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Nano products, Small companies, Big challenges:

An exploration of the value of sustainability assessments for nano-companies

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"There are two ways to get lost. One is not to know where you are going, the other is not to know where you are starting from" – Anonymous

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Had fun along the way. Also;
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Tack tack tack tack tack.

Abstract

There is a global demand for sustainable industrial development and a call to make manufacturing "greener". Nanotechnologies are in a promising position to be early adopters of this concept. Advancements in the nanomaterial industry can help confront global issues, and aid in sustainable development that enables positive economic, environmental, and social changes. Formal evaluation of a product's sustainability through 'sustainability assessments' (SAs) is an objective way to assess products. A wide range of SAs exists, but it is unknown whether they are valuable for companies who manufacture nanomaterials or nano-products. Through interviews with nano-producers and a comprehensive literature review, this thesis examines the barriers nano-companies face that prevent them from performing SAs, and also the benefits that performing a SA can provide. Based on these barriers and benefits, fourteen different SAs are evaluated to highlight common problems associated with SAs, and also to determine the specific challenges that nano-companies face. The performance of a SA can help companies lower costs and ensure compliance, open up business opportunities and, ultimately, create new markets. The common shortcomings of SAs include their heavy reliance on expertise, an inability to incorporate all dimensions of sustainability, a lack of nano-relevant indicators, the inaccessibility of well-developed tools, and the fact that they only have value during narrow periods of product development. Nano-companies face additional barriers; they struggle with accessing reliable data and have limited resources to put towards SAs to make the necessary sustainability improvements. This research ultimately helps companies understand the benefits and costs they can expect to incur from performing SAs so that they are better informed about SAs that could be valuable to them. Investors and procurers can use this research as guidance to help them make more sustainable decisions. Researchers and those developing SAs can use the recommendations to develop more effective SAs.

Keywords: sustainability assessment, nanotechnology, SME, nanomaterials, manufacturing, LCA, products

Executive Summary

Advancements in the nanomaterial industry can help confront global issues and aid in sustainable development that enables positive economic, environmental, and social changes. Nanotechnology is a driver of new businesses and economic growth, and green nanotechnologies will provide significant contributions. Market groups estimate that the global nanotechnology market in environmental applications alone has reached USD 23.4 billion in 2014, and will approach USD 41.8 billion by 2020 (BCC Research, 2009).

Nanotechnologies are in a promising position to be early adopters of 'greener' manufacturing. Many companies assert that nanomaterials are positively contributing to sustainable development; however, there is much debate on whether the opportunities provided through the production of novel nanomaterials outweigh the risks. Product sustainability assessments (SAs) can provide an objective way to assess nano-products. SAs support comparisons to existing benchmarks, help a company comply to regulatory requirements, ensure the development of safe products, improve market competitiveness, support stakeholder relationships, identify areas of high resource use during manufacturing, improve recognition of sustainability issues amongst employees, and fulfill ethical responsibilities. However, evaluating, choosing, and implementing effective SAs is challenging.

Little is known about the application of SAs in the nanotechnology sector. Nano-companies are mostly start-ups, or micro, small and medium enterprises (SMEs) (Fernández Ribas, 2010; Groves, Frater, Lee, & Stokes, 2011; J. Wang, 2007). In general, most studies researching sustainability overlook SMEs, and SMEs do not apply sustainability tools to the same degree as large companies (Graafland, van de Ven, & Stoffele, 2003). Since SMEs account for 70% of the world's production (Moore & Manring, 2009), represent 99.8% of the EU businesses (Audretsch, Thurik, Kwaak, & Bosma, 2003), and account for 64% of industrial pollution in Europe (European Commission, 2012a) there is a particular need for research in these areas.

This thesis critically assesses existing methodologies available for product sustainability assessment. *The overall aim of this thesis is to explore the value of product sustainability assessment methods for nano-companies.*

The aim was addressed by answering the following **research questions**:

1. What are the barriers preventing nano-companies from performing SAs?
2. What are the benefits a nano-company can achieve from performing a SA?
3. How do existing sustainability assessments compare for their use in nano-companies?
4. What are the trends and tradeoffs associated with the features of different SAs?
5. What are the features of SAs that can improve or limit their value?

Through interviews with nano-companies and extensive literature reviews, the barriers preventing nano-companies from performing SAs, and the potential benefits of performing a SA were determined. Then, fourteen SA methods were compared and evaluated to determine their coverage of different aspects of sustainability, and to compare their relative cost, time, and expertise needed to perform the assessment. Finally, the trends and tradeoffs associated with different features of SAs were determined, and the features of SAs that improve or limit their value were identified and discussed.

It was found that **there are many benefits associated to being sustainable, and sustainability assessments can help access these benefits**. By performing SAs, companies can *lower business costs and ensure compliance* through cost savings and risk management; *open up business opportunities* through product differentiation, stakeholder interaction, increased access to

capital, and reporting; and, eventually, nano-companies can *create new markets* and become leaders through long term strategic planning.

There are many barriers keeping nano-companies from performing a SA. *For all companies*, a lack of awareness of sustainability issues or a lack of perceived value could keep them from doing a SA. The development stage of a product was also a main factor; products in research and development stages were still undergoing manufacturing and design changes that prevent a full assessment. *For all SMEs*, they tended to have less access to financial resources, time, and tools, and therefore face greater challenges in performing SAs. A lack of easily accessible expertise was a problem *for both SMEs and nano-companies*; SAs require expertise in many domains. Large companies often have access to departments and employees that only focus on sustainability, but most small companies do not have access, nor have the ability to hire expertise. Finally, a lack of reliable data was identified as a major challenge particular to *nano-companies*. Nanotechnology companies are part of a new and emerging field, therefore there are many unique uncertainties and difficultues; for example, there is a lack of public databases, a dearth of available data, and challenges in using traditional methods to collect data for nanomaterials.

There are many different kinds of sustainability assessments and they range in complexity, outcomes, resource requirements and expertise needs. There are three that have been developed specifically for nanoproducts. In general, most SAs can be adapted to assess nanoproducts. Due to constraints on companies, especially at different stages of growth, the benefits will vary. With fewer resources, companies can perform SAs that achieve short-term benefits, and those that can afford to spend more resources will achieve more long-term benefits. In general, all SAs require financial-, time-, and resource- investment, high data inputs, and comprehensive expertise. *Nano-companies face even more challenges due to their generally small size, early product development stages, and inability to access quality data.*

There are common limitations amongst all SAs that prevent companies from achieving maximal value. Assessments *struggle to incorporate all dimensions of sustainability*, often ignoring social dimensions, and not considering nano-relevant dimensions such as regulation, technical performance, benefits, and risks. They rely heavily on *self-evaluation and expertise*, which can lead to subjective results and can be a prohibitive factor for nano-companies that do not have the expertise. They have *value only during narrow periods of product development*; an assessment that is performed too early in the product development process (*e.g.* research and design stages) will not have enough data, and done too late in the development process (*e.g.* commercialization stage) may face challenges in being able to change the technologies and processes. One of the biggest problems discovered was that *many well-developed SA tools are not accessible*; large amounts of funding have been spent on developing comprehensive and sound SAs, but these projects do not continue after the funding period is over, so the tools go obsolete, or become inaccessible to the public.

There are limitations amongst all SAs that prevent nano-companies from achieving the maximal value. In addition to the limitations discussed above, nano-companies face additional challenges. *Getting reliable data related to the manufacturing, use, disposal, and safety* of nanomaterials is a challenge, and many data gaps exist. There are *few sources of updated and reliable information on nanomaterials*, and even the sources that exist are difficult to use. Many nano-companies have developed from old industries, and therefore *cannot afford to change their technologies or processes* to address sustainability issues. The importance of capturing *nano-relevant criteria,* like legislation, the definition of 'nano', or public acceptance are often not included in SAs, or are difficult to assess. Since some nano-products have novel functions, assessments based on comparison to a reference product are a challenge.

Finally, it is recognized that there are **some conditions where completing a full sustainability assessment may not create value**. Companies in early development stages will not have enough data or knowledge of their final product to properly perform an assessment. Those *manufacturing at small volumes* may not have enough significant impacts to require a SA. Companies that already *have sustainability "embedded" in their DNA* have likely already performed a series of informal assessments, and are already going above and beyond regulation and compliance to satisfy their own intrinsic values.

Based on these results, it can be concluded that SAs can bring value to nano-companies, provided that they can overcome the barriers to performing them. Companies will be able to access more benefits as they have more resources to dedicate to the assessments. In general, there was an interest in sustainability amongst nano-companies, but many were unsure as to whether SAs would be of value to them. For nano-companies, where there are heightened concerns over human and environmental safety, and uncertainties regarding future risk, doing a systematic SA will ensure that they have thought about all sustainability aspects prior to commercialization. 'Nano' is, and will continue to be, scrutinized more carefully than conventional materials; **it is imperative that the nano-sector moves forward in a safe and sustainable manner.** This research has laid out the benefits a company can expect to receive given the resources they can use, and makes it easier for companies to decide whether they see the value in pursuing a sustainability assessment. Investors and procurers can use this research as guidance to help them make more sustainable decisions when deciding which nanoproducts to support. Researchers and those developing SAs can use the recommendations provided in this thesis to develop more effective SAs for nano-companies.

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Abbreviations

B2B	Business to Business
C-NSF	Cinelli's holistic Nano-Sustainability Framework
CSR	Corporate Social Responsibility
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
m-SAS	Modular-Based Sustainability Assessment and Selection
MCDA	Multiple Criteria Decision Aiding
Nano-company	Any company producing raw nanomaterials, using nanomaterials as intermediates, and/or incorporating nanomaterials in their products
Nano LCRA	Nano Life Cycle Risk Analysis
Nano-SME	Any start-up, micro, small and medium sized nano--company
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
SA	Sustainability Assessment
SDS	Safety Data Sheets
S-LCA	Social Life Cycle Analysis
SME	Start-Up, Micro, Small and Medium Sized Enterprises

1 Introduction

The growing global demand for resources is continually putting pressure on the earth. There is a predicted 48% increase in energy demand from 2012 to 2040 and a 55% increase in water use, mainly due to a 400% increased demand for manufacturing (US EIA, 2016; OECD, 2012a). These pressures accentuate environmental, social, and economic stressors that are resulting in catastrophic environmental changes that often affect the most vulnerable (UN, 2015). The international community is calling for actions to support sustainable development, so that we can continue to meet humanity's needs in a way that does not negatively impact the ability of future generations to take care of their needs (UN, 2016; WCED, 1987).

Innovation in the chemicals industry is an important driver for sustainable development (High Level Group, 2008). Advancements in the nanomaterial industry can help confront sustainability issues, and aid in global development that enacts positive economic, environmental, and social changes. Overall, the field is still at an early stage of development (OECD, 2012b); research and development efforts are occurring at the academic, government, and private levels, and there are many initiatives to aid and accelerate the commercialization of nano-products (National Research Council [NRC], 2015; Roco, 2011). Some nanomaterials, such as nanosilver, are already at a quite advanced stage, and are on the market (Tran, Nguyen, & Le, 2013).

Many nano-enabled products have novel or better applications than the conventional products they are displacing. There is potential in every sector; they can make sunscreen less greasy while providing better protection from UV (Nasir, Wang, & Friedman, 2014), they can make tennis rackets lighter but stronger (Esawi & Farag, 2007), they can make clothes stain-resistant and anti-bacterial (Ki, Kim, Kwon, & Jeong, 2007; Sundaresan, Sivakumar, Vigneswaran, & Ramachandran, 2011), and in the future we will be able to create thin foldable electronic displays (Hosseini, Wright, & Bhaskaran, 2014), and detect and target tumours with nanomaterials (Liu et al., 2007). Not only can nanomaterials improve products, but can support more sustainable development by enabling 'green nanotechnologies' (Table 1-1). Nanomaterials can substitute for toxic substances, reduce our reliance on scarce materials, and limit the need for non-renewable raw materials (Ellenbecker & Tsai, 2011). Nanomaterials also facilitate practical applications like environmental clean-up and improved energy storage (Ellenbecker & Tsai, 2011; EPA, 2007; Jenck, Agterberg, & Droescher, 2004; OECD, 2012b). Nanomaterials can help optimize resource consumption during use phase of products; for example, enabling lighter car panels or reduced-friction tyres, resulting in lowered fuel consumption (Shatkin, Wegner, Bilek, & Cowie, 2014).

Nanotechnology is a driver of new businesses and economic growth, and green nanotechnologies will provide significant contributions. Market groups estimate that the global nanotechnology market in environmental applications alone has reached USD 23.4 billion in 2014, and will approach USD 41.8 billion by 2020 (BCC Research, 2009). Improvements in nanotechnology-enabled lighting were estimated to reduce global energy consumption by more than 10% (USD 100 billion per year), resulting in a reduction of 200 million tons of carbon (National Science and Technology Council, 2000). The drive to commercialization and mass application means that overall environmental, health, and socio-economic impacts of nanomaterials must be considered.

Table 1-1 Selected examples of nanotechnologies that support sustainable applications

Type of Sustainable Contribution	Nanomaterial	Potential Application	Reference
Replace/reduce toxic substances	Silver	Replace lead in electronics	(Y. Li & Wong, 2006)
Replace scarce materials	Graphene	Replace indium tin oxide in LCD displays and PVs	(Segal, 2009)
Reduce reliance on petroleum based products	Nanocellulose	Performs the same task as plastic packaging	(F. Li, Mascheroni, & Piergiovanni, 2015; Shatkin et al., 2014)
Environmental clean up	Zero valent iron	Break down pollutants to clean up contaminated water	(Karn, Kuiken, & Otto, 2009)
Improved energy storage	Nanocarbon	Incorporated into batteries, it can extend the life and increase the power	(Vlad, Rolland, Hauffman, Ernould, & Gohy, 2015)
Optimize resource use	Silica	Incorporated into tyres, it can reduce friction and thus energy	(Jenck et al., 2004)

A thorough sustainability evaluation of products requires examining whole life cycles – source materials, manufacturing, use, and disposal. Despite ever increasing published studies on nanomaterials, there is no consensus over whether the benefits outweigh the risks; and, with the wide-range of materials, this can vastly differ. There is uncertainty over the safety of nanomaterials, their long-term fate and behavior in the environment, and whether the production of nanomaterials is less resource intensive than the materials they are replacing (Erbis, Ok, Isaacs, Benneyan, & Kamarthi, 2016; Miseljic & Olsen, 2014; Sutherland et al., 2016). As nanomaterials are on the precipice of going to market on a mass scale, this is the ideal time to consider how to take a sustainable approach to the manufacturing of nanomaterials. Manufacturers of nanomaterials or nano-products ('nano-companies') can perform sustainability assessments (SAs) of their products to improve their social, environmental, and economic impacts. The goal of this thesis is to explore and critically assess the existing methodologies available for product sustainability assessment, and determine whether they can be effectively and economically used within nano-companies.

1.1 Problem definition

There is a global demand for sustainable industrial development and a call to make manufacturing "greener". Nanotechnologies are in a promising position to be early adopters of this concept. Many companies assert that nanomaterials are positively contributing to sustainable development; however, there is much debate on whether the opportunities provided through the production of novel nanomaterials outweigh the risks. Product sustainability assessments (SAs) can provide an objective way to assess a product and compare against existing benchmarks. In performing SAs, companies can improve environmental, social, and economic performance. There is limited information on how many nano-companies are actually performing SAs, though a general examination of company websites shows a paucity of sustainability data, suggesting that they are not doing SAs.

Both the company itself and society as a whole benefit from companies performing SAs. For example, SAs can help a company comply to regulatory requirements, improve market competitiveness, support stakeholder relationships, identify areas of high resource use during manufacturing, improve recognition of sustainability issues amongst employees, and can fulfill ethical responsibilities. Despite all these benefits, evaluating, choosing, and implementing effective assessments is challenging. For example, Häkkinen et al. (2016) found that despite an abundance of energy performance assessment tools in the building refurbishment sector, 38% of companies said that a lack of tools was a barrier, and concluded that there is not enough training or aid to help select and apply the right tools.

Little is known about the application of SAs in nano-companies. Nano-companies are mostly start-up, micro, small and medium enterprises (grouped together as "SMEs" here) (Fernández Ribas, 2010; Groves et al., 2011; J. Wang, 2007), and most studies evaluating sustainability overlook SMEs. Typically only larger organizations implement sustainability tools, and in general, SMEs do not apply these tools (Graafland et al., 2003). There is a data gap in the literature on how SAs can help nano-companies evaluate their manufacturing processes. To close this gap, this thesis focuses on gaining more insight into the challenges that nano-companies face that prevent them from doing SAs.

A study and collection of data on nano-companies is needed to improve the sustainability profile of the sector. There are many SAs that cover a wide range of sectors, interests, and dimensions of sustainability. Given that there will likely be challenges specific to the nanosector, it is worth evaluating the existing SAs to determine which ones are of value to nano-companies. Creating an evaluation of SAs that takes into account the challenges faced by the companies will make it easier for companies to decide which SAs to use, and help direct future efforts in developing SAs.

1.2 Aim and research questions

Little is known about how SA methodologies can be applied in the context of nano-companies, therefore the overall aim of this thesis is to *explore the value of product sustainability assessment methods for nano-companies*.

The aim will be addressed by answering the following **research questions**:

1. What are the barriers preventing nano-companies from performing SAs?
2. What are the benefits a nano-company can achieve from performing a SA?
3. How do existing sustainability assessments compare for their use in nano-companies?
4. What are the trends and tradeoffs associated with the features of different SAs?
5. What are the features of SAs that can improve or limit their value?

The results will be used to provide nano-companies with an overview of the benefits and costs they can expect to incur from performing SAs. The results will also be used to assess the common features of SAs that can limit their value. It will also provide an understanding of how SAs can bring sustainable value to companies, and provide the basis of a framework for evaluation of SA tradeoffs for nano-companies. This will help sustainability assessors and developers understand the needs and barriers of nano-companies, thereby allowing for improvements in the SAs.

1.3 Scope and limitations

This thesis was performed between June and Sept 2016 and focused on companies producing raw nanomaterials, and/or incorporating nanomaterials into intermediates or final products (referred to as 'nano-companies' as a whole). These companies were chosen because there is little information on the unique challenges nano-companies face regarding sustainable production. Relevant SAs are evaluated for their usability in, and value for, nano-companies. While a large number of SAs exist, only those that addressed the manufacturing process and the impacts that could be directly related to nanomaterial production were considered. Aspects related to the functioning of the company (*e.g.* consideration of the lighting or water used in the offices) were not considered a challenge that is unique to nano-companies, therefore they were not included in this evaluation.

Much of the collected data to answer Research Questions 1 and 2 was based on interviews of individuals from nano-companies. Due to the uncertainty of regulation regarding nanomaterials, and a lack of a universal nanomaterial definition, many companies do not advertise that they produce nanomaterials, therefore it is unclear what a 'representative' sample of interviewees were. While the goal was to interview representatives from different types of nano-companies globally, the interviewees who responded were primarily contacts from Canada, the United States, and English-speaking parts of Europe, and therefore represent a restricted geographic area; data were lacking from some major nanomaterial-producing parts of the world (*e.g.* Asia). Because studies have found that the geographical, political and socio-economic situations can have a strong impact on sustainability reporting practices (Bjorn et al. 2013; Fifka, 2013), this study cannot be assumed to represent all geographical areas.

The interviewees from nano-companies were all involved in the production of the nanomaterials, and therefore had some expertise and direct experience with the nanomaterials. While efforts were made to contact employees that appeared to be most knowledgeable about potential sustainability issues within the production process, any offer of an interview were accepted. Therefore, the individuals interviewed are not necessarily representative of the whole company, nor the whole nano-sector.

An attempt was made to contact developers related to each SA included here – not all responded, and therefore some of the assessments were only evaluated on their publically available information and peer-reviewed published data. In most cases, this was adequate to make a rational evaluation.

