consider them to be relevant to the respective field of research. Furthermore, most focus was on direct effects at the beginning of the life-cycle, such as occupational health problems; an all-embracing life-cycle perspective was lacking. A confidence in nanotechnology risks being assessable and manageable on a" business as usual" basis is suggested by the authors as possible explanation as to why there is little proactive risk assessment.

When it comes to health and environmental risks it is important to remember that "risks of nanotechnology" is more or less translatable to "risks of nanomaterials", which in turn almost have become synonymous with "risks of nanoparticles". Among nanoparticles, the ones that are free and airborne likely pose the biggest threat, but for the time being these are rare to find in products as shown by Hansen (2009).

Taking this view on nanotechnology risks, it appears that there is a limited area of industry where the reason for concern is more justified. Therefore, the unanimous view among the studied companies is understandable and probably representative for Swedish companies in general to a large degree. Although the sampling method prohibits generalizing, a majority of companies operate within the same branches of industry and with the same types of nanotechnology as the ten in the study. Thus, it is plausible that most companies outside the study also believe their use of nanotechnology to be safe.

Assuming that the results are more or less representative for the majority of Swedish nanotechnology companies, there are possibly implications for how the work on nanotechnology risk should progress. Following the aspirations of a national strategy, it begs the question of what could be expected from these companies in the striving for a reflexive force of innovation. Much of literature agrees on that the amount of risk focused nanotechnology research has been insufficient so far, and there are many knowledge gaps left to close. At the same time, this study show signs of companies reacting on what they consider to be a disproportionately large significance given to risk assessment and management measures, e.g. in project stipulations. These mixed views on risks leads to questions pertaining to risks in general and what role companies have in mitigating them:

- Should there be less focus on risks in general; could some types of nanomaterial be declared "safe" and excluded from the discussion?
- What are the incentives for a company to become more involved in risk research, if the own product is considered safe and the attention already given to risk by outside actors is considered unmotivated?
- What insights need to be reached at company level for an innovation system to be reflexive and how can policy promote reflexivity on company level?

While it is beyond the scope of this thesis answer these questions, the approach from a policy perspective is worth reflecting on. In the light of the perceived zealous attitude of authorities, policy makers should thread carefully so as not to come off as overly risk focused. Policy must also keep up the innovation angle on reflexivity and communicate the purpose and benefits of such an approach to companies. For policy to have credibility it is important that companies sense there is sufficient knowledge among policy makers to distinguish between differences in nanotechnology and that efforts are focused where they should.

In literature it is pointed out that with nanotechnology there is an opportunity to, for the first time, include social sensitivity and environmental awareness at an early stage of the technology's development (see e.g. Colvin in Einsiedel and Goldenberg (2004)). Among the suggestions in the strategy, one concerns the need for increased communication with the public to promote the perception of nanotechnology as a safe technology; something considered important to fully exploit its potential (VINNOVA, 2010).

However, when engaging in public dialogue it is important that policy actors are clear with the objective of such communication. It should not be considered the proponents' way to convince skeptics of the technology's benefits. Einsiedel and Goldenberg (2004) remark that a better informed public is not necessarily more supportive of the technology in question. Therefore, a dialogue should not be held with the sole intent to get the public "on board and on side". Ebbesen et al. (2006) make a similar observation, noting that trust and acceptance is often assumed to be more easily achieved if educating the public, without considering the possibility that enlightenment could lead to more skepticism.

For policy it will be a balancing act between not alienating companies by focusing on risks in communication, while at the same time show credible interest in whatever public concerns may arise. In the case of GMOs, Wilsdon (2004) claims the breakdown of public trust was rooted in a concern that GMOs were "promoted uncritically by government and corporations, at the expense of the wider public interest" (Wilsdon, 2004, p. 20). Thus, attempts of presenting an image that is perceived as too rosy could backfire and be taken as deceptive.

