Chapter 2
Nanomaterial and Nanotechnology Firms: A Typology

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Abstract Despite many studies opening with ambitious forecasts of a rapidly evolving nanomaterial and nanotechnology industry, the industry's boundaries are not clearly delineated. This is problematic because, in order for regulators to regulate, insurers to underwrite risk, and capital providers to provide funding, they must first have an in-depth knowledge of the industry and the idiosyncratic risks of its constituents. In this study, 517 nanomaterial and nanotechnology firms were identified, then systematically categorized under six emergent themes: Analysis, Bioanalysis, Drug Delivery, Electronics, Energy, and Materials. Such a system of categorization thus provides the starting point for a risk assessment, whereby those belonging to a certain category inherently pose similar levels of occupational, consumer, and environmental risk. Data was also gathered on each firm's size, ownership structure, and source of funding. The majority of firms were found to have less than 50 employees and were privately held, many of which were funded by venture capital. This too has implications for industry stakeholders as their actions could potentially have an adverse impact on what is evidently still a nascent, emerging industry.

2.1 Introduction

As with many novel emerging technologies, much hype surrounds the growth of the industry and this hype is accompanied by impressive growth projections. For instance, it has been reported that governments, corporations, and private investors (venture capitalists) invested $18.5 billion in nanotechnology in 2012, that revenues from nano-enabled products grew from $339 billion in 2010 to $731 billion in 2012, and that the global value of nano-enabled products, nano-intermediates, and

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nanomaterials will reach $4.4 trillion by 2018 (Lux, 2012). Such precise figures presuppose the existence of an identifiable nanotechnology sector or industry grouping. Yet the Industry Classification Benchmark (ICB) uses a system of ten industries, which are subdivided into 19 supersectors, 41 sectors, and 114 subsectors, none of which contain the term "nano" (ICB, 2014). Perhaps the reason for this is that nanomaterials and nanotechnologies are prevalent across such a wide range of industries. Indeed, Mills (2013) posits that the biggest reason for the unique situation facing nanotechnology is that in no other field are so many distinct and diverse players involved in the development of a science, from medicine, biology, electronics, optics, and physics to materials engineering. For example, carbon nanotubes (CNTs) can be incorporated into a diverse range of commercial products from rechargeable batteries, automotive parts, water filters, and thin film coatings to microelectronics (De Volder, Tawfick, Baughman, & Hart, 2013). Quantum dots can be incorporated into a similarly wide range of applications from bioimaging to photovoltaic solar cells (Nozik et al., 2010; Zhu et al., 2011).

Hence, a sober analysis of the industry is required, particularly as there are potential risks associated with nanomaterial and nanotechnology firms that may require regulatory action (USEPA, 2007). We present such an analysis taking the unique approach of categorizing nanomaterial and nanotechnology firms according to their operations. Beforehand, however, the definitions of nanomaterials and nanotechnology deserve consideration. The US Environmental Protection Agency (EPA) uses the catchall term "nanotechnology" for both, defined as research and technology development at the atomic, molecular, or macromolecular levels using a length scale of approximately 1–100 nm in any dimension; the creation and use of structures, devices, and systems that have novel properties and functions because of their small size; and the ability to control and manipulate matter on a small scale (USEPA, 2007). Using such a definition, three very different firms, for example, one involved in electron microscopy, another involved in the manufacture of CNTs, and another involved in nanofluidics, could all be considered as nanotechnology firms even though their operations, and hence operational risk, are markedly different. For the remainder of this study, *all* such firms are referred to as nanotechnology firms.

Six dominant themes emerged: Analysis, Bioanalysis, Drug Delivery, Electronics, Energy, and Materials. Furthermore, three stakeholder groups were identified, which could benefit from such an "industry" typology: (1) regulators, who are tasked with regulating both an ever-increasing variety of nanotechnology firms (Maynard, 2007) and an ever-increasing number of nanomaterials across their entire life cycle (Helland et al., 2007; Linkov & Seager, 2011), (2) insurers seeking to profile the relative risk of different nanotechnology firms (Mullins, Murphy, Baublyte, McAlea, & Tofail, 2013), and (3) capital providers seeking to assess the market before making funding decisions.

Additionally, data was gathered on each firm with respect to size and ownership structure in response to Beaudrie and Kandlikar (2011), among others, who anecdotally observe that, like other new technological domains, nanotechnology innovations are often made by small companies and start-ups. Consequently, overly burdensome regulations risk increasing such firms' costs, thereby dampening the

pace of innovation. There have been previous attempts at characterizing nanotechnology firms, according to firm size at least: Schmid and Riediker (2008), in examining the use of nanoparticles in Swiss industry, find that out of 48 Swiss firms interviewed, 18 (38 %) had less than 50 employees; Helland, Kastenholz, and Siegrist (2008), in examining industrial perceptions of the human health and environmental impact of nanomaterials, find that out of 40 Swiss and German firms surveyed, 25 (63 %) had less than 100 employees; Conti et al. (2008), in examining health and safety practices in the nanomaterial workplace, find that out of the 82 international firms surveyed, 52 (63 %) were working with nanomaterials at either small or pilot scales.