It is recognized that the composition of nano-companies and the challenges faced are in fact complicated, and not as simplified as it is here. Therefore expecting an increased 'value' based on the ability of a company to address only one factor (*e.g.* finances, product development stage) is a gross simplification. However, the results here can still provide a basis for future studies and research.

1.4 Ethical Considerations

Conducting interviews and using data from companies creating novel and innovative materials who want to keep their trade secrets private requires consideration of ethical aspects. Information such as company size, outputs, inputs, challenges, and so forth, are sensitive pieces of data that must be kept anonymous. All nano-company interviewees agreed that information gathered during the interviews could be used for this thesis, as long as the information was kept anonymous and unidentifiable.

Furthermore, prior to, and during the thesis period, I was employed as a consultant that works with nanomaterial producing companies. Any identifying or sensitive information gathered from the interviews were kept confidential and separate from any work-related tasks, and my professional affiliation was disclosed to all interviewees prior to the interview.

1.5 Target Audience

This thesis evaluates existing SAs with the goal of highlighting the potential SAs that could be used within nano-companies. The thesis will highlight the value of SAs, underscore challenges associated with doing SAs, and make it easier for nano-companies to choose a SA that is appropriate for their situation. Therefore, the primary target audience will be any nano-company producing or using nanomaterials, with an emphasis on SMEs, where a company may face more barriers to implementation than a large company with lots of resources. In addition, the results presented here can help those wanting to assess nanomaterial sustainability, for example, procurers or investors.

The results will also help individuals creating, developing, and/or implementing SAs increase their understanding of the challenges that companies face when considering, or trying to perform SAs, and therefore can use the information presented here to improve their assessments methodologies.

Finally, the thesis will identify knowledge gaps regarding the value of sustainability and SAs for nano-companies. It will highlight critical issues regarding the sustainability view of nano-companies. This will pave the way for future work for researchers or scholars, to explore better approaches to assess sustainability, and also develop ideas on the environmental, economic, and ethical implications of the value of performing SAs.

2 Background

2.1 Nanotechnology

Nanomaterials are rapidly penetrating the market and being used in a number of different fields, including the chemical, cosmetic, medical, food and feed, agriculture, and consumer goods sectors. The concept and use of 'nanomaterials' is not new – for example, gold nanoparticles were found in the Roman Lycurgus Cup from the 4th century, which gave it properties that made it look red when lit from behind and green when lit from the front (Freestone, Meeks, Sax, & Higgitt, 2007). However, our improved understanding of nanomaterials, and our ability to produce and manipulate them *en masse* is a relatively recent breakthrough. There has been a rapid development in the innovation and production of novel types of nanomaterials that confer new and improved properties in products and processes, including those related to sustainability (Roco, 2011).

The definition of a nanomaterial is still under debate (Satalkar, Elger, & Shaw, 2015), but for the purpose of this thesis, I define 'nanomaterials' pragmatically as any engineered material that has at least one dimension between 1 and 100 nanometers, where its small size provides unique or novel applications. Due to their small size and unique properties, there is potential for nanomaterials to interact with biological matrices differently than larger particles. These properties usually relate to their higher reactivity due to their larger surface area to volume ratio, when compared to their larger, conventional (also called "bulk", or "traditional") counterparts. Examples of the novel properties of nanomaterials are provided in Table 2-1.

Table 2-1 Selected examples of novel nanomaterial applications

Nanomaterial	Nano-specific characteristics	Potential applications	Reference
Carbon	Stronger and stiffer than any other material (tensile strength and elastic modulus), high thermal conductivity, both metallic and semiconducting capacity	Stronger lighter sports equipment, antifouling paint, improved energy storage in batteries, multifunctional coatings	(De Volder, Tawfick, Baughman, & Hart, 2013)
Silver	High reactive surface area, electrical and thermal conductivity, chemical stability, unique optical behaviour	Improved water treatment, higher anti-bacterial capacity, electrically conductive inks	(Tran et al., 2013)
Cadmium selenide	Novel optical behaviors, fluorescent, stable	Improve efficiency of solar panels, increase colour range of LEDs, better biomedical imaging, better colour quality on tvs	(Bourzac, 2013; Lim, Smith, & Nie, 2014)
Nanocellulose	High tensile strength, high viscosity (“thick fluid”), good barrier properties (gas impermeable, form dense networks)	Better barriers, strength and weight for packaging materials, lighter car parts, stronger cement	(Shatkin et al., 2014)

Changing the surface properties such as surface coating, size, charge, or combining them with other materials is needed in order to make nanomaterials useful for different applications. As of yet, it is not well understood how changing these properties will change their environmental fate and behavior. For example, different conditions will dictate whether the nanomaterials will break down, stick together, or stay in nanoparticle form, move between air, water and soil, or stay suspended or settle down to the bottom of bodies of water (Klaine et al., 2009). The limited understanding of how the nanomaterials behave in nature makes it difficult to predict how organisms will encounter these materials (‘the exposure’). To determine the risk of a nanomaterial, we need to know the concentrations, routes of exposure (*e.g.* inhalation, over the skin, ingestion), form of the nanomaterials, and so forth. Understanding *how* nanomaterials will be used in the future, and to what extent they will get released into the environment is difficult to predict. Since the type of applications and the final uses are constantly developing and changing, predictions of global release into the environment is challenging. The most recent estimates predict that environmental concentrations will be 1 to 7 orders of magnitude lower than those of the corresponding conventional materials (Gottschalk, Sun, & Nowack, 2013; Mueller & Nowack, 2008; T. Y. Sun, Gottschalk, Hungerbühler, & Nowack, 2014)

Currently there are international efforts underway to assess and predict the behavior, toxicity, and safety of nanomaterials. Areas deemed of higher risk, such as occupational safety, aquatic ecosystem effects, and inhalation studies, have received considerable attention. Due to the huge range of materials, there are research efforts to “speed up” testing. This can be achieved by using high throughput tests that can test hundreds of substances at once, replacing live animal vertebrate tests with less resource intensive *in vitro* tests, trying to create predictive models through computational modeling, and development of screening methods to prioritize high-risk materials for testing (Shatkin & Ong, 2016). While many standardized and commonly used tests are appropriate for nanomaterial testing, some have been found to give false results due to interference with the nanomaterials themselves, and therefore there has been a focus on confirming the reliability of these tests (Kroll et al., 2011; OECD, 2014b; Ong, MacCormack, Clark, Ede, & Ortega, 2014). Careful evaluation of toxicity reports is needed ensure there are no misleading results.

2.2 Sustainable development

After several catastrophic events such as the 1969 explosion of an oil well off the coast in the U.S. Pacific (Clarke, 2002), the gradual linking of human effects such as poisoning, tumours, and birth defects with the dumping of toxic wastes around the world through the 1950s to 70s (*e.g.* Love Canal and Minamata Bay) (Goldman, Paigen, Magnant, & Highland, 1985; Kudo & Miyahata, 1991), and the release of popular books such as Rachel Carson's Silent Spring (1962) and Schumacher's Small is Beautiful (1973), there was a rising awareness, discussion, and heated debate surrounding sustainability. Links were starting to be made between impacts such as the depletion of finite resources and the increases in pollution and environmental degradation, and the rising population and subsequent development. In 1987, a United Nations-created committee, the World Commission on Environment and Development (WCED), also known as the "Brundtland Commission", released "Our Common Future", a report that addressed these issues. This report shaped the well-known definition of sustainable development:

"*Sustainable development…meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987).

This created momentum that built up to the 1992 Earth Summit in Rio, where sustainable development at the business level started coming to the forefront of public interest. Here, the UN General Assembly laid the foundations for a global agreement and commitment to responsibilities related to the pursuit of sustainable development (United Nations [UN], 1992). The strong emphasis on environmental issues in the document have since come to include more economic and social aspects over time to further develop the concept of sustainable development.

An increased focus on the how commercial sectors could contribute to sustainable development was established by the OECD's Green Growth Declaration (2009). It recognized that there are drastic social, economic, and environmental costs associated with growth and its related impacts. Extreme climate events, like Hurricane Katrina in 2005 cost USD 125 billion in economic damages (OECD, 2015). Development is causing global terrestrial biodiversity to decrease by 10% by 2050 (OECD, 2015). Externalities such as outdoor air pollution resulted in a 4% increase in premature deaths between 2005-2010, and there was an estimated societal cost of 4-10% GDP (OECD, 2014a; 2015). To counter this, 'green growth' encourages the creation of economic opportunities to improve living standards, the lessening of reliance on non-renewable resources, and the lowering of environmental impact and climate change- and pollution-related impacts (OECD, 2015). This is particularly important to the manufacturing sector.

While the Brundtland definition is appropriate to describe sustainable development as a whole, it is not particularly specific with relevance to industrial production; the U.S.

Department of Commerce's Sustainable Manufacturing Initiative (2011) suggested that sustainable manufacturing can be described as:

"*…the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, as well as being safe for employees, communities, and consumers and economically sound*".

Options for sustainable manufacturing that still allows for growth are being explored. In many countries, the relative growth of innovations related to green technologies is increasing (OECD, 2014a). Consumers and retailers are demanding more sustainable products along the whole supply chain, resulting in some major companies such as Walmart and Nike responding to such demands by introducing supplier certifications, developing sustainability indices, and promoting transparency (Lloyd, 2011). Public and investor interest in corporate sustainability has pushed companies to publish sustainability reports, and corporate sustainability performances can be compared via public analyses, such as the Dow Jones Sustainability Index. The concept of 'cleaner production', a preventative approach to production that includes use of cleaner, more resource efficient equipment over the whole life cycle, has been an evolving concept since the late 1990s (Ayres & Ayres, 2001), and has been actively practiced in the chemical industry long before that (Eder, 2003). Eco-efficiency, or the more resourceful use of raw materials and energy and the minimisation of waste have been beneficial to chemical companies for cost-savings and improved competitiveness (Eder, 2003). All these efforts appear to be working, with global trends moving towards the "uncoupling" of CO_2 emissions from economic growth, indicating that we are able to becoming more efficient at "making more with less" (OECD, 2014a).

2.3 Sustainability assessments

The goal of performing a SA is to help become more sustainable. In accordance with the definitions provided in Section 2.2 regarding sustainable development and sustainable manufacturing, a product sustainability assessment shall be defined here as:

A formal, systematic, and documented assessment that can help decision-makers decide which actions they should or should not take in an attempt to make their manufactured product have fewer negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers, and are economically sound.

SAs can be used to improve internal processes, aid in obtaining funding, ensure regulatory compliance, and gain customer and user confidence. Many SAs already exist, and evaluate a combination of factors including environmental, human health, social, economic, risk, and sometimes cultural and value-based judgements. SA tools can be used retrospectively to evaluate an existing product or with a prospective view prior to production (Ness et al. 2006). Companies that are producing new chemicals or materials have the opportunity to change their design processes prior to scaling development – since nanomaterials are still a relatively new innovation, nano-companies may be able to implement these tools prior to commercialization. This is beneficial to companies as it is easier and cheaper to change production processes prior to going large-scale. Technological innovation often comes with organizational improvements (Baregheh, Rowley, & Sambrook, 2009); therefore, it is an ideal time for the nanotechnology sector to include innovative sustainability initiatives in their activities. For companies that are already established, they can make changes in their processes for cost saving purposes or might consider marketing or sustainability reporting opportunities.

While sustainability is commonly discussed in terms of the "triple bottom line", where environmental, social, and economic issues are integrated, many SAs do not encompass all of these categories. A review of corporate sustainability reporting in nano-companies found that reports focused mainly on the health and environmental safety impacts (Groves et al., 2011). Academic publications on sustainability reporting tend to focus on only environmental issues (28% of publications), or environmental plus either social or economic dimensions (36% of publications), rather than an integration of all three aspects (2% of publications) (Hahn & Kühnen, 2013). The assessment of social issues is only covered in 7% of papers, but these values appear to be increasing over time (Hahn & Kühnen, 2013). Since many SAs are developed initially in academic labs, this suggests that the social and economic indicators are not as well researched as environmental indicators, and the integration of all three may be still be under-developed, thereby skewing SAs towards environmental data.

There is no "one-size-fits-all" SA that fulfills the needs and values of each company. The EPA analysis of SAs is based on several principles (National Resource Council [NRC], 2011). First, no single tool is likely to be comprehensive, and combinations or sets of tools might be needed. Quantitative assessments are desirable, and relatively transparent methods that are easily explained are desirable. Finally, data availability will be a factor when choosing a tool, and uncertainty and sensitivity analyses is required. These factors were therefore used in this study as a starting point in evaluating SAs.

The goal of performing a SA is to provide options for a company to improve its sustainability profile. To do this, a company will likely have to assess the trade-offs necessary to make the most beneficial decision. Ideally, a 'win-win' situation, where economic gains, social improvements, and enhanced environmental protection, occurs (NRC, 2011). Unfortunately, this is rarely the case. Realistically, a company must assess its needs and values and consider the potential gains they will achieve from performing a SA. These will be company specific, and each company will have to do make their own decision as to whether a SA is providing enough value in order to pursue it.

2.3.1 Nanomaterials and sustainability assessments

The principles of green chemistry can be applied to nanomaterials and SAs can help achieve the goal of producing greener, more sustainable nanomaterials. It is not known whether nano-companies use SA or participate in sustainability activities. Published research mostly focuses on their involvement with environmental health and safety practices and risk assessment (Groves et al., 2011). Some large or multi-national companies involved in nanomaterial production provide sustainability data online (through corporate social responsibility reports, or CSR), however, only 12% of these reports make any reference of nanomaterials, and none contain explicit or detailed discussions about their activities related to nanomaterials (Groves et al., 2011).

Similar to other chemicals and products, the majority of literature on SA for nanomaterials is focused on LCA studies. In many of the studies, a reference to "sustainability assessment" was almost unanimously related to the performance of a LCA (*e.g.* LeCorre, Hohenthal, Dufresne, & Bras, 2012). Research to date suggests that the use of LCAs for nanomaterials is not yet well developed (Miseljic, Diaz, & Sánchez, 2014; OECD, 2013). In general, most of the studies are cradle-to-gate (*i.e.* from raw material to the factory gate, prior to going to consumer) rather than the typical cradle-to-grave required of an LCA (Kim & Fthenakis, 2012; Miseljic & Olsen, 2014). This is likely due to that fact that the future use- and end-of-life phases are not yet determined and are difficult to predict (Miseljic & Olsen, 2014). Few definitive studies exist that examine the fate of nanomaterials that consider the release of nanomaterial from the product, the movement and fate of these particles in the environment, *and* their transformations throughout this part of the life cycle. In addition, it is still unknown as to whether nano-products will require special treatment in waste facilities. It is not immediately clear whether other SAs will suffer from the same problems as LCA, and issues such as a lack of data and uncertainty will be explored in this thesis.

2.3.2 SMEs and sustainability assessments

Many of the companies producing nano-products are SMEs, start-ups, and small spin-offs (Youtie, Hicks, & Shapira, 2012). Several hundred new nanotechnology based start-ups were identified in the U.S. in 2005 (Wang, 2007), and SMEs held 37% of all global patent filings in nanotechnology in 2006 (Fernández Ribas, 2010). SMEs and spinoffs play a significant role in nanotechnology commercialization (Wang, 2007; Youtie et al., 2012), and reports of pilot plants producing novel nanomaterials are increasing. While each company might be small, SMEs account for 70% of the world's production (Moore & Manring, 2009), represent 99.8% of the EU businesses (Audretsch et al., 2003), and account for 64% of industrial pollution in Europe (European Commission [EC], 2012a). Therefore, SMEs should not be overlooked or exempt from considering sustainability. SMEs face unique challenges – long development phases, economic struggles, pressures to deliver quick returns, difficulties finding investors, a lack of time, a small number of employees, etc. These barriers could prevent start-ups and SMEs from engaging in sustainable improvements and performing formal SAs. However, it has been stressed that SMEs are vital to the long-term viability of the chemicals industry (EESC, 2016).

The focus of sustainability studies by academics, decision-makers, and practitioners tends to be centered on large companies (Ramos, Cecílio, Douglas, & Caeiro, 2013). Most SAs are developed for larger companies, who have access to more resources. As a result, the implementation of formal sustainability measures tends to be higher in large companies, compared to SMEs (Bos-Brouwers, 2009). For example, Ramos et al. (2013) found that the adoption of Environmental Management Systems, such as ISO 14001, was more common in large companies compared to SMEs, and usually only larger companies published sustainability reports (Bos-Brouwers, 2009; Fifka, 2013; R. Hahn & Kühnen, 2013). Smaller nano-companies djd not report their CSR activities, with 86% of micro-companies and 73% of SMEs not formally completing any sort of code of conduct, policy statement, or annual report addressing sustainability issues (Groves et al., 2011).

In general, SA tools are not easily applied by SMEs, partially due to the heterogeneity of the sector (Johnson et al. 2016). For nanotechnology, due to the newness and uncertainties in this area, other considerations, such as risk analysis in terms of public perception, environmental and human health risk, or potential regulatory changes, and accounting for uncertainty in gathering and analyzing data may also be requirements in sustainability assessments. Nanomaterial production on a large scale is relatively new, therefore the stage of growth at various companies range from research and development stages to pilot scale plants to full commercial production. Different SAs might be more suitable for these various stages. Furthermore, since some nanotechnologies can support or enable sustainable activities, their future benefits should be taken into account.

SMEs do have some advantages that can be conducive to sustainable pursuits. SMEs generally have informal leadership style, flexible organization capacities, and motivated personnel who generally have similar values as the management (Bos-Brouwers, 2009). Drastic changes can be made over shorter periods of time, and employees have a higher ability to enact change. For most SAs, different departments, such as accounting, finance, technical production, and environmental management have to work together to perform assessments; in SMEs these may be easier as there are usually less defined roles and all the employees may have a higher awareness and involvement in each of these areas.

3 Research Methodology

The methodology was developed to address the aim of exploring the value of product sustainability assessment methods for nano-companies. First, barriers and benefits were identified through a literature review and interviews with nano-companies. Then, a range of SAs were evaluated to compare their features based on these potential barriers and benefits. Finally, trends and and tradeoffs associated with performing SAs were determined, and the features of SAs that limit their value were identified and discussed.

3.1 Barriers and benefits to performing sustainability assessments

3.1.1 Literature Review

A comprehensive literature review was conduced that focused on peer-reviewed articles and books, gray literature, published online resources, and company reports. The scope of the literature review on the benefits and barriers to performing SAs was focused on any literature pertaining to nano-companies, chemical companies, innovative industries, SMEs, and manufacturers, sustainability issues, and sustainability assessments though other relevant topics were also used. This helped limit the scope and allow for reporting on industries that may have similarities to the nano-industry. SMEs and start-ups were a focus based on the assumptions that: 1) the majority of nano-companies are SMEs or start-ups (Fernández Ribas, 2010; Groves et al., 2011; J. Wang, 2007); and 2) SMEs face the same, plus more, challenges than larger or more established companies. Furthermore, there is a lack of literature on SMEs and a focus on SMEs can contribute to the general body of literature on sustainability is SMEs. The literature review formed the basis of the background, the answers to RQ 1 and 2, the interview questions, and also supported the analysis and discussion.

3.1.2 Interviews with nanomaterial producers or users

Interviews were performed to support and further develop the criteria used to evaluate and categorize SAs and to determine and unique barriers and incentives unique to nano-companies. Interviewees were individuals involved in a company producing nanomaterials or companies using nanomaterials ('nano-companies'), and companies of all sizes were interviewed. Interviewees were initially chosen first by 'convenience sampling', based on their willingness to perform an interview at the Amsterdam BioBased World Meeting (2016) and the TAPPI Nanomaterials' Conference (2016) and by targeted expert sampling, where those involved in nano-companies were sought. Then these interviewees were asked for recommendations for others to speak to ('snowball sampling').