Suggestions for future studies

Having established the risk perception among some of the companies that can be said to be more in the "mainstream" in their nanotechnology use, a natural continuation of this study would be to focus more narrowly on the nanomaterials thought to be dangerous. A similar study but focusing on university research groups instead of companies would perhaps result in less concordance and expose technological uncertainty having more to do with the health and environmental risk. The "riskier" substances are presumably more common in university research where the primary objective is not necessarily to incorporate the substance in a marketable product.

Another consideration worth taking for future studies concerns the importance of nanotechnology in relation to industry characteristics. Being the enabling technology it is, companies utilizing nanotechnology in their business seem to identify much more with the "main" branch of industry they are active in, rather than viewing themselves as "nanotechnology companies". Some companies most likely do not reflect on working with nanotechnology. Therefore it may be wrong to talk of nanotechnology companies and how they perceive risks; just as nanotechnology itself is multi-faceted, so is the group of companies that make use of it. Instead, risk perception and response is likely more related to the specific industry and its standards and regulations that have been in place before nanotechnology was hyped.

A future study could also approach the concept of risk from a different perspective, both regarding the type of risk and its time of appearance in the product life-cycle. The topic of societal risk is only briefly touched upon in this thesis and could be investigated in much greater depth. Societal risks and their ties to new technology would also put more focus on nanotechnology as such, and not specifically on nanomaterials. As for the product life-cycle perspective, the end-of-life stage, when products become waste, is probably the least researched as far as nanomaterials risks are concerned. This thesis is primarily focused on the production and usage, but it may very well be that the greatest hazards lay in the last stage.

Even though the result of the study may have turned out to be less exciting than what was initially hoped for and also expected, this account from Swedish companies of how nanotechnology cause little or no stir in their processes, is a result in its own right. Whether good or bad is first and foremost a matter of perspective. On one hand it would have been reassuring to see more signs of proactive work since prevention is better than cure. On the other hand one can reconcile with the notion that most of the current nanotechnology used, even nanomaterials, does not seem to pose a threat. The situation may change in the future for both better and worse; it all comes down to what knowledge exists today, what knowledge exists tomorrow and the best way to bridge that gap so that the effects can be foreseen rather than acknowledged in hindsight.

Discussion

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Appendix 1: Interview guide

About the company and the interviewee

1. What is your position in the company?

2. Short facts about the company:
    a. Branch of industry? (in Sweden)
    b. What importance does nanotechnology have to the company? How is it commercialized?
    c. What type of customers are the most important?

Risk related questions

3. How does the company view the risks of nanotechnology?
    a. What kinds of risks are linked to nanotechnology?
    b. Do these risks have relevance for the companies' business?

4. Does the company have experience of handling other kinds of health or environmental risks?
    a. What kinds of risks?
    b. Are nanotechnology risks perceived as different in how they are handled?

5. Does the company pursue any research related to nanotechnology risks, either on its own or in some project context?

6. Where does the company get information about nanotechnology risks?

7. Is there a special department or individual responsible for environmental risk management?
    a. If not, how are environmental risks managed?
    b. Is there any cooperation between this department/individual and the development department?

8. How does the company perceive environmental laws and regulations?
    a. Does the company try to influence legislation?

Innovation process questions

9. What does the process for developing new products look like?
    a. Research and development in Sweden?

10. Are their other stakeholders with influence on the innovation process?
    a. Any connections to universities?
    b. Any connections to customers/other companies?
    c. Other influencing factors?

Connection between risks and innovation

11. What is the relationship between environmental risk management process and innovation process?
    a. Is one process secondary to the other?

12. What importance does the input from the environmental risk management process have?
    a. At what point during the innovation process does the input come?
    b. Why at this point?

13. What does the communication between the processes look like?
    a. Where does responsibility for information exchange lie?
    b. How often is information exchanged?

14. Is the company actively working to change the relationship between the processes?
    a. What changes does the company want to achieve?