All of the aforementioned studies use either interviews or surveys to elicit data directly from nanotechnology firms themselves, which can be biased as a result of either nonrespondents or self-reporting (Armstrong & Overton, 1977; Podsakoff, MacKenzie, Lee, & Podsakoff, 2003). Notwithstanding such biases, it is apparent that nanotechnology firms are predominantly small- to medium-sized enterprises (SMEs), defined as having less than 250 employees (EC, 2005). Moreover, researchers have suggested that nanotechnology is experiencing a shift from research to commercialization (Shapira, Youtie, & Kay, 2011) and that small, private firms form the primary site of large-scale nanomaterial use and production (Engeman et al., 2012). As an indication of how important a consideration the size profile of nanotechnology firms should be to regulators, Engeman et al. (2012), in examining international nanomaterial firms' risk perceptions and safety practices, find that these firms expressed a strong preference for autonomy from regulatory agencies, believing themselves to be better informed and sufficiently trustworthy to self-regulate. Similarly, Helland et al. (2007) find that smaller firms identified cost concerns as the biggest barrier to health and safety management, which suggests that smaller firms could be affected most by regulation. Indeed, in assessing the response of California-based producers and importers of CNTs to a mandatory call-in of information about, for example, monitoring methods used in the workplace, Beaudrie and Kandlikar (2011) suggest that the reason that half of the six private firms involved provided very brief responses is that they were likely small, venture capital-based firms lacking the resources to respond fully to questions.

In order to overcome these potential biases in this study, a larger, more comprehensive sample of nanotechnology firms was constructed. Moreover, rather than depend on anecdotal assumptions or surveys with their associated biases, data was instead manually compiled from online resources on each firm's main line of operations (Analysis, Bioanalysis, Electronics, etc.), firm size (proxied by a number of employees), ownership structure (whether privately or publicly held), and the identity of their capital providers (venture capitalists or otherwise). To our knowledge, this is the first study to investigate the size profile of a large sample (>100 firms) of nanotechnology firms. Furthermore, to our knowledge, this is the only study to examine either the ownership structure or the sources of funding for nanotechnology firms, with a large sample or otherwise. It is hoped that this first, clear typology of nanomaterial and nanotechnology firms will assist regulators, insurers, and capital providers in accurately assessing the relative risks of such a diverse sector.

2.2 The Sample

The sample consists of 517 European firms identified primarily from the Nanowerk database (Nanowerk, 2014). Engeman et al. (2012); Meyer, Curran, and Gonzalez (2009); and Musee (2011), among others, similarly use the Nanowerk database in their respective studies. Nonetheless, there are few suitable alternatives: the NanoVIP worldwide database used by Conti et al. (2008) is now defunct; the Consumer Products Inventory compiled by the Project on Emerging Nanotechnologies (PEN, 2014), whose reliability, from an academic point of view at least, has been questioned by Berube, Searson, Morton, and Cummings (2010), includes all downstream users of nanomaterials, from cosmetics firms to automobile manufacturers. Such firms could hardly be classified as nanotechnology firms and are thus excluded from the Nanowerk database. Likewise, in this study, we constructed a sample of firms that could feasibly be described as nanotechnology firms, i.e., their main line of operations, and hence operational risk, is nanotechnology related. Large cosmetics or auto manufacturers that benefit from nanotechnologies downstream, but whose operations do not largely depend on its sustained growth, were not considered to be nanotechnology firms.

The Nanowerk database, itself, is not ideal. Beaudrie and Kandlikar (2011) concede that it does not provide a means to check the accuracy of information provided nor should it, as it is intended as a business-to-business directory rather than an academic resource. Consequently, each firm's official website was double-checked to confirm that the nature of their activities was indeed nanotechnology related. Each firm was then characterized into one of the six categories: Analysis, Bioanalysis, Drug Delivery, Electronics, Energy, and Materials. These categories arose from recurring themes in the operations of firms in the sample. Further details on our rationale are given in the following section. Each firm was also classified as either publicly or privately held. Furthermore, if any of the privately held firms disclosed the identity of the venture capitalists that provide financing, this was recorded. Lastly, a proxy for firm size was sought. As we subsequently show, the majority of nanotechnology firms are privately held. As such, they are under no obligation to publish quarterly or annual financial results. Hence, in the absence of data on the more traditional measures of firm size (market capitalization, total revenues, or total assets), data was gathered on the number of employees in each firm. This information was most often contained in downloadable company brochures or the "About us" or "Meet the team" sections of the firms' websites.