All interviews were semi-structured around these general questions: Describe your company and products; Explain your role in the company; Discuss whether you think your products are sustainable; Describe the application of any current or past sustainability assessments; Describe the motivation to do sustainability assessment; Highlight the barriers and challenges to performing sustainability assessments. Near the end of each interview, if interviewees had not discussed issues relating to economic, social, environmental, or risk, I would ask another question relating to these aspects. Interviews lasted between 15 and 45 minutes, were recorded and pertinent sections were transcribed. Online data was reviewed to confirm factual data.

3.1.3 Identification of trends

For each identified barrier, data from the literature and the interviews were used to identify any trends related to company size.

Since there were very few companies that had performed a SA, trends related to benefits could not be directly identified in relation to company size. However, based on Lubin and Esty's (2010) framework on the stages of value creation, they suggest that sustainability can be achived in stages. Therefore, the benefits were grouped according to their ability to achieve the different stages, with the assumption that most nano-companies are starting at the lowest stage (research and development) and can build from there. The authors suggest that pioneering companies in sustainability first start by focusing on risk and cost reductions (stage 1), then move to redesign and optimization processes (stage 2), then to transforming core business through innovation and new market expansion (stage 3), and finally new business model creation and differentiation of the company (stage 4). As this thesis is only focusing on the direct manufacturing-related processes, not company-wide changes, it considers the benefits that could be achieved in relation to stages 1-3 and categorizes them accordingly. This model is used as a representation for what could reasonably happen in the nanotechnology sector as companies grow from research and development stages to commercialization.

3.2 Evaluation of sustainability assessments

3.2.1 Selection of sustainability assessments

Sustainability assessments are defined here as "methodologies that evaluate a combination of social, environmental, and economic issues directly related to the production of a nanomaterial". An attempt was made to include SAs that directly related to nanomaterials, SMEs and/or chemicals.

SAs were chosen dependent on the following criteria:

- Information describing the SA is accessible to the public, for example through a website or a published paper or report;
- Methodological information on how to apply the SA is publically available, or easily and freely accessible through direct contact with the developers;
- Covers at least two sustainability dimensions (as defined in Table 3);
- Has logical methodology that culminates in a final result;
- Case studies are available;
- May be applicable and valuable to nano-companies.

3.2.2 Interviews with sustainability assessment experts

Sustainability assessment methods are often well explained online or in the literature, but interviews with developers of these methods can improve the understanding and evaluation of these methods. Therefore, developers (if it could be determined) were contacted. Interviewees were chosen if they had both been involved in the development of the SA, and/or had experience with the tools, for example through performing case studies.

All interviews were unstructured, with the goal of gaining better understanding of the assessment and how it could be applied to nano-companies. They were tailored to each interviewee, based on the amount of information available publically on their SA, the knowledge of the interviewee about nanomaterials, and interviews were allowed to venture in other relevant discussion areas (*e.g.* past experiences with case studies, viewpoints about the value of SAs, etc.). Interviews lasted between 30 and 60 minutes. Online data was reviewed to confirm factual data.

3.2.3 Evaluation and comparison of sustainability assessments

Based on the criteria developed in Section 3.1, an assessment table was developed to evaluate the different SAs. The intention to objectively evaluate different SAs that will aid in determining the tradeoffs associated with each method. The outcome was a comparative table to help companies decide which SAs are appropriate based on their needs and barriers. The comparative table provides the basic information needed for a company to assess which SA is appropriate for them. It shows whether the SA is developed specifically for nanotechnologies, highlights the sustainability dimensions addressed within the SA, and estimates the relative cost to perform the assessment, the relative time needed to perform the assessment, the relative level of expertise needed, describes the potential uses of the assessment, and gives a brief qualitative description of the outcome.

The SAs assessed were classified based on their complexity, data needs, and amount of guidance provided. SAs were grouped as checklists, methods, guidances, or frameworks. *Checklists* are list of elements that a company can check off, usually as 'yes' or 'no' to assess sustainability. *Methods*, involve only one or two primary approaches that tend to focus on only one or two sustainability dimensions, and can also contribute to a larger assessment. *Guidances* are more complex and comprehensive SAs that build on and incorporate one or more methods as part of a multi-stage assessment and sometime provide tools like software or worksheets to complete them. *Frameworks* provide the general concepts and indicators to perform a SA, but do not provide any step-by-step guidance on how to go about an assessment.

Although the definition of sustainability is often based on a three-pillar model (economic, environmental, and social dimensions), these categories are not always mutually exclusive, and therefore it is difficult to catalogue the SAs into these categories. Based on the SAs assessed in this study, seven categories that help differentiate these concepts are defined. Here, SAs were marked as addressing the dimensions: environmental resource use, environmental toxic impact, human health, social well being, economic, risks, and benefits (Table 3-1). If a SA assessed a dimension not categorizable here, they were noted under "other".

Based on the influencing factors found in the literature review and interviews, evaluation categories included: costs involved in performing the SA ("Cost"), including the costs of the software and costs to gather the data; time needed to perform the SA ("Time"); and the minimum level of expertise needed ("Expertise"). Relative ratings are used since absolute values will differ according to the situation. Each category is rated as '$' or '+', where one symbol indicates the lowest cost, least time, or lowest requirement of expertise, and three of the same symbols ('$$$' or '+++'), indicate the highest cost, most time, and highest requirement of expertise. Since LCA is currently the standard and most well-known in the industry, and is a component of many other tools; it is used as a baseline for comparison (*i.e.* set as the average, or "$$" or "++" for each category).

Table 3-1 Definitions of the sustainability dimensions

Sustainability dimension	Definition	Examples
Environmental resource use	Aspects related to our use of valuable resources	Depletion of rare or non-renewable materials, land use, biodiversity depletion, water use
Environmental toxic impact	Aspects related to emissions or releases to the environment	Generation of greenhouse gases, fish death, production of waste, release of chemicals
Human health	Aspects related to occupational (worker) and consumer health	Exposure to nanomaterials during processing, safety of machinery, leaching of nanomaterials from final products
Social well being	Aspects related to society as a whole	Stakeholder involvement, possibility of exploitation of product (*e.g.* weaponizing), job creation, child labour, regulatory compliance
Economic	Aspects related to the financial status of the company	Manufacturing costs, costs of waste treatment, costs of having to remediate ecosystems
Risks	Aspects related to precautionary measures a company can take to avoid potential negative impacts	Modeling future impacts, potential changes in public perception, possible changes in legislation, potential for accidents and spills
Benefits	Aspects related to the advantanges conferred by the commercialization of the nanomaterial	Novel functionalities, can be used for environmental clean-up, will make a product use less energy, substitute for more toxic chemicals

How a SA addresses uncertainty is important to note for nanomaterial SA, as there are large data gaps and ambiguities related to all dimensions. For some assessments, an inability to deal with uncertainty could make it less feasible for a nano-company.

Finally, a short qualitative description of the outcome of each SA will give the reader an understanding of the type of results they can expect from performing the SA.

3.2.4 Identifying trends and tradeoffs

To gain a better understanding of the types of SA features needed to gain higher benefits, each SA evaluated in section 4.2 was categorized into one of the three benefit categories established in section 4.1.2 ('improve business as usual', 'open up business opportunities, or 'create new markets'). Then, the cost, time, expertise, company development stage, and features of the SAs were evaluated and relevant trends and tradeoffs were discussed.

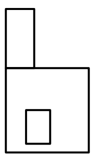
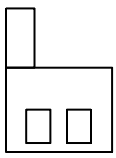
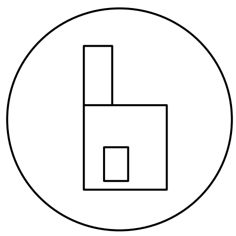
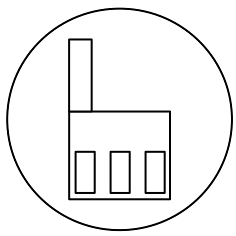
4 Results and Analysis

Several interesting observations and results emerged from the analyses. The interviews were in accordance with the results from the literature review regarding SME-specific motivations and challenges and the factors influencing nano-company's choice to performing SAs. The interviews highlighted some factors that are unique to nano-companies compared to companies producing more conventional products, and found challenges unique to nano-SME. The evaluation of SAs revealed that a wide range of assessments exist, and they each have advantages and disadvantages for nano-companies.

4.1 Factors influencing the choice to perform product SA

The literature review revealed a number of benefits and barriers associated with a nano-company performing a SA. There are few papers specifically focusing on SAs, but many that report on the barriers to SMEs performing or implementing formal environmental or *sustainability activities* (*e.g.* sustainability reporting). Since one step to implementing these sustainable activities would be to perform an informal or formal SA of the company, these influencing factors are likely similar to those associated with performing a SA. Therefore, these are used as a proxy, and the most commonly discussed factors are reviewed.

Table 4-1 Size characteristics and representative icons of companies interviewed

	Standalone ('*StAl*')		**Connected to an affiliate ('*Aff*')**	
	Micro (<10)	**Small (<50)**	**Micro (<10)**	**Medium (<250)**
Number of companies interviewed	5	5	2	2
(Representative icon)				

Interviews highlighted factors that influenced a company's decision to performing SAs. Interviewees came from a range of different sized companies (Table 4-1). Some companies were independent, with no formal business connections to other companies ("standalone", or "*StAl*"). Or, they were affiliated with other companies ("affiliates", or '*Aff*'), such as through joint ventures, subsidiaries, or distinct departments that have employees working specifically on a nano-product, but were connected to a larger parent or partner company otherwise focused on non-nano products. These were distinguished from stand-alone companies, as they have the support of the larger companies. Therefore, there were 5 distinct categories of companies interviewed: standalone micro ("*StAl*-micro", <10 employees), standalone small ("*StAl*-small", <50 employees), a micro group (<10) connected to a large affiliate (>250) ("*Aff*-micro"), and a medium group (<250) connected to a large affiliate (>250) ("*Aff*-medium"). Out of the 62 of nano-companies contacted, 14 companies replied and were interviewed. Two *StAl*-small companies and one *Aff*-medium had performed SAs, all of which were LCAs. Overall, the interviewees confirmed the findings from the literature review, but there were also some differing viewpoints amongst nano-companies.

4.1.1 Barriers preventing the performance of SAs

Financial Resources

A lack of financial resources is the most commonly mentioned barrier in the literature preventing SMEs from carrying out formal SA or engaging in sustainability activities (Commission of the European Committees [CEC], 2007), and is often cited as the *main* barrier (Collins, Roper, & Lawrence, 2010; Yu & Bell, 2007). SMEs generally have fewer financial resources than larger companies, are already struggling in the short term to keep the business going and cannot afford to perform expensive activities.

There is a belief that implementation of sustainability-related initiatives is expensive, and may not pay back (Ramos et al., 2013; Simpson, Taylor, & Barker, 2004). For example, 63-75% of United Kingdom and 51% of New Zealand manufacturing and service SMEs see costs as a major barrier to making environmental improvements (Collins et al., 2010; Revell, Stokes, & Chen, 2009; Simpson et al., 2004). Furthermore, over two-thirds of these SMEs did not believe that being environmentally friendly would increase profits (Revell et al., 2009), and many believe that these costs would not be recouped through their customers due to the need to maintain competitive prices (Simpson et al., 2004). Therefore many SMEs think financing SAs would put them at a competitive disadvantage (Collins et al., 2010). In China, 66% of SMEs reported that the high cost was the number one barrier to environmental management, and some stated that they would rather pay the fines associated with environmental pollution than pay for environmental management measures, as the companies perceived this to be cheaper (Yu & Bell, 2007).

Some SMEs have implemented sustainability measures but then dropped these practices after they found that they were too difficult to implement, were too expensive, or were not cost effective (*e.g.* New Zealand horticulture companies; De Silva & Forbes, 2016). The trade-off between the initial cost and the short- or long-term payback may be a factor in whether a company will follow through with sustainable actions. Smaller companies tend to take a short-term economic perspective when evaluating their priorities, which can prevent them from pursuing a SA, which may be perceived as a long-term project (Gunningham, 1995).

In the interviews, it was clear that the smallest companies faced more financial challenges than the largest companies. One the small end, the *StAl*-micro companies definitively stated that cost was the barrier, both *Aff*-micro companies stated that cost was "not really" a barrier, and the *Aff*-medium company definitively stated that cost was not a barrier due to the support from their affiliates (both in terms of staff and money).

Interestingly, the "in between companies" – the *StAl*-small companies - had differing opinions. One *StAl* felt that the *main* barrier to doing SA was cost, and the other three felt that, while cost was an issue, "it hasn't been prohibitive", and two of those companies had in fact performed LCAs. These differing opinions among *StAl*s may be explained by both relative size differences and their stages of development. The company that found cost as prohibitive was closer to the low end of a "small" company, and the others had at least 3 times as many employees. The two that had performed SAs had already gone commercial, compared to the mostly research and development stage of the smallest *StAl*-small company.

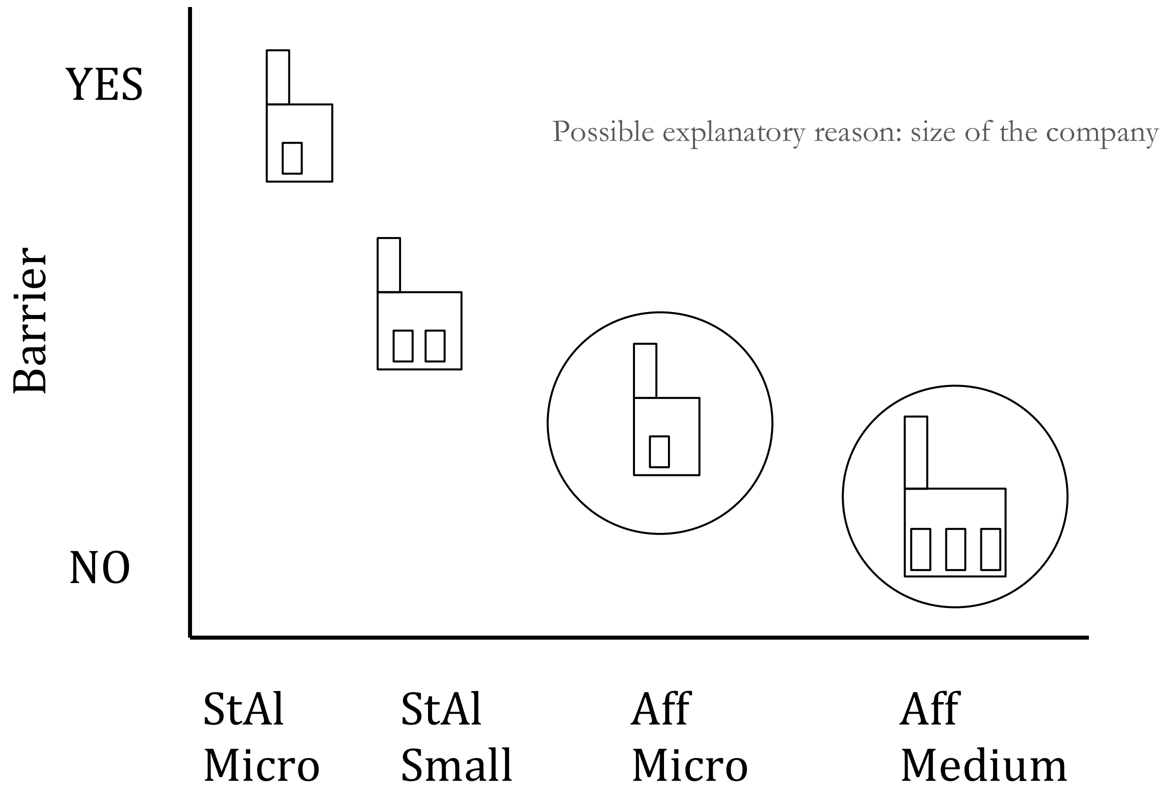


Figure 4-1 Relationship between company size and cost as a barrier

All nano-SMEs felt that SAs are expensive, and most referred to the performance of an LCA as an example of a costly SA. Since SAs were not a priority in most companies, the majority of companies did not find that spending money on a formal SA would be justified. Many SMEs, especially standalones and/or those in pre-commercial stages, are already dealing with the chance of commercial failure with their nanomaterials, which would be financially devastating to the company. Therefore, they perceive that they do not have the necessary financial resources to spend on sustainable initiatives. Most of the companies identified that cost of production and running the basic business is a priority, and was the main driver of most activities. Most companies would be willing take on these assessments if enough monetary return, or other value, could be created by performing a SA. Therefore, for companies to even consider performing a SA, it will have to be at low cost, or at least result in benefits (financial or otherwise), preferably in the short term.

Time

Time is needed to implement sustainability initiatives. For example, managerial time is needed to research and decide what types of initiatives to employ; employee time is needed to learn and administer the projects; and time is needed to hire and support experts such as consultants. Due to a general lack of employees and resources, some SMEs believe that time is a major barrier to implementation of sustainability initiatives. In the UK and New Zealand, 53% and 39% of SMEs perceive time to be a major barrier to environmental action (Collins et al., 2010; Revell et al., 2009). Interestingly, in China, only 7% of SMEs reported that time was a limitation (Yu & Bell, 2007). The average work hours are much higher in China compared to UK and New Zealand (OECD, 2011), therefore it is possible that time is a minor barrier in comparison to financial or resource-based impediments. In this study, all interviewees came from countries with similar work hours; therefore it is difficult to determine whether this was a factor.

More complex sustainability projects can be time consuming; for example, developing an environmental management system (EMS) within a small company often requires time to find reliable advice and information. Occasionally more time was required for EMS implementation that anticipated, and some also found that some consultants had developed ineffective systems, thereby wasting time (Hillary, 2004). Initiating and performing SAs may be even more complex, difficult, and time consuming (Bjørn et al., 2012; Heidrich & Tiwary, 2013; Tokos, Pintarič, & Krajnc, 2011), and therefore is it expected that time will be a major barrier for nano-SMEs.

Similar the trends were seen regarding financial barriers, with smaller companies citing time as an issue, whereas larger companies did not. Statements from *StAl*-micro and *StAl*-medium interviewees such as "…it's difficult to focus…", "…we have a lot of things to do…", "…we have to not only do research but also try to find the customers and identify the markets…", and "If you don't have someone willing to buy this materials…[the performance of sustainability assessments] is kind of a hypothetical question…if you never produce [the nanomaterials]" suggested that these smaller companies felt that they had a lack of time to dedicate to performing sustainability assessments.

None of the larger companies, or those that could tap into the resources of a larger company found that this was a barrier. Companies that were in earlier stages of development tended to more emphatically state that time was a barrier. Furthermore, companies that had collaborations or partnerships with academic labs, other companies, or government labs did not find time an issue. Interestingly, the smallest of the StAl-small companies had been contacted by academic labs offering to perform tests, but they felt that they could not effectively collaborate with those labs at this time due to a lack of time. Therefore, companies must reap value in the time allotted to the SA, or have the ability to hire an outside expert.