2.3 Findings

Before presenting summary statistics, it is necessary to outline the criteria used for categorizing nanotechnology firms. Each firm's main line of operations was deciphered from their official websites and promotional literature. If not directly found

on a firm's home page, this information can usually be found in the "What we do," "Products," "Solutions," or "Applications" pages. Hence, for each firm in the sample, a single paragraph description (approximately 50 words) of their activities was recorded. Then, using a relational database management system (MySQL), the entire sample was examined for emergent themes and similar firms were grouped together. From this, each firm was given a short, one-line description (one to five words), from which they could then be characterized into six categories. Accordingly, there was no preconceived idea of how many categories there would be. Data was gathered between September and December 2014.

Table 2.1 provides a summary of the short, one-line descriptions of the firms in each category. It serves to highlight the diversity, not only within the sample but also within each category. The Analysis firms' activities predominantly include the various types of microscopy and spectroscopy. It is important to note that the activities are not mutually exclusive. For example, some firms' activities include both scanning electron microscopy (SEM) *and* transmission electron microscopy (TEM). Similarly, some firms active in nanopositioning are also active in the field of spectroscopy. As such, if a firm performs one or more of the activities listed in column 1, it is categorized as an Analysis firm.

Analysis firms are distinguishable from Bioanalysis firms because many of the latter's activities specifically relate to nanoscale metrology in the life sciences sector, for example, various types of assay development and fluidics that measure or manipulate cells rather than particles.

The Drug Delivery category includes firms who use nanotechnology and nanomaterials as a means to targeted drug delivery. For example, functionalization is one such method, whereby nanoparticles (or fullerenes, CNTs) can be conjugated with different biomaterials such as nucleic acids (DNA, RNA), enzymes, antibodies, carbohydrates, and peptides and delivered to specific areas of the body with the aid of, say, a magnetic field.

Electronics firms' activities include integrated circuit (IC), micro-electro-mechanical systems (MEMs) fabrication, and nano-electro-mechanical systems (NEMs) fabrication. This involves, among other processes, the deposition of thin film, nanomaterial layers onto a substrate (e.g., silicon wafers), onto which patterns are written using various types of lithography, the permutations of which make it impossible to discuss in appropriate detail here (Judy, 2001). Suffice to say that any firm involved at any stage in the production of ICs, MEMs, or NEMs is included under the Electronics heading. Furthermore, a separate Energy category was created because a sizable number of firms devote their operations exclusively to energy storage (photovoltaic cells, battery cells, supercapacitors), albeit using similar processes to Electronics firms.

Lastly, firms that manufacture nanomaterials were categorized under the Materials heading. These include the production and supply of nanoparticles, nanofibers, CNTs, fullerenes, quantum dots, and graphene. This category also includes firms who produce and then supply custom nanomaterials for specific applications, for example, nanofibers that can be used for filtration applications, nanoparticles for catalytic converters, CNTs for mechanical reinforcement of polymers and

Table 2.1 Categorization of nanotechnology firms

Analysis	Bioanalysis	Drug delivery	Electronics	Energy	Materials
3D holography	Assay development	Antibody-derived therapeutic proteins	Carbon nano tube transistors	Graphene supercapacitors	Advanced materials for adhesion promotion
3D tomography	Chemical separation assays	Biocompatible gold nanoparticles	CMOS technologies	Organic solar films	Alumina nanofibers
Cantilever sensors	Fluorescent and bioluminescent dye assays	High-hydrophilic nanoparticles	Conductive nano-scale carbon	Photovoltaic panels	Aluminium nanoparticles
Confocal 3D measurement systems	Immunoconjugates and immunoassays	In vivo magnetofection	Atomic layer deposition	Silicon based battery anodes	Binding agents for polymers
Dimensional metrology	Magneto-sensor assays	Magnetic hyperthermia	Atomic vapour deposition		Carbon nano tubes (CNTs)
Kelvin probe systems	Nucleic acid assays	Nano-sized drug delivery pumps	Chemical vapour deposition		Catalysts for particulate filtration
Magnetic field sensors	Resonance light scattering assays	Nanoparticulate encapsulation technology	Expitaxial layer deposition		Catalytic compounds for gas sensors and bio-sensors
Metallography	Biochips	Signal transduction	Plasma enhanced atomic layer deposition		Catalytic converters for the auto industry
Microarray products	Biomaterial testing	DNA transfection	Pulsed plasma deposition		Cellular metal for industrial strength applications
Atomic force microscopy	Bioreactors for cell cultures	Femtosecond laser transfection	Thin film deposition		Chemicals for paper/pulp
Ion-induced electron emission microscopy	Biosensors through surface plasmon resonance (SPR)		Dry processing for IC devices		CNTs for electronic packaging
Photoemisson electron microscopy	Cell imaging		Electron grafting		Diamond tools
Rapid probe microscopy	DNA sequencing		Electronic ink		Elastomers