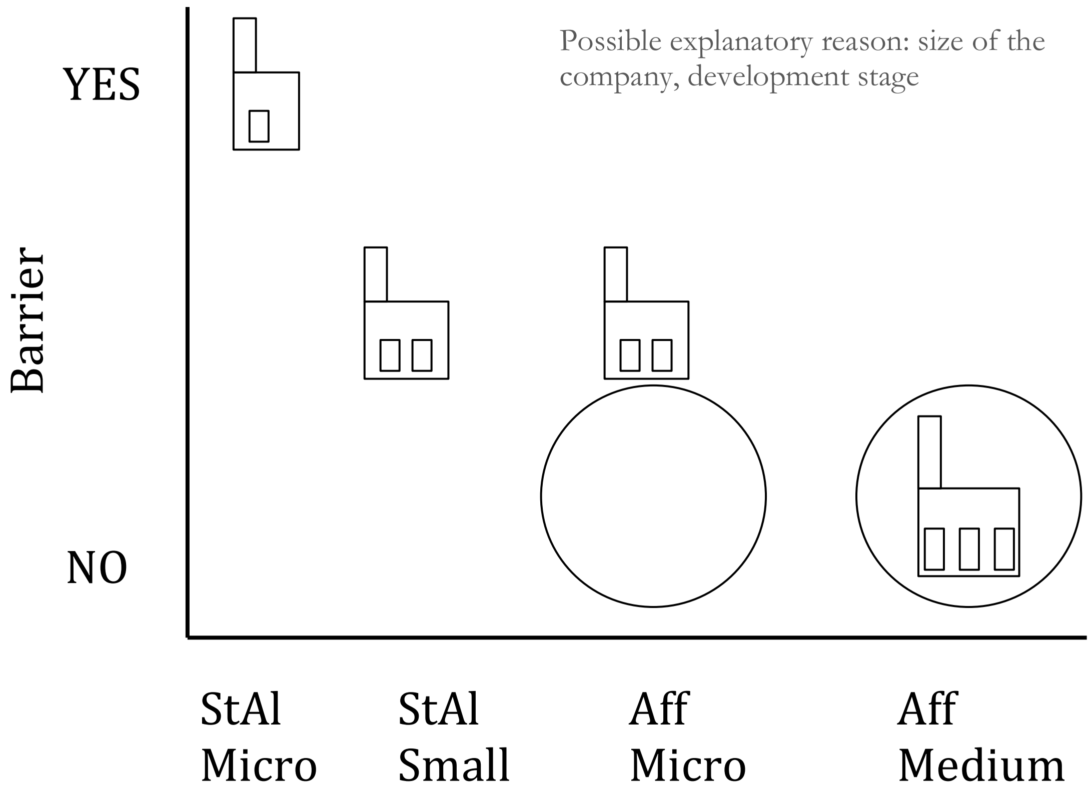


Figure 4-2 Relationship between company size and time as a barrier

Expertise

Expertise is often required to perform SAs that result in reliable findings. Small companies are often made up of few employees with specialized skills, who do not have the required expertise to perform SAs (EC, 2015; Ramos et al., 2013; Rybaczewska-Blazejowska & Luscinski, 2014; Tarantini, Loprieno, Cucchi, & Frenquellucci, 2009). In China, 48% of SMEs reported that insufficient training and education is a barrier, and 41% felt they had insufficient expertise (Yu & Bell, 2007). Sustainability tools are often developed for large companies, and are not designed for use by SMEs (Borga, Citterio, Noci, & Pizzurno, 2009; Johnson & Schaltegger, 2015; Salimzadeh & Courvisanos, 2015). For example, many breweries find SA and reporting to be very complex and difficult (Tokos et al., 2011), and EMS programs might not efficiently integrate into smaller companies (Hillary, 2004). Compared to larger companies, SMEs in Malaysia suffered from a lack of guidance and resources for sustainable procurement (McMurray, Islam, Siwar, & Fien, 2014). LCAs are often reported to be too complex, even for large companies with many resources (Tarabella & Burchi, 2011; Zackrisson, Rocha, Christiansen, & Jarnehammar, 2008). Simplification of LCA such as screening LCAs are being developed and might be more suited to smaller companies (Klöpffer, Curran, Frankl, Heijungs, & Köhler, 2007). Even after sustainability initiatives have been implemented, they may be discontinued if they are too difficult, or take too much time; De Silva (2016) found that sustainability practices would be discontinued after they had been implemented if there was too much paperwork. In the U.K., 38% of SMEs reported that a lack of information on how to be 'environmentally friendly' prevented the implementation of sustainable initiatives (Revell et al., 2009). Le Pochat et al. (2007) suggested that even if a wide-range of tools were available, if a tool is too difficult, they might not become widespread; this could reduce the overall uptake of sustainability initiatives. Therefore, SAs for SMEs either have to be simple enough for a non-expert to perform it, or training must be available.

All interviewed SMEs believed that no one in their direct working group would have the expertise to perform SAs, with the exception of the largest company. Many expressed a desire to have a specialized staff member, lab, or division to perform these assessments. Many nano-companies start with the majority of employees as product developers, chemists, engineers, who all are involved in many aspects of the company, with little differentiation amongst roles. *StAl*-micros and *StAl*-smalls said. "…everybody does everything…", "…as a small company we all wear many hats", and had no one with expertise in SA. The three companies that had performed LCAs had either an affiliate company that could provide the resources and expertise to perform these assessments (through established sustainability departments), or had already established a relationship with an expert in the field of assessment in a previous project. Furthermore, companies that had performed SAs were characterized as those that were collaborative and had actively searched for partnerships with outside companies or governmental agencies that could perform assessments or parts of assessments (*e.g.* perform environmental health and safety research). Therefore, for SAs to be appropriate for nano-SMEs, they should be able to be performed by one of the team members (usually engineers or chemists). Or, a company has to find this expertise outside of their company.

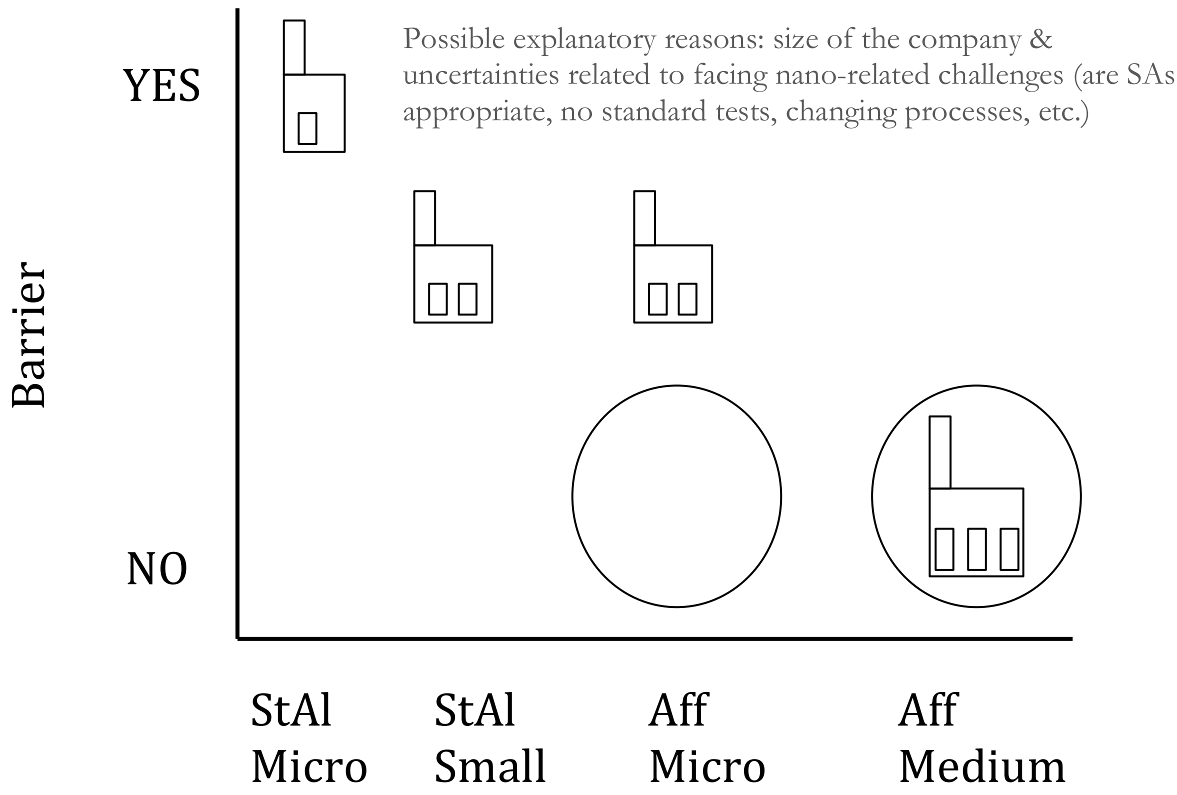


Figure 4-3 Relationship between company size and expertise as a barrier

Inadequate tools or insufficient access to tools

A lack of appropriate assessment tools and insufficient access to tools are reported to be a barrier to environmental improvements in some fields (Borga et al., 2009; CEC, 2007; Tarantini et al., 2009). For example, 38% of SMEs in the refurbishment sector believe that lack of tools is a barrier; on the other hand, 46% of those interviewed in the same study said that this does not hinder participation, and instead felt the real barrier was limited training available to help select and use the available tools (Häkkinen et al., 2016). Some SMEs believed that the available tools are too formal for smaller, informally organizationized companies (Johnson & Schaltegger, 2015). As the concept of sustainability grows, managers are realizing that they need to know more, and might be interested in adopting sustainable practices. Collins et al. (2010) found that 31% of New Zealand SMEs felt they lacked the knowledge and skills to implement sustainable practices, but would like to know more; however, "…getting information on what do to is difficult".

In the interviews, access to software, equipment, and tools to perform SAs were sometimes cited as a barrier. Only one company explicitly stated that they did not feel like they had the necessary software or technology to do advanced assessments; this *StAl*-micro company said "…we're using the same web platform as some grandma selling her bobbles and knitting". One *StAl*-small expressed their desire for more resources, saying that it "would be good to have an established lab that is qualified to do standard measurements". Since the larger companies had existing departments for SA or the means to hire outside expertise, this was not an issue for them. Again, the companies that had performed SAs had actively found collaborators who could provide the tools or access. In general, a lack of access to tools was not discussed as a barrier – since most of the companies did not seem to have a desire to do SA, it is likely that most SMEs have not looked into the types of tools available or needed. When evaluating which SA to perform, platforms that require basic software or technological needs, or provide open platforms (*i.e.* users can freely download the tool), will make them more accessible to companies.

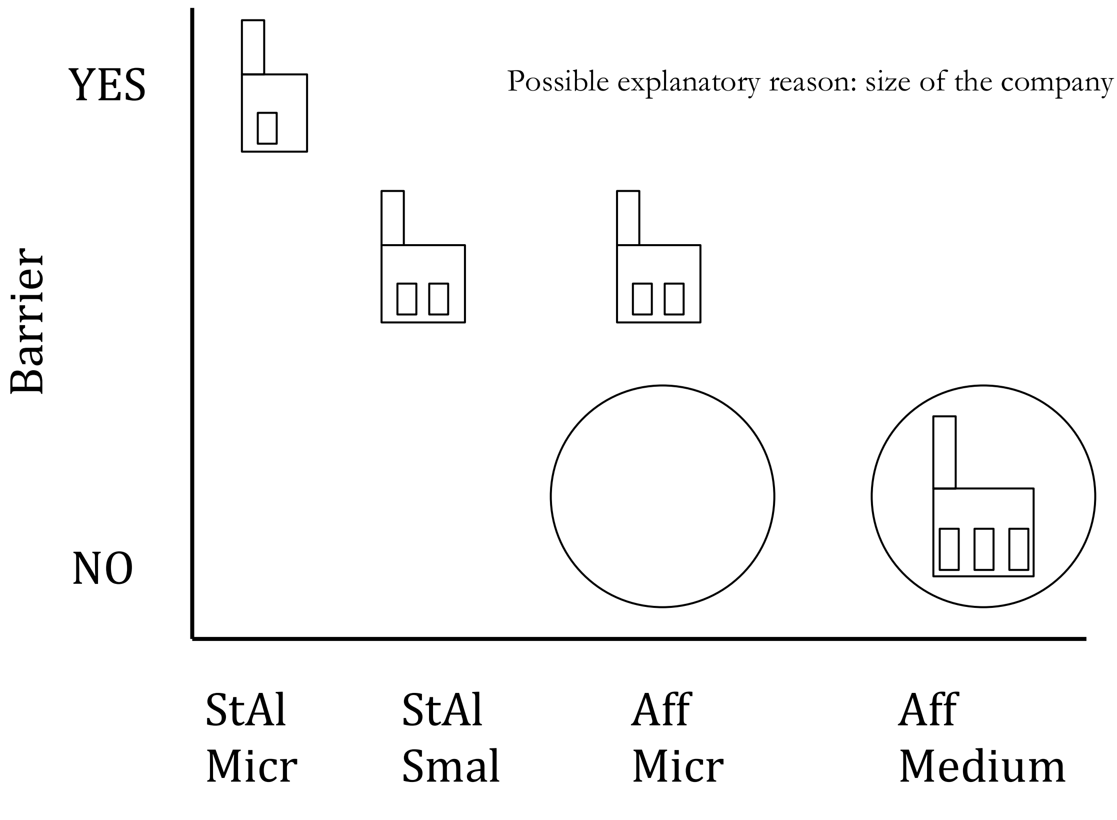


Figure 4-4 Relationship between company size and access to tools as a barrier

Lack of data

Some SAs require intense or comprehensive data inputs. To do assessments, considerable initial data (*e.g.* energy/water/raw material use, environmental impacts, supply chain information) is needed, and sometimes companies are not capable of collecting these data themselves, or the information is not made publically available, or by their suppliers. Häkkinen et al. (2016) found that 68% of companies thought that a lack of data was a barrier to doing energy performance assessment, whereas only 9% thought this was not a challenge. It is often not clear who is responsible for collecting or providing these data (Häkkinen et al., 2016). LCA is a particular data-intense assessment; however, in some sectors, the necessary input data are similar amongst companies and therefore preclude the need of a company to actually generate their own data. Databases for LCA contain immense amounts of information. Despite this, these databases can often be expensive, complex, or hard to find, and thus be a barrier for SMEs (Rybaczewska-Blazejowska & Luscinski, 2014). Furthermore, the data in these databases may not be applicable for nano-companies using novel processes.

In general, smaller companies had not thought much about data needs. All companies had at least some basic information on their processes, such as energy use and water use, and larger companies tended to already have more data (Figure 4-5). A few SMEs were at an early developmental phase meaning they were not sure what the predicted scaled-up manufacturing process would be. Any company that was near, or at commercialization would probably have adequate data to perform at least a basic SA. One *Aff*-micro company that had not yet performed a SA remarked that, "We're getting to the point of development now where we'll actually have the data we need to input into some of these models to get a sustainability metric or measure for our material".

Another barrier to data collection is that even if there are resources, expertise, and money available, the methods to collect data for SAs are unreliable or not well defined for nanomaterials. One company suggested that they had performed a number of different tests (*e.g.* biodegradability, toxicity), but it was unsure as to whether they were representative of their material in realistic situations. There were certain areas of concern, even the largest company who had performed an LCA expressed their concern, stating "…at the moment.

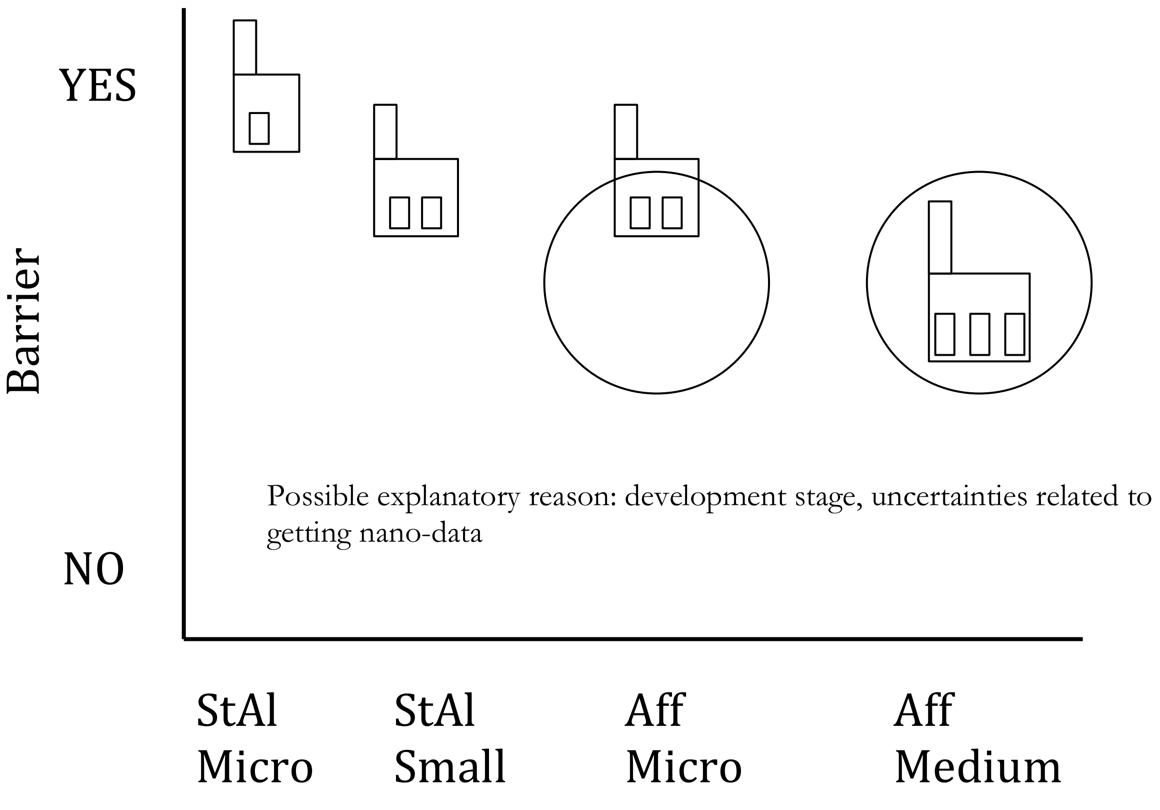


Figure 4-5 Relationship between company size and lack of data as a barrier

All the interviewed companies acknowledged that a lot of data would be needed for SAs and most companies expressed reservations in sharing data. Most indicated that they would consider sharing data if others were, but many questioned whether other companies would do the same (*e.g.* "…some companies want to see [LCA data], but they don't want to supply"). One large company, while stating they would not disclose their energy consumption to their competitors, thought that creating a consortium with well-defined non-disclosure agreements would be beneficial for all. Similarly, one SME suggested that an open source LCA containing nanomaterial-specific data would be valuable.

SAs aimed at nano-companies, especially smaller ones, must be able to deal with a lack of data, or at least provide some value with only limited data. SAs must take into account that some tests are not available or appropriate for nanomaterial assessment. In addition, releasing publically accessible data and the sharing of resources amongst nano-companies would help alleviate this pressure.

Product development stage

Sustainability assessments performed on immature technologies will only provide a snapshot of their potential future impacts (Kim & Fthenakis, 2012). Based on an evaluation of the availability of CSR reports in nano-companies, in general the lowest level of reporting occurs amongst companies in the research and development stages. The companies interviewed encompassed a range of product development stages, ranging from research and development, to pilot scale, to full-scale industrial plant. The fact that most companies were still experimenting with different raw materials, production processes, and end product/application use, was often cited as a reason to not perform a SA. Furthermore, one SME in research and development stage stated "I think we have to get to a certain scale…to have better numbers in the calculations", indicating that they thought that it is more useful to perform SA on materials at later stages of development. Even large companies that had performed LCAs disclosed that they felt that the LCAs would have to be re-done in future, as production processes and materials continued to change. One large company stated that they performed informal assessments at each stage of development to give indications as to the final features of the products (*e.g.* "We can't end up with a hard-to-recycle material with an increased carbon footprint"), and to guide their development process.

A lack of awareness

While some companies may not believe they have sustainability impacts, an even larger problem may be that companies are not even aware that such problems exist (CEC, 2007; Johnson & Schaltegger, 2015). Indeed, this appears to be a problem in many countries, such as Italy (Tarantini et al., 2009), Malaysia (McMurray et al., 2014), and China (Yu & Bell, 2007).

Most of the companies interviewed appeared to have at least a basic awareness of sustainability issues, especially in the environmental health and safety domains. All companies felt that: 1. They had done enough tests (*e.g.* environmental toxicity) to show that their nanomaterial was safe; or, 2. There was enough evidence on the conventional material to feel confident that it was sustainable; or, 3. They had done enough informal assessments to get a good sense of their product's sustainability. When asked if their nano-product was sustainable, each nano-company varied on different aspects of sustainability addressed. Answers ranged from safety of the conventional material, the use of renewable raw materials, the creation of more renewable and compostable products, the replacement of more harmful or heavier materials, the release of less toxic chemicals, the energy savings associated with more efficient manufacturing processes, the replacement of animal-based products, and so forth. All of the

StAl micro companies, half of the *StAl* small companies, and all of the *Aff* micro companies stated that doing a formal SA was not a priority, and all felt that there was no point in doing SAs on their materials. Since all the companies at least partially believed that their products were sustainable, they did not appear to believe there was any point in doing them. For example, one company said "…they are not dangerous, so it is not a top priority", and another, "for us…it hasn't been prioritized...[our material] is sustainable…. But sooner or later we'll have to do those tests". In contrast, two companies that had performed a SA felt as though they had identified impacts they could improve on. Interestingly, one of the companies that had performed an LCA thought that it was too specific; they had performed the SA as a requirement of the investment process, but the interviewee thought it was not useful for giving an accurate picture of their process, and did not put too much stock into the results.