Scanning electron microscopy	Genomics		Epitaxial synthesis of advanced nanowire structures		Ferrofluids
Scanning hall probe microscopy	Lab-on-a-chip		Flexible electronics		Filters for air purification
Scanning ion conductance microscopy	Magnetic separation		Focused ion beam nanofabrication		Fullerenes
Scanning probe microscopy	Micro- and nano-fluidics		Hydrophobic electronic coatings		Functionalized graphene
Transmission electron microscopy	Nucleic acid purification kits		Electron beam lithography		Glass coatings
Nano-forceps	Oligonucleotides		Extreme UV lithography		Glass polarizers
Nanoparticle counters and sizers	Opthalmic metrology		Ion beam lithography		Glass to metal seals
Nanopositioning systems	Pharma-toxicological research		Maskless lithography		Graphene
Piezoelectric actuators	Picodroplet technology		Nanolithography		Iron nanoparticles
Piezoelectric sensors	Proteomics		UV nanoimprint lithography		Magnetic and fluorescent nanoparticles
Piezoelectric transducers	Thermophoresis		X-ray lithography		Magnetic and fluorescent quantum dots
Powder and single crystal X-ray diffraction			Micro-electromechanical systems (MEMS)		Magnetic nanobeads
Scanning profilometry			Microlithography and photomask printing		Mesoporous and microporous structures
Optical spectroscopy			Molecular beam epitaxy		Metal nanopowders

(continued)

Table 2.1 (continued)

Analysis	Bioanalysis	Drug delivery	Electronics	Energy	Materials
Atomic spectrometry			Nano-electromechanical systems (NEMS)		Multilayered graphene
Mass spectroscopy			Nanowire light-emitting diodes (nLEDs)		Nanofibers for air and liquid filtration
UV spectroscopy			OLEDs (organic LEDs)		Nanofibers for fine dust filtration applications
Photon cross correlation spectroscopy			PCB (printed circuit board) protective plasma surface finish		Nano-membranes
Fluorescence correlation spectroscopy			PLEDs (polymer LEDs)		Optical coatings for high quality optics
Emission spectroscopy			Quantum Information Processing and Communication		Quantums dots
Absorption spectroscopy			Thermoelectronics		Silica nanoparticles
X-ray fluorescence spectrometry			Thin film field effect transistors		Silver nanoparticles
Surface plasmon resonance			Wafer bonding		Thermoplastics
Tribology					Thin film surface coatings
Ultrasonic homogenizing					Titanium nanoparticles
					Tungsten carbide nanopowders
					Zinc nanoparticles
					Zirconia nanopowders

This table describes the operations of six categories of nanotechnology firms: Analysis, Bioanalysis, Drug Delivery, Electronics, Energy, and Materials

Table 2.2 Country-wise and category-wise breakdown of European nanotechnology firms

	Analysis	Bioanalysis	Drug delivery	Electronics	Energy	Materials	Total
Austria	3			2		4	9
Belgium	1		1			8	10
Bulgaria	1						1
Cyprus						1	1
Czech Republic	1		1	1		4	7
Denmark	5	1	1		2	4	13
Estonia	1				1	1	3
Finland	2			7		5	14
France	15	3	5	8		7	38
Germany	64	17	6	17	4	62	170
Greece						2	2
Hungary	2						2
Ireland	1	3				1	5
Italy	4	3		2		5	14
Lithuania		1					1
Netherlands	7	2		6		6	21
Norway				3	1	3	7
Poland						1	1
Portugal						2	2
Spain	7	2	4	2		16	31
Sweden	1	5	2	7	1	5	21
Switzerland	13	4	2	6	2	7	34
Turkey						6	6
UK	39	14	5	15	4	27	104
Total	167	55	27	76	15	177	517

composites, quantum dots for flexible electronic displays, or magnetic and fluorescent nanoparticles for medical applications. Essentially, in providing the raw materials, these nanomaterial manufacturers form the first life cycle stage common to product manufacturing (Mohan, Trump, Bates, Monica, & Linkov, 2012).

Table 2.2 provides a country-wise breakdown of nanotechnology firms in Europe. Germany has the largest proportion with 170 out of 517 firms (33 %). The UK has the next largest with 104 firms (20 %), followed by France with 38 (7 %), Switzerland with 34 (7 %), and Spain with 31 (6 %). Table 2.2 also provides a category-wise breakdown of the same firms. The "Materials" category, i.e., nanomaterial manufacturers, has the largest proportion with 177 out of 517 firms (34 %), followed by "Analysis" with 167 (32 %), "Electronics" with 76 (15 %), "Bioanalysis" with 55 (11 %), "Drug Delivery" with 27 (5 %), and "Energy" with 15 (3 %).