When questioned about some lesser-known aspects of sustainability, such as societal benefits, the interviewees were less sure about their activities in these aspects. One felt that regulatory compliance would be enough to ensure social equality (*i.e.* decent worker wages), one felt that their awareness of the supply chain actors and the source of their raw materials fulfilled this need, and another company felt that social equality was part of their country's culture. This uncertainty is also reflected within the development of SAs where the choice of social indicators and the system for measurement vary drastically between methods. Environmental and human health issues have been at the forefront of sustainability efforts and legislative actions; however, the social aspects have yet to catch up.

For the nano-companies interviewed, there seemed to be a high level of awareness of potential sustainability issues, though a comprehensive understanding of all aspects might be lacking.

A belief of neglible sustainability impacts

If a company does not believe it has environmental impacts, then it will likely not implement any sustainability measures. Some studies have suggested that many SMEs believe they do not have significant environmental impacts, and therefore feel little responsibility towards the environment and society (Salimzadeh & Courvisanos, 2015). In Portugal, the third most cited reason (36% of respondents) for not performing sustainability reporting was that they believed that they did not generate any significant impacts (Ramos et al., 2013). While small companies might not individually generate impacts on the same scale as larger companies, the combined impact of all companies is 60-70% of all impacts (Calogirou et al., 2010).

There was hesitation from most nano-companies to unequivocally say that their nano-product was sustainable, and many questioned the concept of sustainability, saying, "That's a difficult question…Depending on how you look at them" and "Depends on how that is defined". This uncertainty is expected and reasonable since 'sustainability' is a relatively broad domain and is difficult to capture in one measure, as pointed out by one company who said, "I know enough about sustainability to not make any broad statements about sustainability". These statements indicated that most companies have a relatively good understanding that sustainability is a mix of various factors. Companies that performed an LCA felt confident that their products were sustainable in terms of carbon footprint.

Interestingly, at least nine companies stated that they thought they were pretty sure their materials were sustainable (the other five did not answer clearly), despite the fact that six had not performed any formal sustainability assessment on their materials. Statements such as "…we feel that this should be a safe material…", "…[the conventional material] has been used as a medical excipient…so there are strong indications that there's not going to be a killer tomato around the corner" indicate that most of these statements are based on intuition, feeling, and/or experience with similar materials. Companies that used waste products as starting materials had particularly strong convictions as to their product's sustainability.

An interesting point made by some nano-companies is that they felt that they were more advanced in terms of technology and processes than companies producing the conventional counterparts – some companies felt that they had the opportunity to 'leap ahead' through the ability to purchase the newest technologies and implement improved or novel manufacturing processes for their materials. Indeed, companies such as the pulp and paper industry may have old machinery, even though newer and more efficient models have been developed. A company in the graphene industry that had purchased traditional equipment, but had performed some modifications unique to their materials, felt that they were able to pass on knowledge to the traditional pulp and paper industry to improve their processes.

Since this was an open and broad question, it is hard to identify any emerging trends from this in terms of sizes of nano-companies. It would be interesting to ask each company about their products' sustainability in terms of different aspects (environmental/social/economic impact in each of the raw material extraction, production, transport, use, and end of life phases). Most companies felt they had done enough to address the major sustainability aspects of their products as this point in time through informal means and did not necessarily need to do formal SA as this point in time.

Narrow view of sustainability

The interviewee's perception of sustainability was not directly asked, but it was observed during interviews that many companies had different ideas of what sustainability means. Interviewees equated sustainability with 'Good Laboratory Practices' (a standardized quality system of management controls a lab must follow when doing chemical testing, which are often required by regulatory agencies), good internal quality control, environmental health and safety, scalability, risk assessments, safety of products, the use of renewable base materials, and/or any material that is not toxic. While all the companies spoke about these economic, environmental, and human health aspects of their products, none mentioned any global societal aspects (*e.g.* job creation, stakeholder participation, social equality) without prompting. When asked about global impacts, most companies responded that they felt that they were aware of the activities of the actors along the supply chain, they knew the source of their raw materials, and that their employees were treated well. Interestingly, when prompted to discuss whether they evaluated any overall social or societal impacts or aspects associated with the production of their products, they all took a longer time to reflect on and respond to the question, in comparison to other questions. This may be interpreted as a lack of attention or awareness within companies to address social issues, but also is understood to be an abstract question. If a company believes that sustainability is simply related to one aspect, for example the source of its materials, then a company might believe that it is 'sustainable' if it fulfills this criterion. This might be considered a barrier to deciding to a SA. It should be noted that many companies did recognize that sustainability had many dimensions

Performance of informal sustainability assessments

By nature, any company, especially those dealing with technological processes, are attempting to reduce their resource needs to reduce their costs. The costs associated with manufacturing have pushed producers to improve their environmental performance, for example through reduction of energy-, water-, and raw-material use. This is an essential component of any chemical- or product- manufacturing company, and is especially relevant for start-ups producing innovative and novel materials. The companies interviewed commonly referred to 'closing the loop', 'reduction of chemical use', or 'decrease of mechanical energy use' as their strategies for reducing costs and making processes more efficient for nanomaterial production. While they may not be performed purely for a sustainable purpose – they do contribute to sustainable improvements.

While all SMEs stated they were not performing SAs, many were actually performing assessments that could, in part, contribute to a full SA. For example, high energy use during nanomaterial production was often cited as the main concern in terms of environmental impact. The companies that discussed this had already done informal assessments and made changes to their manufacturing process to reduce this use. Many already performed tests like biodegradability and ecotoxicity to ensure regulatory requirements were satisfied. Occupational safety was a major concern of most of the producers, and interviewees felt as though they had taken measures to avoid worker exposure.

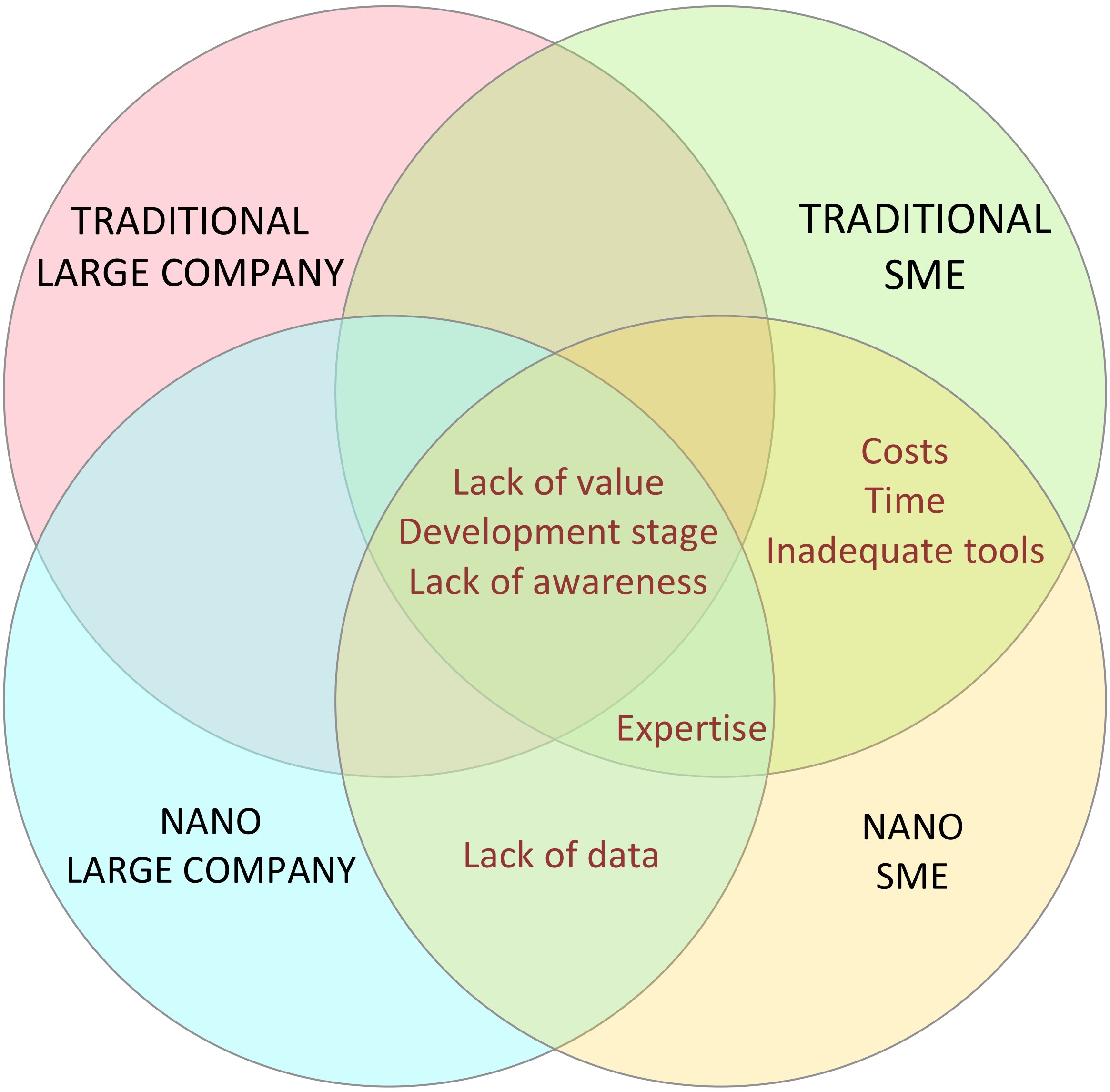


Figure 4-6 Summary of barriers

Other barriers

Some other factors reported in the literature that prevent companies from doing SAs or implementing sustainability initiatives included a lack of legal obligation or pressure (*e.g.* tourism in Cyprus; Farmaki, Constanti, Yiasemi, & Karis, 2014) and environmental reporting in Singapore (Perry & Tse Sheng, 1999). In the UK, 71% of SMEs had difficulties keeping up with legislation that may have particular sustainability requirements (Simpson et al., 2004). Some companies report that a lack of political support hinders their ability to be more sustainable (McMurray et al., 2014). Long-term planning is necessary to implement and advance sustainability projects; for many SMEs, they are constantly dealing with the chance of immediate failure and financial ruin, but have an inability to do the long-term planning (CEC, 2007; McMurray et al., 2014; Tarantini et al., 2009). Some reports showed that employees believe that a flawed management structure is to blame for a lack of sustainable actions (Yu & Bell, 2007).

Summary of the barriers

Based on the results found in sections 4.1.1 to 4.1.13 it was determined that barriers preventing nano-companies from performing SAs were varied. Some barriers were more prohibitive for smaller companies than larger companies, and some barriers were specific to nano-companies. Figure 4-6 is a summary of the barriers and their general relation to different sized companies (where 'large' constitutes more than 250 employees, and in this case is inclusive of employees at parent companies), and also to whether a company is involved with nanomaterials ('nano') or not ('traditional').

4.1.2 Benefits encouraging the performance of SAs

Companies who are pro-active in their sustainability efforts can access many benefits. Interviewees cited a number of different incentives and motivations to do SAs or be sustainable, which supported findings from literature. Nano-companies that engage in sustainability can manage their risks more effectively, encourage company growth, and access returns on capital (Bonini & Swartz, 2014; EY, 2013).

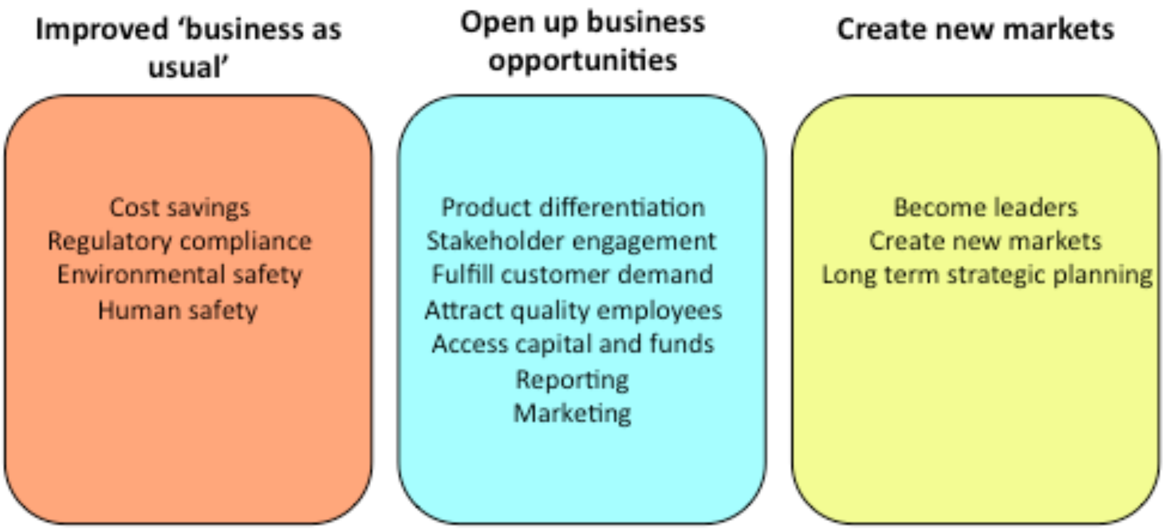


Figure 4-7 Different stages of benefits creation

In the past, market leaders in sustainability have progressed through stages of sustainability (Lubin and Esty, 2010). The main benefits discovered here fit with this observation, and are grouped accordingly (with a limited scope on manufacturing, not whole company improvements). The first focus of a company may be reduced waste, risks, and costs. Then companies move to optimal product performance and differentiation. At the highest level, companies may start looking to the future and other markets. Figure 4-7 shows these three categories and the specific benefits accessed by functioning in a sustainable manner.

Internal assessment benefits – "Improved business as usual"

These benefits come from an assessment of only internal processes to make improvements, resulting in an "improved business as usual" scenario. These include:

- Cost savings
- Regulatory compliance
- Reduced environmental safety risks
- Reduced human safety risks

SAs can help achieve these benefits by helping identify hotspots and resources inputs and outputs to improve manufacturing efficiency and ensure safety to reduce the chances of injury and damage to the environment, to workers, and the public. They ensure that a company and its products are in regulatory compliance, and health and safety risks have been assessed and dealt with to ensure that there are no concerns. In general, these benefits can be achieved in short time periods, and can confer short-term benefits and cost savings. The do not necessarily take all aspects of sustainability into account, benefit in the longer term, as they do not provide for differentiation from other companies, take stakeholders into account, or consider long term risks.

External assessment benefits – "Open up business opportunities"

These benefits come from an assessment that looks beyond the internal workings of the company, and can 'open up business opportunities". These include:

- Product differentiation
- Stakeholder engagement
- Fulfill customer demand
- Attract high quality employees
- Open opportunities to new capital and funds
- Use for reporting
- Use for marketing

SAs can help achieve these benefits. They can result in product differentiation through improving its sustainability profile while also reducing internal costs. SAs ensure interaction and inclusion of stakeholders to understand current markets. The can produce results that fulfill customer demand and be disseminated through reports or marketing. The performance of SAs can attract employees who have similar values. New opportunities may be accessed through a higher sustainability profile. In general, these benefits can be achieved either in short time or relatively long time periods, and can confer short and long term benefits and cost savings. They try and take all aspects of sustainability into account and might provide protection against future risks.

Future assessment benefits – "Create new markets"

These benefits come from an assessment that takes potential future possibilities into account, and can 'create new markets' for their nanoproducts. These include:

- Becoming leaders in the field
- Creation of new markets for the company's product
- Long term strategic planning

SAs can help achieve these benefits. They can result in the company becoming a leader in its field by showing that it is taking measures to improve all dimensions of sustainability. In addition, they encourage research into future risks and opportunities which allow for suitable protection measures to be put into place. This long term planning can reduce uncertainty and improve long term stability of a company. It ensures a current and future market, and can result in creating a new and stable market for the company's product.

4.1.2.1 "Improved Business as Usual"

Cost savings

The savings and return on capital associated with sustainability has been well documented. Chemical companies all over the world are reporting significant gains when implementing eco-efficient measures in their production processes. Production processes can be made more sustainable and also save costs by reducing raw material use, lowering energy and water consumption, producing less waste, and closing chemical loops through re-use (Eder, 2003; Jenck et al., 2004). DuPont introduced more sustainable manufacturing technology for Lycra, and cut 2 ktpa of waste, while earning an added USD 4 million/year (Jenck et al., 2004). Bayer expects that a resource-efficiency check will result in waste water and resource reduction will save more than USD 10 million pear year (Bonini & Swartz, 2014). It is estimated that approximately 25% of earnings can be impacted by supply chain disruptions and up to 60% by the rising costs of operation (Bonini & Swartz, 2014). Dow chemical invested less than USD 2 billion to improve energy intensity, resulting in USD 9.4 billion in savings.

Interestingly, few companies believe that there was substantial economic value resulting from investment into sustainability options. In Australia, only 19% of SMEs believe that they will benefit financially from sustainability investment (McKeiver & Gadenne, 2005). In Singapore, over 40% of companies do not believe that environmental investments will result in improved opportunities, including both cost savings or better support from shareholders (Perry & Tse Sheng, 1999). Simpson et al. (2004) (Simpson et al., 2004) found that half of SMEs did recognize the potential to increase their revenue, or reduce costs in the future through environmental improvements. The concept of 'cleaner production', a preventative approach to production that includes use of cleaner, more resource efficient equipment over the whole life cycle, has been a rapidly growing concept since the late 1990s (R. U. Ayres & Ayres, 2001), and has been actively practiced in the chemical industry long before that (Eder, 2003). In terms of SAs, researchers in Italy have found that one of the main barriers to performing these assessments are related to their awareness of their benefits (Tarantini et al., 2009). 42% of SMEs thought that a lack of understanding regarding the benefits of carrying out energy performance assessments was a barrier. Based on the interviews, it seems as though nano-companies, especially smaller ones, are interested in cost savings through sustainable measures, but do not see these happening through the performance of a SA (see Section

4.1.1). However, most of the companies indicated that they would be willing to do a SA if they thought there would be substantial financial rewards.

Regulatory compliance

Governments are proceeding cautiously, and while there are few "nano-specific" regulations in place, they are generally taking a preventative approach, and requiring that the use of nanomaterials be judged on a case by case basis (EC, 2012b; FDA, 2014). While the European Commission recently rejected the idea of creating a EU-wide nano-register, some countries such as France, Belgium, Denmark, Norway have created their own mandatory registries (ChemSafetyPro, 2016). Sweden just announced a mandatory nanoregister for 2019 (KEMI, 2015). "Nano" must be put on the labels of some products in high-risk sectors such as novel foods (EU regulation No 258/97), cosmetics (EC No 1223/2009), biocides (EU regulation No 528/2012). The administrative costs related to complying to regulations can be significant, especially for SMEs (RPABiPro, 2014). Being aware of these will allow companies to ensure their products comply, and make decisions as to whether it is worth pursuing these options.