Of the 517 nanotechnology firms in the sample, data was available on both the number of employees (our proxy for firm size) and ownership structure for 398 firms. As Table 2.3 Panel A shows, 121 (30 %) of these firms have less than ten

Table 2.3 Relationship between firm size and ownership structure

Panel A. Full sample									
# Employees	1–10	11–50	51–200	201–500	501–1000	1001–5000	5001–10,000	10,000+	Total
Privately held	120	136	53	16	5	8	1	1	340
Publicly held	1	5	11	6	5	11	4	15	58
Total	121	141	64	22	10	19	5	16	398
Panel B. Analysis firms									
# Employees	1–10	11–50	51–200	201–500	501–1000	1001–5000	5001–10,000	10,000+	Total
Privately held	31	52	28	1	3	4	0	0	119
Publicly held	0	2	0	2	3	3	0	0	10
Total	31	54	28	3	6	7	0	0	129
Panel C. Bioanalysis firms									
# Employees	1–10	11–50	51–200	201–500	501–1000	1001–5000	5001–10,000	10,000+	Total
Privately held	14	22	4	0	0	0	0	0	40
Publicly held	1	2	1	1	0	2	1	0	8
Total	15	24	5	1	0	2	1	0	48
Panel D. Drug delivery firms									
# Employees	1–10	11–50	51–200	201–500	501–1000	1001–5000	5001–10,000	10,000+	Total
Privately held	10	6	1	1	0	0	0	0	18
Publicly held	0	0	3	2	0	0	0	0	5
Total	10	6	4	3	0	0	0	0	23
Panel E. Electronics firms									
# Employees	1–10	11–50	51–200	201–500	501–1000	1001–5000	5001–10,000	10,000+	Total
Privately held	16	12	9	8	1	0	0	0	46
Publicly held	0	0	3	1	2	3	1	5	15
Total	16	12	12	9	3	3	1	5	61

Panel F. Energy firms

# Employees	1–10	11–50	51–200	201–500	501–1000	1001–5000	5001–10,000	10,000+	Total
Privately held	3	5	3	0	0	1	0	0	12
Publicly held	0	0	1	0	0	1	0	0	2
Total	3	5	4	0	0	2	0	0	14

Panel G. Materials firms

# Employees	1–10	11–50	51–200	201–500	501–1000	1001–5000	5001–10,000	10,000+	Total
Privately held	46	39	7	6	1	4	1	1	105
Publicly held	0	1	4	0	0	1	2	10	18
Total	46	40	11	6	1	5	3	11	123

This table describes the relationship between firm size (proxied by the number of employees) and ownership structure (publicly or privately held)

employees. Of these, all but one is privately held. A further 141 firms (35 %) have between 11 and 50 employees, of which all but five are privately held. Hence, 262 (66 %) of the firms in the sample have less than 50 employees, with the overwhelming majority being privately held. This trend continues: as the number of employees grows, the fewer nanotechnology firms we find, but a higher proportion of those found are publicly held. Of the 21 firms (5 %) with 5000+ employees, 19 are publicly held. In the following section, each of the six categories of nanotechnology firms is analyzed in greater detail with respect to composition, size, and ownership structure.

2.3.1 Analysis Firms

As alluded to in the previous section, there is a degree of overlap in the sample insofar as some firms are involved in a multitude of activities. This is particularly the case for Analysis firms. Nevertheless, in this section, their most popular activities are recounted, mindful that some firms perform more than one. Of the 167 Analysis firms, at least 18 are involved in scanning probe microscopy (SPM), 14 in atomic force microscopy (AFM), ten in SEM, eight in X-ray diffraction (XRD), and six in TEM. However, many firms do not specify the analytical instrumentation they use, instead listing "metrology," "tomography," "particle sizing," "metallography," "nanopositioning," "nanoprobing," "thin film characterization," "profilometry," "tribology," and "rheometry," among others, as their main activity. These firms could use SPM, AFM, SEM, etc., but do not explicitly state so. It is therefore difficult, if not impossible, to state that the numbers of firms using SPM, AFM, SEM, etc., are absolute. Table 2.3 Panel B shows that, of the 167 Analysis firms in the sample, data on both the number of employees and ownership structure was available for 129 firms. 119 (92 %) of these are privately owned and 85 (66 %) have less than 50 employees.