Regulation is often an important determinant in driving environmental innovation (Horbach, Rammer, & Rennings, 2012). In this study, all of the companies came from countries with stringent chemicals regulations, and therefore were performing a base level of safety testing and demonstration, which is commonly observed globally (Horbach et al., 2012). Two large company and one SME specifically *regulations and compliance* as a reason to perform a SA, and all companies that had commercialized, or were close to commercialization, had performed the tests required to address regulatory concerns. As the regulations change, such as the mandatory registration of nanomaterials in Sweden in 2019 (KEMI, 2015) or the overhaul of chemicals regulation in the U.S. (Shimkus, 2016), it can be expected that this will be a driver for sustainable changes within these companies. While global regulations on nanomaterials are not harmonized, changes in regulations abroad will likely be a driver for nano-companies to make changes. For examples, any nano-companies wishing to export nanomaterial-containing food to the EU must follow REACH regulations requiring registration, safety testing, and labeling of any nanomaterials in food due to their new classification as "novel foods" (EU, 2015). Interestingly, some of the micro-companies specifically mentioned that they did not have anyone in the company tracking changes in regulation.

Human health and environmental safety

Nano-companies have an exceptional challenge of proving to customers and the public in general that their products are safe. Nanomaterials are still a relatively new product, with many confusing messages. Some dangerous products that have been labeled 'nano' have turned out to not containing any nanomaterials. For example, in 2006, the use of a "NanoMagic" spray resulted in at least 153 reported cases of respiratory harm (Pauluhn, Hahn, & Spielmann, 2008). This caused a recall in the product; but after inspection of the product, no nanomaterials were deemed to be actually in the product (Pauluhn et al., 2008). Being proactive and ensuring that data to support safety claims will be beneficial for nano-companies. Public perception of nanotechnology is still uncertain; surveys indicate that the general public has a higher perception of risk from nanotchnologies than academics, government officials, and industry (Capon, Gillespie, Rolfe, & Smith, 2015). The public also has different perceptions than nano-businesses of the riskiest applications for nano (food vs pesticides) (Capon et al., 2015), therefore companies should not assume that their views are mirrored by the public. The companies surveyed here recognized these issues, and all thought that ensuring *occupational safety* was important, for example stating that "Occupational health and safety questions are maybe even more important [than public safety] since these workers will be at risk of directly inhaling the materials." One SME thought they would be important to help gather public safety data, to ensure that "…everybody within a 5-mile radius [doesn't] grow flippers". Companies that spend time getting to know their stakeholders will benefit by open dialogue, preparing data that will support any claims of safety and sustainability, and also being better informed in the technologies that carry the least risk.

Risk management is reported by 61% of sustainability managers as one of the top three reasons driving sustainability initiatives (EY, 2013). It is not known if nano-companies see this as a concern, but it would be in their best interest to anticipate risks. This is still a young field with few examples of commercialization so far; therefore changes in regulation, uncertainties in safety risks, and potential for rapid public changes in opinion mean that nano-companies should be aware of, and prepare for any changes in these areas with a long-term strategy. The risk of *not being sustainable* has been demonstrated in many high-profile cases; for example, BP's Gulf of Mexico oil spill and deaths of 11 crew members that occurred as a result of gross negligence resulted in losses of more than USD 32 million per day in brand value, and its stock and image continued to decrease after initially dismissing the damage of the spill (Chamberlin, 2014; IFC, 2015).

4.1.2.2 "Open up business opportunities"

Product differentiation

In theory, product differentiation can lead to premium prices, an increase in customers, and bringing greater buyer loyalty (Porter 1985). By the nature of containing what are considered new technologies, nanoproducts are already differentiated. However, having an improved sustainability impact can also be used as a leverage point for companies, and SAs can be used as a tool to lead to product redesign with improved sustainable impact. Some SAs also consider the benefits of the materials, which can highlight their positive impacts, even if some aspects are more negative than the alternative materials.

Product differentiation based on sustainable properties can appeal to customers based on their characteristics (*e.g.* fairly traded products), or their promise for efficiency and cost savings during the use phase (*e.g.* fuel efficiency). Products that help customers save energy and costs are piquing customer interest; sales are increasing in areas such as energy-efficient appliances and lighting and home materials that save energy (*e.g.* heat-reflecting windows) (Ottaman 2006). Some companies have capitalized on product differentiation in sustainable areas; for example, Philips has increased its sales of 'green' products to 54% of its total sales, and these are steadily increase in all of healthcare, consumer, and lighting sectors (Philips 2015). Given the potential for nano-products to help in these fields, there is great opportunity for producers to start thinking about product differentiation on the basis of sustainability while also providing added functionality.

Most of the companies believe that their materials are better than the materials they are replacing, because their use can save material and replace plastic, metals, and petrochemicals, are renewable and biodegradable, are lighter, and use fewer raw materials. Interviewees were very confident about the sustainability of their materials, stating, "…it will always be positive, it will outweigh the negative", "…the gain is so much that it'll be worthwhile to fix any kind of environmental downfall", and "…on the whole, it's a gain". Many companies are already using the use-stage benefits of their products as selling points. Three interviewees were asked whether they thought that marketing a lowered environmental impact of the manufacturing phase would be useful, and not one thought this would help, and considered this more related to lowering costs. These companies can leverage these benefits to access new markets.

Green marketing potential and stakeholder demand

By performing SAs and improving their sustainability profile, companies tap into the ability to market based on sustainability. There is in increase in sustainability reporting (GRI 2009) and sustainability disclosures can act as a differentiator and improve investor confidence as well as trust in other stakeholders, like employees (Ey, 2013). Voluntary disclosure has been correlated to the increased interest in dedicated investors and a reduction in cost of equity of capital (Dhaliwal, 2011).

There are mixed indications as to whether investors, customers, regulators, and other stakeholders are interested in sustainability actions, and therefore benefits may not been seen in terms of performing a SA to fulfill stakeholder needs. Certainly, if these actions are related to cost-savings and increased competitiveness, then it is valued. In Portugal, one main reason CSR activities are low because there is a lack of external stakeholder demand (Ramos et al., 2013). Long term energy performance assessment does not interest investors (Häkkinen et al., 2016), and SMEs in the UK do not believe that customer satisfaction are related to environmental good practice; 47% thought it would have an effect in the future (Simpson et al., 2004). Few SMEs publish sustainability reports because they believe there's a lack of public visibility (Bos-Brouwers, 2009); 70-81% of small and medium Italian furniture companies are not interested in any sort of environmental communication tool (Borga et al., 2009). A study looking at environmental product declarations (EPDs) from different types of SMEs determine that there was a lack of market pull in all sectors tested; when customers were presented with the EPDs, there was mixed response, with some customers appreciating the information while others were concerned that there was increased cost due to the EPD (Zackrisson et al., 2008).

When asked about the demand for sustainability data from customers, the answers were mixed – all companies that had done SAs said there was demand, and companies that had not performed SAs stated that up until this point, customers had not specifically asked for quantitative data for their products. The firms that indicated that customers wanted the data were adamant that it was necessary; one company stated that *all* customers are concerned about the carbon footprint of their products and another stated 'To be able to launch a product, you must launch it with an LCA", and that it was part of the investment process.

When asked about the possibility of the need for data in the future, nano-companies had differing opinions. A company suggested that the extra cost would not be worth it to the customers, stating, "Most people, I don't think, will want to spend money to get extra green stuff'. One *Aff*-micro stated that they did not think it would be necessary, due to the positive response they have received up until now, while another said, "I suspect that as we develop our customer base further, we will be asked at some point for [sustainability] data"; the driving factor for this company to perform a SA would then be direct customer demand. One of the companies said that as long as their products passed the regulatory hurdles and approvals (*e.g.* for safety) then their customers were happy and did not demand the data or numbers. One *StAl*-micro company felt that the customers, or those buying the nanomaterials, should be doing the assessments. On the contrary, a different SME, who buys nanocellulose materials to make products stated, "…we're depending on them [the producers] to do the assessments".

There was also indication that interviewees had seen a shift away from interest in energy consumption purely as economical question and more as an ethical question. SMEs have had experience having to provide some sustainability data, primarily biodegradability and toxicity data, or a safety data sheet (SDS) to customers, especially when in business to business (B2B) exchanges, where "…the safety data sheet is the price of admission into a number of these places…if we [the SME] want to sell to these guys, we have to do this [sustainability assessments]". One *StAl*-micro observed that "customers still need the products to have the same attributes and price as the products they are replacing, and if these aspects were satisfied, *then* the green aspect would be 'loved'".

Open opportunities to new capital and funds

Since nano-companies are generally still in early development stages, and have shown themselves to be innovators, they need to continually find new investors, customers, and funders. Introducing sustainability measures can help access new markets and new capital. While eco-efficiency is an important part of cost savings and overall lower sustainable impacts, it is important to also focus on creating new processes and technologies in order to meet market demands, or even to create markets for innovative, sustainable products. Performing sustainability assessments can push innovation and improve the sustainability of products, thereby opening up new opportunities and diversifying the portfolio. The internal company is also an important component of growth; happy, fairly treated and paid employees can ensure stability and promote positive growth.

Investors and funders have a growing interest in green technologies; they may be interested in the sustainability profile of the product, but also interested in their beneficial uses (UNEP, 2011). In some sectors, such as agriculture and energy, there is a growing interest in private investors, and they often demand full environmental and social disclosure for risk monitoring (UNEP, 2011). In the U.S., investment in firms that have environmental and social priorities is rapidly increasing and socially responsible investment now accounts for >11% of all managed assets (Bonini & Swartz, 2014). In addition, companies that can show they produce sustainable materials can access unique funding sources. Many funding agencies have research priorities that are solely sustainability-based, and require proof of positive environmental, social, and economic impacts, such as EPA's Small Business Innovation Program (US EPA, 2016) and Sustainable Development Technology Canada (SDTC, 2016).

Internal growth

A company may perform a SA to fulfill their *intrinsic values*; where they believe that being sustainable should be an important part of business that is not necessarily linked to economic or business goals. Global surveys have shown that attitudes towards environmental issues differ drastically from country to country. For example, the World Values Survey (2000) showed that the majority (85-96%) of North Americans, Europeans, and Japanese believe that humans should coexist with nature, whereas over 40% of those in Jordan, Vietnam, Tanzania, and the Philippines believed that human beings should 'master' Nature (Leiserowitz, Kates, & Parris, 2006). Interestingly, in countries where pollution may more obviously directly affect the quality of life, citizens may have a stronger desire for some more "environmentally friendly" products. For example, 28% of people in high income countries are willing to pay 10% more for gasoline if the money would be used to reduce air pollution, whereas in low income countries, 36% would be willing to pay (Leiserowitz et al., 2006). An increased level of sustainability awareness may be related to education and public programmes (Potts, 2010) and the active role of governments and legislation (Gadenne, Kennedy, & McKeiver, 2008; Salimzadeh & Courvisanos, 2015).

Having a more sustainable company may result in a more stable base of employees and draw in more talent (Jones, Willness, & Madey, 2014). Sustainability is important to many people looking for work; up to 40% of job seekers use a company's sustainability report to make application decisions (KPMG, SustainAbility, Futerra Sustainability Communication, 2010).

Employees who are part of an organization that is admired for its sustainability tend to feel more pride in their company (Jones et al., 2014). Having sustainability activities has been shown to draw the interest of job seekers; in having sustainable policies it implies that the company cares about its employees, and also appeals to those who have similar values (Jones et al., 2014). Companies that adopt environmental standards is also associated with greater productivity at the workplace (Delmas & Pekovic, 2012).

In general, the nano-companies appeared to place a high intrinsic value on sustainability. Both large companies and SMEs stated that sustainability was a part of their *company's agenda or mission*. For example, one large company said, "Our main mission is doing good for the people, and the plan to replace plastic and be a renewable material company", and an SME stated, "We always try to think 'why are we doing this'. We want to contribute to a sustainable future." One company that had already performed an LCA felt "…very proud of our work, I feel like we're on the forefront of demonstrating the claims that people say in the literature and conferences, that it's a 'sustainable, low-carbon footprint material'…[because] if you don't make it the right way it's not!".

Despite this reported interest in sustainability, it should be noted that the 'action-value gap', where what an individuals says is different than what an individual does, is commonly reported (Gadenne et al., 2008). That is, owners/managers of companies may have positive attitudes towards sustainability; however, actual implementation of 'green' practices is low (Gadenne et al., 2008). Consequently, while individuals at companies may *want* to be sustainable, any barriers preventing them from implementing sustainable projects are important to consider. In the case of the nano-companies here, five of the companies interviewed explicitly stated that sustainable values was part of their company mission, and that all the employees in their company had similar vision. In these cases, none of the companies were *StAl* micro companies, and this was reflected in their views on doing SAs, with one stating "they are not a top priority", and another bluntly stating, "there's no point in doing an SA, there's no value in doing them". There was no direct link between companies that stated they had intrinsic sustainability values and the performance of a SA, which may a result of the action-value gap, they did indeed already have a good grasp on their sustainability without doing a formal assessment, or the fact that other barriers were keeping them from performing SAs.

4.1.2.3 "Create new markets"

Long term planning, innovation, and access to new markets

The nanotechnology market is relatively new and quickly changing. The demand for nano is very uncertain, and new applications and markets keep changing. Therefore, it is valuable for companies to develop long term plans in order to address potential future markets and ensure that they are sustainable. The integration of sustainability values into a company in the long term is key to sustainable development. Companies that do this successfully can benefit from increased visibility and positive publicity (GlobeScan 2015). More companies are seeing the importance long-term thinking – 68% of the world's largest companies have a long-term sustainability strategy (Ey 2013). SAs can form the foundation for developing a strategy and provide a framework for continual updating, monitoring, and progress tracking within the company. In addition, it will allow for setting a cohesive message and goals. This can lead to improved stability and consistency within the company, and improve stakeholder and investor trust.

There can be difficulties in breaking into a market with a new technology. As an illustration, bio-based materials have huge sustainable potential as they come from renewable sources and can replace many petroleum based materials (like plastics). However, the sector has faced significant challenges that will likely be similar to those faced by the nano-industry. Many are trying to establish themselves as replacements for conventional materials or are trying to create a new market for products that are not yet in demand. They face challenges such as uncertainty with supply chain, the integration and use of unfamiliar or untested technologies, building new relationships with customers, and ensuring that the outcomes of their products are beneficial (Iles & Martin, 2013). Some suggest that developing innovative business models that creating sustainable value propositions is essential to engaging the market (Iles & Martin, 2013).

The performance of SAs will provide opportunities to collaborate with stakeholders and understand potential future needs. These collaborations may continue to provide benefits throughout the life of the company. For example, one small company interviewed had a long-term collaboration with an LCA expert who they had previously worked with for a non-nano related product. Having already established this trust meant that performing an LCA on their nano-product was not a challenge for their product, and they were able to perform the LCA early in their process and make necessary changes. Many companies felt as though their collaborations with unions, local authorities, NGOs, and especially academic labs would pay back dividends throughout their development. One small company felt that the risk of putting the materials into the hands of researchers was worth the risk of losing intellectual property as, as they were convinced that this would make the product more successful.

Collaboration with suppliers and customers will be essential, along with monitoring the progress of sustainability (Iles & Martin, 2013). Asking customers for their needs will allow for nano-companies to capitalize on new markets and stay competitive. In general, good communication and effective collaboration are important characteristics of successful innovative firms, and companies that have employed environmental standards and subsequent training encourage employee interaction and idea sharing, which can lead to better problem solving and innovation development (Delmas & Pekovic, 2012; Rothwell, 1977).

4.2 Evaluation of product sustainability assessments

A wide range of SAs was found and they ranged from specific methodologies to generic frameworks. There are many product- or sector- specific assessments; since nanomaterials span a wide range of sectors, and even one type of nanomaterial can be used in many different types of products, then none of these SAs will apply to one type of nanomaterial, or even class of nanomaterials. Therefore, SAs that were generic enough to apply to all nanomaterials and nano-products were included.

Most of the SAs have a similar approach (with the exception of checklists) (Figure 2). First, the user defines the goals of the study, which sets the overall context to guide the study participants; then defines the scope, which sets the boundaries so that the system(s) to be evaluated are well defined, and often includes a schematic diagram to be drawn; then develops an inventory of the input and outputs of the process in question (*i.e.* manufacturing, use, etc.); performs the impact assessment, where outputs and inputs are categorized and characterized according to the magnitude of their impact, and expressed as an impact equivalent (*e.g.* global warming potential); analyzes the data to satisfy the goals (*e.g.* to identify hotpots, to compare to another product); and finally, reports in either a formal or informal manner.

Figure 4-8 General approach of sustainability assessments

Here, each SA is described, compared, and evaluated based on whether nanocompanies are capable of performing the SA based on the barriers and the outcomes they may provide. Comparative evaluations are provided in Table 4-1 (Methods), Table 4-3 (Guidelines & Checklists), and Table 4-4 (Frameworks).

4.2.1 Checklists

Checklists are straightforward and easy to understand and can provide a company a simple way to ensure they have considered many different aspects of sustainability. As an outcome, companies may identify areas that need to be improved, or may have missed, and can come back to the checklist throughout many stages of development and can see if they are progressing.

These types of analyses are advantageous for companies looking for a simple way to assess the current status of the company, look for any gaps in knowledge, or track general progress over time. They generally do not have a quantitative or integrated aspect of assessment (*i.e.* each answer is binary, "yes" or "no"), therefore cannot be used for comparative purposes, and do not have a weighting or prioritization component to rank the important of different indicators. Some questions may be vague and difficult to answer as "yes" or "no", and may be a challenge to interpret consistently, especially if different people perform the assessment.

The Green Chemistry Checklist

The Green Chemistry Checklist was developed by the Michigan Green Chemistry Roundtable and the Green Chemistry and Commerce Council (Michigan Green Chemistry a Council, 2014). It is a general checklist of activities and metrics developed for companies that make products and chemicals to measure progress in manufacturing safer products. The four categories of focus are: education, hiring, design and innovation, and support and communication. Within each of these categories, companies can check whether they have measures in place within their company to support 'green chemistry'. The checklist does not explicitly require any complex measurements, and in theory encompasses many dimensions of sustainability, but through relatively general requirements like "commercialize products with Green Chemistry advantages over existing chemicals or products". This may be difficult for companies to assess as there can be many dimensions this; economic, environmental toxic impact, social, etc. For nanomaterials that have a novel function not captured in conventional materials, this type of question is impossible to answer. This tool is more for ensuring that a company has the innovation building capacity and company culture necessary to support the development of greener products, such as through the hiring of candidates with green chemistry experience. The checklist does help companies realize areas not often included in other SAs, such as collaboration with local academic institutions, the inclusion of requirements for 'green chemistry' training in new hires, and supporting Green Chemistry training for all relevant employees. Therefore, it may be a good supplement to other SAs.

4.2.2 Methods

Methods are SAs that are generally have a systematic linear path, involving only one major tool or piece of software that focuses on one, or a few outputs. They usually provide the user with information on only one or two sustainability dimensions, and can include comprehensive data collection and complex data analyses. Methods can stand alone, or can be incorporated into guidances to form more comprehensive assessments.

Methods are generally useful SAs for users looking at only one or a few areas of sustainability. Often, one method can be standardized by many different organizations, which all follow the same concept. Since they tend to be complex, assessors must have some expertise in collecting, analyzing, and interpreting the results. Results can be use for screening and in some cases can be used for comparative purposes, either within the company over time to gauge performance, and sometimes can be used between companies or similar products.

Life Cycle Analysis (LCA)

Life cycle analysis (LCA) has become the most common and universally accepted method for determining the environmental impacts of a product throughout its whole life cycle. Various versions of LCAs have been available since the early seventies, and the International Standards Organization (ISO) started developing standards to perform LCAs, with the first published in 1997, and now are released as a series of standards (ISO 14001:2004, ISO 14040:2006, ISO 14044:2006). LCA is the most advanced and thorough tool available on the market that produces quantitative data about the related impacts throughout the life cycle. It can be performed for products, chemicals, activities and services, and has been performed on a number of different nanomaterials (*e.g.* Li et a l. 2013; de Figueiredo et al. 2012; Arvidsson et al 2015). It helps in the early ecodesign phase, identifies opportunities to improve the environmental performance of a product, allows for comparison to products with the same functionalities, provides information to decision makers, can be part of an eco-labelling program, and allows for long-term strategic planning (Zbicinksi, Stavenuiter, Kozlowska, & van de Coevering, 2006). Over time, LCA has gone from being a tool used to assess existing technical problems to a tool that helps raise awareness of the shared impact amongst those involved in the manufacturing (Tarabella & Burchi, 2011); it gives information to customers to allow them to make more sustainability consumption choices. The number of published studies on LCAs in nano appears to be increasing; a review and comparison of 29 studies can be found in Miseljic et al. (2014). LCA have been performed on a wide range of raw nanomaterials (*e.g.* TiO_2; Grubb & Bakshi, 2010), and also as part of composites or products (nanoclays for vehicle body panels;. Lloyd & Lave, 2003).