2.3.2 Bioanalysis Firms

Of the 55 Bioanalysis firms, at least ten are involved in microfluidics, nanofluidics, or lab-on-a-chip. However, a further 11 firms are involved in assay development, which may or may not include microfluidics. Other firms list their activities more generally as "biomaterial testing," "pharma-toxicological testing," "diagnostics," "genomics," "proteomics," or "cell processing." Consequently, as with Analysis firms, we can be confident of classifying firms correctly as Bioanalysis firms, but it is difficult to make a more precise classification than that. Table 2.3 Panel C shows that, of the 55 Bioanalysis firms in the full sample, data on both the number of employees and ownership structure was available for 48. Forty (83 %) of these are privately owned and 39 (81 %) have less than 50 employees.

2.3.3 Drug Delivery Firms

The Drug Delivery category is relatively straightforward insofar as these firms' operations are readily distinguishable. All 27 firms are involved in the targeted delivery of nanomaterials that are conjugated with active pharmaceutical ingredients. The applications range from oncology to Alzheimer's research. Table 2.3 Panel D shows that, of the 23 firms on which data on the number of employees and ownership structure was available, 18 (78 %) are privately owned and 16 (70 %) have less than 50 employees.

2.3.4 Electronics Firms

Of the 76 Electronics firms, at least 19 are involved in some form of lithography. This includes, but is not restricted to, electron beam lithography, ion beam lithography, focused ion beam (FIB) lithography, extreme UV lithography, maskless lithography, nanoimprint lithography, and X-ray lithography. At least another 16 are involved in some form of thin film deposition, which includes atomic layer deposition (ALD), chemical vapor deposition (CVD), physical vapor deposition (PVD), pulsed plasma deposition (PPD), molecular beam epitaxy (MBE), and electron grafting. The rest of the 76 Electronics firms are more general in the descriptions of their operations, using terms like "nanoelectronics," "CMOS technologies," "nano-optoelectronics," "MEMs," or "NEMs." Such firms could employ bespoke methods or similar lithographic and deposition techniques to those above but not to disclose it. Table 2.3 Panel E shows that, of the 61 firms on which data on the number of employees and ownership structure was available, 46 (75 %) are privately owned and 28 (46 %) have less than 50 employees.

2.3.5 Energy Firms

The Energy category is comprised of 15 firms, 11 of which are involved in the production of photovoltaics or, equivalently, solar films, organic solar films, or solar cells. Two firms are involved in the production of "ultra" or "super" capacitors, with the remaining two firms producing silicon anode technology for next-generation, high-energy batteries. Table 2.3 Panel F shows that data on the number of employees and ownership structure was available for 14 firms. Twelve (86 %) of these are privately owned and eight (53 %) have less than 50 employees.

2.3.6 Materials Firms

Of the 177 Materials firms, at least 11 manufacture CNTs. At least 21 firms produce nanoparticles including, but not restricted to, alumina, iron, silver, zinc, silica, nickel, zirconium, gold, platinum, and tungsten carbide. A further 12 firms produce nanofibers and 19 firms produce graphene. However, many other firms produce nanomaterials for a predefined application but do not disclose exactly what type of nanomaterial they use. For example, 68 firms produce nanomaterials specifically for coating applications. These include coatings that are heat, corrosion, UV, and scratch resistant, adhesion promoting, easy to clean, anti-fingerprint, antibacterial, hydrophobic, waterproof, and conductive. However, a further 18 firms produce nanomaterial composites that can be used to reinforce polymers or improve electrical conductivity (e.g., for airplane wings) *as well as* for coating applications. At least 11 firms produce nanofibrous filters and membranes for air, water, or dust purification or filtration. However, a further nine firms produce catalysts that can also be used for particulate filtration. Consequently, as with the other five categories above, we can be confident of correctly classifying firms as Materials firms, but it is difficult to make a more precise classification than that. Table 2.3 Panel G shows that data on the number of employees and ownership structure was available for 123 firms. 105 (85 %) of these are privately owned and 86 (70 %) have less than 50 employees.

2.3.7 Nanotechnology and Venture Capital

One hundred and thirty unique venture capital funds were identified that invest in European nanotechnology firms. Importantly, this is just the number of venture capital funds that are disclosed by the investee firms. Many privately held nanotechnology firms disclose receipt of several rounds of financing but do not identify the source. Some disclose that they are seeking further financing, while others might be in receipt of venture capital financing but simply choose not to disclose it. Furthermore, many venture capital funds have several offices around the world so do not necessarily restrict investments to firms in their home country. As Table 2.4 Panel A illustrates, funds from outside Europe (Hong Kong, Singapore, the USA) are actively investing in European nanotechnology firms. Within Europe, 40 (31 %) of the funds identified are from the UK, with France, Sweden, and Germany having 18 (14 %), 16 (12 %), and 15 (12 %), respectively. While care should be taken in interpreting these findings due to aforementioned nondisclosure, these figures are consistent with reports placing these four countries in the top ten countries of the world based on private equity and venture capital investment (Bain&CompanyInc, 2014; PwiceWaterhouseCooper, 2008). Of the 130 funds identified, 103 (79 %) have invested in firms with less than 50 employees. Intuitively, it would appear that venture capital funding is predominantly obtained by nanotechnology SMEs.

Table 2.4 Nanotechnology and venture capital (VC) funds

Panel A

# Employees	1–10	11–50	51–200	201–500	Total
Belgium		2			2
Denmark	1	6	1		8
Estonia		1			1
France		18			18
Germany	8	1	6		15
Hong Kong				1	1
Ireland	5				5
Norway	2				2
Poland	1				1
Singapore		1			1
Spain	6	2			8
Sweden	2	12	2		16
Switzerland	3				3
Turkey	1				1
UK	12	15	7	6	40
US		4		4	8
Total	41	62	16	11	130

Panel B

Category	Analysis	Bioanalysis	Drug delivery	Electronics	Energy	Materials	Total
Belgium						2	2
Denmark	3		1	1	1	2	8
Estonia					1		1
France		9	6	2			17
Germany	3			3	5	5	16
Hong Kong				1			1
Ireland		5					5
Norway				1		1	2
Poland						1	1
Singapore			1				1
Spain	1	2	1	1		3	8
Sweden	2	5		6	3		16
Switzerland		3					3
Turkey						1	1
UK	6	11	4	15		4	40
US				8			8
Total	15	35	13	38	10	19	130

Panel A describes the relationship between VC funds and the size profile of the nanotechnology firms in which they invest. The first column lists the countries of origin of the VC funds. Columns 2–5 describe the number of VC funds investing in differently sized nanotechnology firms. Panel B describes the relationship between VC funds and the categories of nanotechnology firms in which they invest. The first column lists the countries of origin of the VC funds. Columns 2–7 describe the number of VC funds investing in the different categories of nanotechnology firms. Many of the VC funds identified invest in more than one of the sample firms. Additionally, many firms receive funding from more than one VC

Lastly, as Table 2.4 Panel B shows, 38 (29 %) funds invested in Electronics firms with a further 35 (27 %) investing in Bioanalysis firms. So, while Materials and Analysis firms make up the majority of the sample (Table 2.2), our findings suggest that venture capital funding is disproportionately drawn toward the former two categories. This is perhaps due to Electronics and Bioanalysis firms' relatively superior potential for value added. For instance, by virtue of Electronics firms being at a more advanced stage of the product life cycle than, say, Materials firms, they could pose a more attractive prospect for a near-term initial public offering (IPO) or private acquisition—the most attractive exit strategies for venture capitalists, in that order (Hellmann, 2006).

2.4 Discussion

There is growing evidence that nanotechnology firms are becoming recognized as a new industry or sector. As nanotechnology becomes even more pervasive in society, an ever-widening range of firms will therefore comprise the industry. The danger with such a situation is that certain stakeholder groups fail to recognize the myriad of activities within. Consequently, broad-ranging decisions by regulators, insurers, or capital providers could be of detriment. This study finds that European nanotechnology firms are operationally diverse but can be divided into at least six categories. This classification has significance because, from an operational risk point of view, each category should be perceived differently. It would be unfitting of regulators, for example, to generate blanket regulation on the production or use of quantum dots, titanium dioxide nanoparticles, CNTs, and various other nanomaterials. Rather, regulation needs to be nuanced to reflect the context in which these nanomaterials are being produced and used. As such, Table 2.5 presents a simplified risk assessment of each of the six categories from the point of view of occupational exposure, consumer exposure, and environmental exposure to hazardous materials.

Table 2.5 Risk assessment of nanotechnology firms

	Occupational	Consumer	Environmental
Analysis	Low	Nil	Nil
Bioanalysis	Mod	Nil	Nil
Drug delivery	Mod	High	Nil
Electronics	Low	Nil	Low
Energy	Low	Nil	Mod
Marterials	High	Mod	Low

This table provides a means to assess the relative risk of nanotechnology firms, from the point of view of exposure to potentially hazardous nanomaterials. Columns 2, 3, and 4 list each category's risk assessment in relation to occupational exposure, consumer exposure, and environmental exposure, respectively. "Nil" signifies no exposure, "Low" signifies low exposure, "Mod" signifies moderate exposure, and "High" signifies high exposure

As exhibited in Table 2.1, Analysis firms' primary activity is nanoscale metrology. Consequently, there is no risk that consumers could be exposed to hazardous materials. Similarly, as there is no product per se to dispose of, there is no risk of end-of-life, environmental exposure. Workers could be exposed to hazardous nanomaterials, but because Analysis firms are more instrumentation orientated than materials orientated, occupational exposure is likely to be quite low.