Briefly, to determine the life cycle impacts, a company first decides on the *scope* of its analysis (*e.g.* can include raw material extraction, manufacturing, transport, use, disposal stages), and compiles a *life cycle inventory* of all relevant inputs (*e.g.* kWh energy) and outputs (*e.g.* grams of hazardous chemicals to the water) related to the life cycle of the product. Then, a *life cycle impact assessment* (LCIA) is performed, where each inventory item is converted into equivalent impacts (*e.g.* resource use, environmental, human health) using existing databases and classified in terms of impacts (*e.g.* global warming, human toxicity, acidification). Then, these values can be normalized to allow for comparisons and assigned weights to indicate importance. There are many different LCIA methodologies such as TRACI 2.0, Ecoindicator 99, ReCIPe, etc. that can be sector- and case- specific. An analysis of these different methodologies is beyond the scope of this paper, and brief discussion of different tools can be found below, and more information can be found at Hischier et al., (2010) and Huppes & van Oers (2011).

Most LCAs only encompass environmental and human health effects, thereby overlooking aspects such as risk, economic and social impacts, and does not highlight the benefits. Recently, it has been recognized that LCA can be used to encompass more aspects of sustainability by also adding economic and social aspects to the environmental assessment (*e.g.* (Heijungs, Huppes, & Guinee, 2010; Klöpffer, 2008). Databases that contain LCA data can be difficult to access and are expensive, and a lack of access to useable methods and tools are a problem for small companies (Häkkinen et al., 2016). The collection of inventory data is time consuming, and even more so for nanomaterials, as they face even more challenges. There is a lack of published inventory data, an absence of toxicity and fate data, and a large amount of uncertainty regarding their life cycle, especially in the use and disposal phases (Lazarevic & Finnveden, 2013; Miseljic & Olsen, 2014). For these reasons, so far LCAs are employed more often in large companies rather than in smaller companies (Bjorn et al. 2013). If companies want to publish or use their data in a comparative manner, it is recommended that a third party review or perform the LCA to avoid any biased results.

Many different tools to support LCA performance have been developed, with different ranges of capabilities, access to databases, different sector focuses, and at different price points. Here, a brief discussion on two tools that may be appropriate for nano-companies and especially nano-SMEs are discussed. For further information, a review of LCA tools that may be suitable for SMEs can be found at Lehtinen et al. (2011).

The Carbon Footprinting Tool (CCalC2) tool can be used to perform a simplified LCA (for only identifying 'carbon hotspots') as well as more comprehensive measurements (*e.g.* water footprint) (CCalC2, 2007). It is a support tool for calculating and reducing the carbon footprints of different industrial sectors along complete supply chains. The tool can give estimations of the life cycle greenhouse gas emissions, water, and other environmental impacts along the whole supply chain. In addition, the economic impacts can be calculated to help companies realize the tradeoffs between environmental improvements and economic gains. The inventory database contains both data from open literature and also the Ecoinvent database, one of the principle databases used globally. The developers, from the University of Manchester, also provide a two-day training course to anyone interested in learning more about approaches to LCA, and also on how to use the CCaLC tool to calculate carbon footprints. The results can be used for hotspot analysis, to aid in ecodesign, and for internal product improvements. The tool has been used for chemicals and related products, bio-feedstocks, food and drink, and biofuels ("Carbon Calculations over the Life Cycle of Industrial Activities," 2007), though the case study for chemicals (likely the most relevant to nanomaterial production), was not found (CCalC, 2013). The tool itself is free for charge (CCalC, 2007), and is easily accessible to anyone who has Excel software. As in all LCA, it will require expertise in areas such as scope and goal setting, inventory development, gathering reliable data, and interpreting these results, but the platform itself does reduce some complexities. The Excel worksheet guides users through each step, thereby making it easier for a user, and reducing the need to understand all the equations. If pertinent data is available in the database for the user, then it can be relatively quick and simple. Unfortunately, at this point no nano-data exists, though some data related to manufacturing (*e.g.* chemicals used) are in the database.

The EU has been working on a harmonized methodology, the "EU Environmental Footprint Methodology" for product environmental footprint methodology (PEF) that allows companies to evaluate, compare, benchmark, and report their products environmental performance over their life cycle (EU 2013/179/EU) (European Commission, 2013a). Each step is based on recommendations from internationally recognized product environmental accounting methods and standardized guidance documents. The EU PEF can be used for internal use, or external use (without and with comparative functions). It has different mandatory, recommended, or optional levels, dependent on whether the SA is intended to be used internally, or externally with, or without comparative assertions. Within the PEF guidance, and as a support tool for PEFs, Product Environmental Footprint Category Rules (PEFCRs) have been developed that are detailed guidances for specific products or processes. This allows for a higher level of standardization and ease for assessors of these products. Final drafts have been released for products such as household heavy duty liquid laundry detergents for machine wash (AISE Technical Secretariat, 2016), apparel and footwear (Sustainable Apparel Coalition, 2015), intermediate paper products (Pilot Intermediate Paper Product Technical Secretariat, 2015), etc., but no nano-specific PEFCRs have yet been released. The guidance suggests that it is primarily aimed at technical experts, for example engineers and environmental managers, and that no expertise in environmental assessment methods is needed, which would be ideal for smaller nano-companies. While the guidance does provide clear instructions and sets the standard impact assessment model to perform the analysis for each of the 14 mid-point impact categories, expertise is needed to perform each of these analyses. Weighting is not a requirement, and therefore the expert judgment is not needed.

Screening LCA

Screening level LCA can be completed more rapidly than standard LCA to identify 'hot spots', or areas of concern, and can be particularly useful for ecodesign of a product, or prior to large scale product deployment, or can be a starting point for full LCA (Klöpffer et al., 2007; Meyer, Curran, & Gonzalez, 2010; Upadhyayula, Meyer, Curran, & Gonzalez, 2014). This SA still follows the same basic steps as a full-LCA, but has a smaller scope. It usually focuses only on the main input and output inventory items and one or a few indicators.

For nanomaterials, where there is a lack of empirical data, performing a screening LCA may be useful. These LCAs take less time and require fewer resources than a full LCA. Screening LCAs have been done on silver nanoparticles in socks (Meyer et al., 2010) and on electronic screen displays containing carbon nanotubes (Upadhyayula et al., 2014). Screening LCA focus only on environmental and human health dimensions, and still require that the user get data from an inventory or measure the inputs/outputs, and understand how to do the LCIA, and how to interpret the results. In addition, the user must be able to identify the most significant input and output inventory items.

Qualitative LCA

LCAs based on qualitative data, such as the Red Flag Method and the MET (materials, energy, and toxicity) matrix, have been developed to do a more general assessment of LCA. They do not use systematic computational procedures, and are only based on the emissions released and the consumption of raw materials (Zbicinksi et al., 2006). Basically, for the red flag method, a company records all emissions and materials used over the life cycle of the product, then items that are 'harmful', as defined by toxic or hazardous substances, green house gas emissions, use of rare or scarce resources, etc. (Zbicinksi et al., 2006). The MET matrix also assesses a product on limited categories; material and energy consumption, and emissions of toxic substances. A user fills in the matrix with information from each of these categories from each stage of the life cycle, which results in an overview of the environmental impacts of a product.

Only the environmental dimension of sustainability is assessed in these methods, and thereby is quite limited in terms of sustainability assessment. These methods can be used to highlight environmental hotspots and help with ecodesign, but for any in depth analysis and usefulness, they require environmental experts. In general, these types of qualitative methods have poor reproducibility and results can differ dependent on the person performing the SA (Zbicinksi et al., 2006).

Nano life cycle risk analysis (LCRA)

Nano life cycle risk analysis (nano-LCRA) determines the risks of a nanomaterial across its entire life cycle for the purpose of aiding sustainable production and safe commercialization of nanomaterials (Shatkin, 2008; Shatkin & Kim, 2015). The result is a roadmap that highlights the knowledge gaps and the potential future risks to aid in safe development and prioritize research needs. It identifies potential human and environmental risks at each life cycle stage.

Briefly, the user first describes the steps in life cycle of the product; then, potential hazards (*e.g.* inhalation, fire, accidental release) are assessed for each stage and then the potential for exposure (*e.g.* will the be released from the final product, will workers accidentally inhale the materials, etc.) is detailed. Then, given these data, the parts of the life cycle with the highest risk are identified (based on the hazard and exposure potentials determined previously), and these are assessed in detail. Toxicological and exposure data are used to characterize the risk, either qualitatively, or, if enough data exists, quantitatively. The nano-LCRA recognizes uncertainty as a common problem in nano-assessment, and requires that these are clearly documented. After these steps are completed, users can use this to address any areas of risk, and develop risk management alternatives.

This methodology takes risk into account; few of the other sustainability methodologies consider risk in the context of both hazard (the potential harmfulness of product) and exposure (the potential to come in contact with a material). Risk is an important component to the ongoing function of a company, especially when it comes to smaller companies that are already struggling to survive and cannot the handle consequences related to ignoring risks, and also to nano-companies, who face risks unique to this industry. Some aspects, such as the risks to society as a whole (*e.g.* use of rare raw materials, job loss) are not taken into account – therefore, this may be valuable to use in parallel with other methods.

To perform this assessment, someone within the company will need to map the life cycle of the specific product. The general life cycle for many nanomaterials may be similar, and published papers based on this analysis, such as (Shatkin & Kim, 2015) on nanocellulose, may give an indication as to what types of pathways may be of concern. The assessment of potential hazard will likely be dependent on published data, or on tests performed within the company. Therefore, an expert in interpreting these data and determining risk will be needed. With increased data, confidence in the results will increase.

Social LCA

Social LCA (S-LCA) assesses the social and socio-economic impacts on stakeholders along the life cycle of a product or service, and follows the same framework as the ISO 14040 and ISO 14044 for LCA (UNEP, 2009). It complements LCA (which is mostly environmental based), and life cycle costing, allowing for a more holistic assessment of sustainability. On its own, it only provides information on the social conditions of the life cycle, and therefore likely does not provide enough holistic information to be the sole basis for a decision-making at the production level (UNEP, 2009). The social information it provides can support decision making within a company and increase awareness of potential social hotspot impacts, improve internal processes to have fewer negative impacts, and be used for marketing.

It follows the same methodology as LCA, where first the goal and scope of the study are determined, the life cycle inventory is developed, then the LCIA is performed and interpreted. Its main differences are that more qualitative data will be collected, data will often come from stakeholders, rather than databases or literature, and it takes into account more of the positive impacts. In addition, the data has to be more site specific than in LCA (*e.g.* working hours of the workers in a specific factory, political situation of a country, etc.), since technologies on which the data are collected for LCA are often similar worldwide. Data can be collected through desktop research, through company reports, and through direct contact with relevant stakeholders. Benefits are emphasized more in S-LCA than in LCA because this may encourage companies to go beyond compliance, whereas in LCA having 'fewer' or no impacts is generally the desired outcome (UNEP, 2009).

S-LCA are expensive since extensive data is collected. Since much of the data has to be collected from site specific sources, rather than standard databases, this will likely be more time intensive the an LCA, especially of the assessor must visit the sites to do a social audit. The UNEP (2009) S-LCA guidance provides a list of categories a company can assess; however, since social assessment is still relatively new and many uncertainties exist, actual indicators will vary from case to case, and therefore extra time and expertise will be required to consider the most valid indicators in each study. Many of the indicators will be subjective by nature and therefore need an expert to assign and assess qualitative data.

No specific cases where S-LCA was used to assess a nano-product have been published; however, this type of analysis has been incorporated into other tools relevant for nanomaterials, such as the Nano-Sustainability Check.

Life Cycle Costing (LCC)

Life cycle costing (LCC) is a method where all costs related to a product over its whole life cycle are compiled and assessed. It can help a company by showing the most cost-effective option between different technology and manufacturing process alternatives. Three types of LCC exist: conventional-, environmental-, and societal-LCC (Hunkeler, Rebitzer, & Lichtenvort, 2008). Conventional LCC is the calculation of all the costs directly linked to the life cycle of the product that would be borne by the producer (*e.g.* cost of raw materials, maintenance, decommissioning etc.). Environmental LCC would also include the external costs, or monetary costs a company would likely have to pay that result from environmental and social impacts of manufacturing their product (*e.g.* carbon taxes). Finally, societal-LCC encompasses all environmental and social costs borne by any stakeholder who could be directly or indirectly affected. Societal LCC, while reflecting the true cost to society, is extremely broad and complex, therefore is not a practical measurement for companies. Conventional LCC is largely the current practice and is solely an internal tool to make decisions on purchasing and ongoing use of equipment or processes. However, for companies wanting to take into account more sustainable dimensions over the whole life cycle, environmental-LCC is the most appropriate method. By taking into account these external costs, the technology or process chosen will likely be the better option in terms of energy, water, fuel, and raw material consumption over the life cycle (EC, 2016).

Much like LCA, a goal and scope of the study are determined, a life cycle inventory is developed, then the costs associated to each of these inventory items is calculated. Its main differences are that economic data will be collected, which likely comes from within the company records, and the costs associated with use, maintenance, and end of life will need to be predicted. LCC can be used complementary to LCA – if the same scope and functional units are chosen, then one can compare the costs associated with each stage of the life cycle vs the environmental impacts of the same stage.

This assessment will only be useful for companies that have the ability to choose between different processes and equipment, and is likely more help prior to purchasing these technologies. It is likely that companies will already have much of the financial data and internal expertise needed to complete a LCC for the direct inputs and outputs related to the manufacturing phase. Nano-companies may not know how their future nano-product may be used, therefore predicting impacts from the use and disposal phases and related costs may be difficult.

Eco-efficiency analysis

Eco-efficiency ("producing more with less impact") analysis is a life-cycle based method that equally considers the economic and environmental life cycle impacts of a product or process (Verfaillie & Bidwell, 2000). It encourages companies to couple economical and environmental improvements while making a company more sustainable. In general, this concept has been driven by large companies (*e.g.* 3M with the “Pollution Prevention Pays Program and Dow Chemical with the Waste Reduction Always Pays Program) as a way to prevent harmful impacts will also saving money (Côté, Booth, & Louis, 2006). Currently, many chemical companies have formal programs addressing eco-efficiency, such as BASF (BASF, 2016) and Akzo Nobel (Akzo Nobel, 2016). It is mostly used to compare alternatives to manufacturing a product to determine which has the best eco-efficiency.

The eco-efficiency is measured by the ratio of unit value (usually expressed as unit cost, function, or weight, but can in theory be anything considered valuable to the assessor, like aesthetics) per unit of environmental impact (*e.g.* energy/water/materials consumption, greenhouse gas emissions, ecotoxicity etc.). First a LCA is performed to determine the chosen environmental and then economic data over the whole life cycle is measured using existing business data, or, in some cases, national economic models. Then, the unit value is mapped against the environmental impact, and the different alternatives are compared based on their eco-efficiency ratio. Ratios over 1.0 (where the environmental impact and the costs are low) are more desirable than high ratios. A number of tools exist to help users map their ecoefficiency (*e.g.* Côté et al., 2006; Verfaillie & Bidwell, 2000).

Since SMEs are usually struggling financially, performing a combined economic and environmental assessment is reasonable. Since the assessor decides what they want to measure (the unit value and the environmental impact), if data is lacking for one area (*e.g.* ectoxicity), the assessment can still be performed using available data (*e.g.* energy consumption). Given this, assessors should keep in mind that available data should not be used as a proxy for most valuable data. This analysis still requires the use of LCA, which is complex, expensive, and requires expertise.

Modular-based Sustainability Assessment and Selection (m-SAS)

The m-SAS is a practical method designed to systematically assess the sustainability of existing processes or new design, with the goal of "Designing for sustainability" (Othman, Repke, Wozny, & Huang, 2010), with a focus on chemical engineering. It is a systematic & general approach that integrates quantitative economic and environmental indicators with typically qualitative indicators for social criteria (which are here converted to quantitative values). This analysis would be most useful at the early design stage to aid in manufacturing process selection, but can also be used as a tool to assess current processing activities and improve the sustainability impact of products.

This SA only measures the impacts from "cradle-to-gate", where manufacturing to factory gate (*i.e.* before transported to customers). It does cover many dimensions of sustainability, unlike other SAs. Within these dimensions, the assessment is not comprehensive; the environmental aspect is measured by summing all the energy requirements of the system, and therefore does not include aspects such as use of rare raw materials. The social criteria are judged on a scale from 1-10 and mainly cover occupational safety aspects. While gathering the energy input and output data, giving social criteria scores, and economic measurements may be not that complex, the subsequent multi-criteria decision making (MCDM) by use of the analytical hierarchy process, including decisions on aggregation and weighting require a high level of expertise, and these steps can be highly subjective and drastically affect the results (Othman et al., 2010). Since this SA compares the sustainability impacts of a reference system and a prospective system, this will only be useful for nano-companies that are comparing different production processes, or have a comparative traditional product, with the same functional use.

4.2.3 Guidances

Guidance documents are multi-stage assessments that usually guide a user through a number of procedures to assess sustainability. Guidance documents are more complex and comprehensive than method (and can build on and incorporate one or more methods), but they more structured and detailed than frameworks. One of the defining features is that it would require experts in more than one area (*e.g.* human health expert, environmental safety expert, accountant, technical production manager, social scientist, risk expert, etc.) to come together to complete the SA.

The benefits of using guidelines over methods is that they encompass a wider range of sustainability dimensions, bring the user step-by-step through the process, usually giving advice and resources for the user to access, and are more structured than frameworks, therefore the user does not need to spend much time on determining their approach. This sometimes allows for someone who is familiar with the company, but not necessarily an expert, to take on the SA, but may need to bring in extra expertise to fulfill different aspects of the guidance. In this way, more stakeholders are included in the process.

Nano-Sustainability Check

Öko's Nano-sustainability check is a self-evaluation screening method that assesses the risks and benefits related to sustainability of a company's nano-product, compared to a reference product. The objective is to reveal the strengths, weaknesses, opportunities and threats (SWOT) of a specific nano product. The SWOT is performed as a systemic grid to assess nano-products in an integrated manner. It takes the whole life cycle into account, and is specifically tailored to nano-products; it strategically manages the opportunities and threats that a nano-company may face in the future by supporting a company in identifying benefits, new markets, and avoiding bad investments and any future dangers to society. This method was adapted from the well-established Product Sustainability Assessment Guidelines (PROSA) developed by the Öko Institute.

The approach uses 14 criteria in every area of sustainability evaluated in this thesis (TABLE). For the strength/weakness analysis, inherent impacts such as carbon footprint, user benefits, and life cycle costs are considered. In terms of opportunities/threats, the focus is on external impacts, such as employment effects, societal benefits, and risk perception. It is designated as a strength or opportunity if it fares better in a particular indicator than a reference product, and a weakness or threat if it does not. The final matrix can be used as an internal analysis for more sustainable product development and provide for the basis for a strong company strategy, as it assesses potential future risks.

Descriptions for how to measure each criterion are provided in the report; some are more straightforward than others. Some indicators as easily quantified (*e.g.* carbon footprint in kg CO_2-equivalents, energy use in megajoules), while others are less easily expressed as a number. In these cases, the guidance requires semi-quantification, where indicators are given a quantitative classification based on qualitative description (*e.g.* societal benefits, user benefits). There are many methods required within this SA (*e.g.* the carbon footprint is essentially assessed through a LCA, there is a life cycle costing indicator).