A key attribute of Table 2.5 is its malleability. Different stakeholders can add extra layers or drill down to a desired level of detail. For example, an insurer, looking to underwrite an Analysis firm for potential occupational exposure to hazardous materials, can see that its "initial" rating is low risk. Accordingly, the onus would be on the Analysis firm to prove that either relevant health and safety procedures are being adhered to or the type and quantity of nanomaterial being analyzed are sufficiently safe not to trigger a moderate- or high-risk rating. Similarly, a venture capitalist, looking to invest in an Analysis firm, can discard the potential of any consumer or environmental litigation and factor in only the low probability of worker litigation into investment decisions (Metrick & Yasuda, 2007)—from a venture capital point of view, the lower the risk, the lower the cost of venture capital and the higher a firm's valuation (Metrick & Yasuda, 2007).

Bioanalysis firms' primary activity is assay development. At the risk of generalizing what is, of itself, a diverse field, these firms may be deemed to have a moderate risk of occupational exposure due to their handling of biomaterials, while again posing little to no risk of consumer of environmental exposure.

Drug Delivery firms arguably have a similar level of risk of occupational exposure to Bioanalysis firms, if not lower due to the likely smaller quantities of nanomaterials being handled. However, if the "consumers" in this case were patients receiving treatment, the in vivo nature of the treatment would place Drug Delivery firms on a moderate- to high-risk rating. Stakeholder groups, for example, regulators, can reference an increasing body of literature to assess whether the nanomaterial or process being used is deserving of a lower rating and, hence, less onerous regulations (Ghaderi, Ramesh, & Seifalian, 2011; Karmali & Simberg, 2011; Prabhakar et al., 2013). As with both Analysis and Bioanalysis firms, there is little to no risk of environmental exposure with Drug Delivery firms.

As exhibited in Table 2.1, both Electronics and Energy firms' primary activities involve the manufacture of conductive, nanomaterial thin films, mainly in fabrication laboratories. Due to their likely tightly controlled manufacturing environments, occupational exposure would therefore be low. However, similar to Analysis firms, the onus would be on Electronics and Energy firms to prove that relevant safeguards are in place so as to not trigger a moderate- to high-risk rating. From the point of view of consumer exposure, nanomaterials are inevitably encased safely within consumer electronics, nullifying any risk. Likewise, while one could argue that safe handling guidelines for photovoltaics should be mandatory, there is little to no risk of consumer exposure. From the point of view of environmental exposure, electronics goods and photovoltaics pose low and moderate risks, respectively. For instance, consumer electronics could pose a risk if not disposed of responsibly at the end of life. Disposal of photovoltaics poses a higher risk due to their size and shape.

Insurers, for example, might therefore demand that an Energy firm distributes safe disposal guidelines to lower the risk of downstream litigation.

Materials firms would likely have the highest risk of occupational exposure, given the quantities of nanomaterials being handled relative to the other categories. This risk would ladder down as the eventual nano-enabled product or technology moves through its life cycle. Indeed, Helland et al. (2008) find that firms perceive themselves as clearly responsible for potential impacts to human health and environment in the research, development, and production stages, but this responsibility is gradually externalized to others throughout the product life cycle. However, the impact of downstream litigation could be felt both directly by product liability and indirectly through various avenues such as the loss of customers or reputational damage. Regulators could therefore compel Materials firms to internalize a share of downstream, adverse eventualities. Insurers and capital providers should also consider the impact of such eventualities in making underwriting and funding decisions, respectively.

Table 2.5 therefore provides an initial screen for evaluating the relative risk of nanotechnology firms from the perspective of regulators, insurers, and capital providers. As such, it could be used as a precursor to either a multi-criteria decision analysis (MCDA) for selecting nanomanufacturing alternatives (Subramanian, Semenzin, Hristozov, Marcomini, & Linkov, 2014) or a control banding approach for assessing the risk of different nanomaterials (Mullins et al., 2013; Zalk, Paik, & Swuste, 2009). For both the MCDA and the control banding approaches, knowledge of the type of firm using the nanomaterials, and hence its application, is of as much importance as the nanomaterial's attributes (surface chemistry, toxicity, carcinogenicity, mutagenicity, etc.).

Stakeholder groups must fundamentally consider the diverse typology of nanotechnology firms before making decisions with broad-reaching consequences. Furthermore, both the size and ownership structure of nanotechnology firms need to be primary considerations as, based on this study's evidence, the majority are privately held SMEs, many of which are funded by venture capital. Any lack of cognizance of these attributes by regulators, for example, risks stifling, continued innovation in a burgeoning industry. Likewise, both insurers and venture capitalists require the means to categorize the risks associated with particular activities. This study takes a methodological approach and, to our knowledge, is the first to categorize the nanotechnology industry by subsector and to assign broad risk classes to these subsectors. In doing so, this study provides a nuanced approach to a better understanding of the industry for regulators, insurers, and venture capitalists.

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