Many different experts are required to complete a full assessment. Some areas, such as LCA or LCC, will need an expert to complete properly. Some indicators rely on expert opinion to evaluate whether the nano-product is better, worse, or the same as the reference product. This is a mass simplification of the final evaluation of each criterion, as there can be both better *and* worse indicators within each criterion, and the assessor must decide how to weigh these. Nano-products that do not have comparative functionality to an existing product (*i.e.* infer novel properties), will be difficult to assess, as the Nano-Sustainability Check requires a reference product.

OECD Sustainable Manufacturing Toolkit

The OECD developed a start-up guide to help companies improve their production efficiency (OECD, 2011). It is made available as a booklet online as well as an online set of tools; however, the online tools are not yet complete. It is straightforward and easy to read and guides companies through 7-steps for more sustainable manufacturing. It was developed with the goal of helping manufacturing SMEs, but can be used for all sizes and types of organizations. The focus is mainly environmental, looking at the impacts throughout the manufacturing (including inputs) and use phases. It encourages users to prioritize their impacts, then choose appropriate indicators according to their list of 18 "most important and commonly application quantitative indicators". They provide simple explanations of each, and then examples of different types of data that can be collected for each indicator.

It may be appropriate for SMEs looking to do an overview of the major issues in their process, track progress over time, and identify where there is missing data. It is a very flexible guidance for companies with all types of resources – for each step there are beginner, intermediate, and advanced options according to the needs and available resources of the user. Even if a company does not have complete data, it is encouraged that they get started on the assessment so that a company can better understand their performance as far as possible, gain confidence in managing and improving environmental impacts, and allow for tracking of improvements over time. While the guidance starts with a nice overview of sustainability, the assessment is mostly based on environmental, and some, human health impacts, and does not explicitly address social or other issues.

4.2.4 Frameworks

Frameworks give general direction to the user and allow for many choices to be made. They do not provide a step-by-step methodology for performing a SA, but instead provide a solid basis from which a SA can be performed. For example, they may provide the suggested sustainability dimensions, criteria, indicators, and/or pieces of information that are crucial to performing a SA, but have not been fully developed into a guidance. Therefore, users must have some level of expertise, time, and understanding of the framework to be able to perform a reliable SA based on the framework. These may be useful for users who want some flexibility in choosing the dimensions most valuable to their company, or to get an idea of all the possible criteria they could use.

Cinelli's holistic nano-sustainability framework (C-NSF)

Cinelli et al. (2016) recently developed the first holistic framework that evaluates the sustainability of nanomaterials (here abbreviated "C-NSF")(Cinelli, Coles, Sadik, Karn, & Kirwan, 2016). Based on stakeholder input from nanomaterial experts in the economic, environmental impact, environmental risk and management, human health risk assessment and management, social, and technical fields, 68 criteria structured into 6 areas were prioritized and identified for use in an assessment. It covers the widest range of sustainability dimensions of all SAs evaluated, including some areas not included in other SAs, such as regulatory compliance, use of nano-enabled products for military purposes, tackling environmental issues with nanomaterials, the use of alternative testing strategies (*i.e.* non-animal tests), the resources demand trend, the funding trends, and collaboration embedment. In addition, a whole dimension on technical performance, such as reproducibility of the nanomaterial characterization technique, functionality, and reliability, are included, which is particularly important for new innovations, as these may not be well established. Since this is a nano-focused assessment, some issues unique or especially important to nanomaterials, such as the importance of an agreed-upon definition for a nanomaterial, the use of toxicity data on close analogues, and public perception for nanomaterials, were included. The framework serves to highlight nano-relevant criteria, bring awareness to nano-companies about the varied and different aspects related to sustainability (*i.e.* not just environmental criteria), gives assessors flexibility to perform assessments with criteria that is appropriate and most valuable for each individual company. For more advanced assessors, the application of this framework can allow for benchmark evaluation or for comparative purposes, or as part of a Multiple Criteria Decision Aiding (MCDA) method (Cinelli et al., 2016).

A valuable aspect of the study was its ranking from I to III of the importance level (IL) of each criterion within its category. This could aid assessors in choosing the most important criteria, as decided by nano-experts. For example, if a company decided that human health risk and economic issues were very important to them at that moment in time, and environmental and social issues were less prioritized, the company could choose those criteria ranking as IL I and II for the first two issues, and only those ranking as I for the latter issues. Assessors wanting to use this framework should be mindful that only 'experts' in each field were surveyed; therefore, other stakeholder groups like the public, NGOs, and government agencies were not included (Cinelli et al., 2016).

As it is a framework, there are no specific guidelines as to how these criteria should be assessed in terms of quantitative or qualitative indicators. However, in the supplemental information, each criteria is clearly explained and references for each are provided, where users can find more information on potential indicators. One of the challenges that the developer recognizes is dealing with a lack of data in the nano-field (personal communication, M. Cinelli). To deal with this uncertainty, Cinelli et al. (2016) suggest that decreasing the quality of the measurement (*i.e.* going from quantitative to qualitative) is possible in this framework. Since this is a framework that allows for a lot of flexibility, the cost of performance, time, and level of expertise necessary will vary greatly dependent on the assessor's decisions. For small companies with few resources, it may not be realistic to assess all the categories.

Prospective Sustainability Assessment of Technologies (Prosuite)

Prosuite, a sustainability assessment that encompasses environmental, economic, and societal dimensions, was developed through an EU-funded project (Prosuite, 2010). It is a novel methodology for sustainability impact assessment of new technologies and products with a life cycle approach. The goal was to develop an assessment for technologies that would allow for a detailed assessment of the three pillars of sustainability, while also accounting for the rebound effects, or the unintended influence of changing an aspect of one dimension on another dimension. During development the researchers consulted with a wide range of stakeholders such as regulators, analysts, and industry. Of note is that they specifically included stakeholders from SMEs to develop a framework compatible with the needs of SMEs (Prosuite, 2010). The SA is meant to be performed in an early stage of development so that informed technological and process decisions can be made, but can also be applied retrospectively (Blok, Huijbregts, Roes, van Haaster, & Patel, 2013).

Prosuite defines five mutually exclusive impact categories (rather than the typical environmental, economic, and social trio) and looks at impacts on: 1. Human health, 2. Social well-being, 3. Prosperity, 4. Natural environment, and 5. Exhaustible resources. It integrates all these indicators to produce an overall sustainability assessment. They suggest an aggregation methodology, where three commonly used analysis are combined that result in graphical displays and use weighted sum and outranking analysis (Blok et al., 2013).

Since this SA was designed to assess new technologies, it seems that it could be appropriate for nano-products. The software is provided free to perform the analyses, and is linked to OpenLCA (Prosuite, 2013). Guidance documents and step-by-step instructions are provided to direct users through the process (Greve, 2013). However, users need expertise to make choices. For example, under the social assessment, 5 indicators are judged according to "very low, low, medium, high, very high" for a reference product and the nano-product. Categories such as "long-term control function" are not well explained, and "increased risk perception" require expertise to answer. Since the environmental analysis is based on an LCA, data specific for nanomaterials throughout their lifecycle are lacking and therefore assessors must generate their own data rather than rely on databases. Since the analysis in this SA integrates all of the sustainability dimensions, data gaps or poor quality data in one area can affect the results in all dimensions. Therefore, to have higher confidence in the results of this SA, it is recommended that good quality data is available for all areas, and then an integrated SA will be possible. As of September 2, 2016, the free tool was no longer available online, so potential users will have refer to Blok et al. (2013) for more information, or get in touch with the developers if they wish to use the software. Therefore, at this point, it is considered a framework since only the general structure of the method is available in Blok et al. (2013).

LICARA nanoSCAN

The Life Cycle Assessment and Risk Assessment of Nano-products (LICARA nanoSCAN) was developed specifically through an EU FP7 Project as a nano-SME self-assessment tool of sustainability benefits and risks of nano-products. The goal is to support SMEs in making decisions in producing safer and more sustainable products, to provide information from existing best practices, and to result in a coherent report that will help communicate information about the nano-product. It is available online as an Excel-based tool. There are eight modules, and takes a stepwise approach that take nano-specific concerns into account. It starts by first confirming that a product contains nanoparticles, then moves to legislative and regulatory concerns, then requires an assessment of the environmental, economic, and societal benefits, then the environmental and public health, occupational health, and consumer health risks, and finally produces a combined presentation of the results. The final analysis allows for decision support based on the benefits *versus* the risks. A user chooses a relative score (*e.g.* better, equal, worse, unknown) in a drop down menu for each indicator.

The analysis of the data within each module is based upon the principles of LCA, risk assessment, and MCDA. In particular, the modules uses existing tools to do an evaluation; the first step identifying and characterizing nano, as well as the public and environmental risk assessment is based on the Precautionary Matrix (Swiss Federal Office for Public Health and Federal Office for the Environment), the occupational health risk analysis is based on the Stoffenmanager Nano tool (TNO, ArboUnie, Beco), and the consumer health risk analysis is based on the NanoRiskCat (Danish Environmental Protection Agency) (Som et al., 2014).

The user-friendly format, in addition to the semi-quantitative comparative aspect, allow for fast assessment; the average time of completion for SMEs was 4h, which is generally shorter than most assessments (van Harmelen et al., 2016). This SA is also unique in that it addresses regulatory and legal matters early in the approach. Before a user moves forward into assessment, they must first check that their product is compliant with current regulation. This is a valid and relevant concern for producers of nanomaterials, and may save them from moving forward unnecessarily. The regulatory status of nanomaterials continues to change globally. Doing this step will involve some expertise to understand current regulations and also to predict the future regulatory situation.

The developers recognize that uncertainty is a primary concern and common in nanomaterial assessment (Som et al., 2014). To counter this, they suggest that instead of using difficult-to-achieve absolute values, a relative comparison to a reference product is more feasible. If this is unknown, then the user should assume a worst-case scenario. In addition, this tool allows for qualitative arguments to appear in results, to provide transparency to stakeholders. Many indicators are quite vague and can encompass many aspects and therefore may be difficult to assess. For example, answering, "How does the nano-product perform when compared to efforts needed to produce the product using the nanomaterial" can be highly subjective, and difficult for users to evaluate using a simple "better" or "worse".

The output is greatly simplified - a one word result, "high" "moderate" "low" is given to each of the three benefit (environmental, economic, societal) and the three risk (environmental and public health, occupational health, and consumer) categories. While it allows for a direct risk-benefit overview, in depth assessment of the assessments can identify flaws. In case studies, the developers found some limitations. For example, if there are benefits or risks not captured in the indicators, users do not have the chance to include them, and users did not always collect detailed information of the reference product, thereby misjudging the benefits. Since this is based on a comparative process, then it is assumed that there is a comparative reference product, and also the user must know the whole process of the reference product, which can be a challenge. Some sections, such as the hazard assessments, were doable by non-experts, but were more accurate if the user had expertise (van Harmelen et al., 2016).

Overall, the LICARA nanoSCAN tool can be relatively easily used by SMEs as it is straightforward and does not require much time, money, or expertise. However, confidence in the results can increase with a higher level of expertise and as more data is collected for a nano-product. While tempting to base decisions from the simplified output, it is important that users also do an in-depth critical analysis of the SA as a whole to support decisions. It can be used as a good overview of the pros and cons of a product, and can increase the employees' awareness of sustainability issues related to their product.

As of September 2, 2016, the tool was not accessible online, despite multiple attempts to get access. While the published article (van Harmelen et al., 2016) and the guidance document (Som et al., 2014) are informative, a company cannot perform the LICARA nanoSCAN on their own. Therefore, this is considered a framework under this assessment.

Global Reporting Initiative G4 Reporting

The Global Reporting Initiative (GRI) has developed a comprehensive and standardized reporting framework for sustainability of an organization (Global Reporting Initiative [GRI], 2013). The GRI version 4 (G4) Sustainability Reporting Guidelines defines the principles and specific elements that organizations can use to report economic, environmental, and social performance. A nano-company interested in doing a sustainability assessment may consider completing the sections that are relevant to sustainable manufacturing of nanomaterials. For example, identifying aspects of the company that have significant economic, environmental and social impacts, and are most important to stakeholders then reporting on relevant indicators; listing any external economic, environmental, social charters, principles, or other initiatives the company endorses or is part of; and reporting on how the company addresses the precautionary principle (GRI, 2013). If used in this manner, then users will have to make decisions as to which parts of the guidance are most useful to them; therefore, it is here considered a general framework. It should be noted that if a company does not complete all aspects of reporting, it is not considered "in accordance" of the guidelines by GRI.

Over 24000 GRI reports have been filed on GRI's sustainability disclosure database (SDD) (GRI, 2016). Larger companies tend to use this type of reporting to address stakeholder needs whereas smaller companies do not employ GRI as often, as evidenced by the 3434 SME reports filed in the SDD versus the 21983 large company reports (as of September 2, 2016). Interestingly, some companies have reported 'nano' in their GRI sustainability reports, but most have very little about the sustainability of these materials. In some, there is just one reference to the fact that they are involved with nanotechnologies (*e.g.* DuPont, 2015; Lockheed Martin, 2015); others describe the nanotechnology (*e.g.* Samsung, 2015; 2016); others address their work in safety research with nanomaterials (*e.g.* BASF, 2015).

Full G4 reporting is comprehensive, and therefore can be financially-, time-, and resource-, intensive. However, if a nano-company chooses to use the G4 guidelines as 'inspiration' for a SA, they can benefit from the straightforward reporting guidelines, the flexibility to choose the indicators most relevant to them and for which data is available, and the fact that in depth analysis is not an absolute requirement, therefore the expertise needed to do a basic assessment is not necessarily extensive. The process of evaluating each aspect can be valuable for a company to be aware of its potential impacts. The main benefits a company can gain from performing elements of the G4 Reporting is the active engagement of stakeholders during identification of most relevant material aspects, which gives the company a better understanding of how they fare given their stakeholder's values. In addition, if companies choose to report their findings, trust can be gained through transparent reporting of the risks and opportunities faced.

UNEP's Sustainability Assessment of Technologies

The UNEP's Sustainability Assessment of Technologies (SAT) is a 173-page guidance document that leads decision makers through a series of steps that will allow for technological, environmental, socio-economic improvements when choosing process equipment, and includes participatory decision making (UNEP, 2012). The approach is very adaptable for different situations, and can help companies choose the right technology to create their nano-products. It is a well researched, simple, but also detailed guidance document, that considers various criteria and indicators, the whole life cycle, the risks and restrictions related to technology choices, and local capacities. It contains both strategic and operational assessment, though for the purposes of this thesis only the operational assessment will be considered to allow for comparison to other SAs. Worksheets are provided so that companies have some guidance when doing their assessment.

First the company analyses their general situation and defines targets. Then, they do general screening of existing technologies; from this, they can eliminate any obviously unfeasible technologies based on a series of simplified yes/no answers (*e.g.* policy restrictions, not economically viable, not proven technology). Then, stakeholders are consulted to determine which technical, financial, social, and environmental criteria are most important to them, and from this, a weight is assigned to each criterion. Then, the remaining technological options undergo a scoping assessment and scored using these weighted criteria and indicators, resulting in a ranking of technological options. After this, the top ranking technologies may be re-evaluated and compared in detail, for example through the drawing of star diagrams (UNEP, 2012).

Since quantitative values are applied for both stakeholder-assisted weighting of criteria and indicator scores for each technology, some understanding of quantitative procedures will be needed. Six commonly used quantitative methods are explained in document, from least to most complex, allowing for flexibility in expertise. Criteria and accompanying guidance notes and verification requirements are provided in the Annex, thereby making it easier for companies to perform the analysis. The inclusion of stakeholders in determining criteria weights makes the assessment more value-based. This assessment must be performed prior to purchasing new technologies – it is not useful for companies that already have the equipment they must use.

4.2.5 Other Assessments

There were a number of other assessments that appeared to be viable to assess the sustainability of nano-companies. However, if the tools cost money, or were inaccessible, then there were not evaluated here. Appendix I lists these assessments and reasons for not evaluating them.

Table 4-2 Comparative evaluation of sustainability assessments - Methods

	Name of SA	Nano?	Sustainability dimensions addressed								Potential Barriers			Uncertainty analysis	Outcome
			Environ - resource use	Environ - toxic impact	Human health	Economic	Social well being	Benefits	Risks	Other	Cost	Time	Expertise		
METHODS	Life Cycle Analysis	No	Y	Y	Y	N	N	N	N		$$	++	++	Sensitivity & uncertainty analyses	Comprehensive environmental results; quantitative value of all environmental and human health impacts across life cycle
	Screening LCA	No	Y	Y	Y	N	N	N	N		$ to $$	+ to ++	+ to ++	Sensitivity & uncertainty analyses	General results; quantitative value of some environmental and human health impacts across life cycle
	Social LCA	No	N	N	Y	N	Y	Y	N		$$	+++	+++	Qualitatively document uncertainty	Overall comprehensive quantitative and qualitative indicators on many social dimensions over the whole life cycle.
	Life Cycle Costing	No	N	Y	N	Y	N	N	N		$	+	+	Not stated	Total costs (economic and environmental) borne by the company for use of a technology or process. Compare technologies
	Qualitative LCA	No	Y	Y	Y	N	N	N	N		$	+	+++	Qualitatively described	General results that highlight environmental hotspots across life cycle
	Ecoefficiency	No	Y	Y	Y	Y	N	N	N		$$ to $$$	++ to +++	++ to +++	Not stated	The ratio of product to the costs across the whole life cycle to compare different manufacturing alternatives.
	m-SAS	No	N	Y	Y	Y	Y	N	N		$$ to $$$	++ to +++	++ to +++	Not stated	Comparison of different manufacturing alternatives in terms of individual social, environmental, or economic basis, or as a combination of these dimensions.
	Nano-Life cycle risk analysis	Yes	N	Y	Y	N	N	N	Y		$ to $$	++	++ to +++	Clearly record uncertainties	A roadmap of the potential environmental and human health risks along the whole life cycle and options to manage these risks.

Table 4-3 Comparative evaluation of sustainability assessments - Guidances & Checklist

	Name of SA	Nano?	Sustainability dimensions addressed								Potential Barriers			Uncertainty analysis	Outcome
			Environ - resource use	Environ - toxic impact	Human health	Economic	Social well - being	Benefits	Risks	Other	Cost	Time	Expertise		
GUIDANCE	**Nano-Sustainability Check**	Yes	Y	Y	Y	Y	Y	Y	Y		$$$	+++	+++	Recognizes that nano-data is lacking, different aspects given a rating only if there is sufficient data	A SWOT matrix showing the intrinsic and external advantages of manufacturing the nanoproduct.
	UNEP Sustainability Assessment of Technologies	No	Y	Y	Y	Y	Y	N	Y		$ to $$$	++ to +++	++ to +++	Not stated	A ranking of manufacturing technologies, based on technological, environmental, and socio-economic factors as determined by stakeholders.
CHECKLIST	**Green chemistry Checklist**	No	Y	Y	Y	N	Y	Y	N		$ to $$	+ to ++	+ to ++	Not stated	A checklist of items that a company should refer to regularly to ensure that they are building innovation building capacity and the company culture necessary to support the development of greener nanoproducts

Table 4-4 Comparative evaluation of sustainability assessments - Frameworks

	Name of SA	Nano?	Sustainability dimensions addressed								Potential Barriers			Uncertainty analysis	Outcome
			Environ - resource use	Environ - toxic impact	Human health	Economic	Social well - being	Benefits	Risks	Other	Cost	Time	Expertise		
	Cinelli's Nano Sustainability Framework	Yes	Y	Y	Y	Y	Y	Y	Y	Y	$ to $$$	+ to +++	+ to +++	Decrease the quality of the data (*i.e.* go from quantitative to qualitative)	Depending on how the framework is used, the user can have an outcome that shows impacts in up to six different dimensions (with 68 criteria) related to sustainability.
	Prosuite	No	Y	Y	Y	Y	Y	N	N		$ to $$	+++	+++	Not stated	With software, can compare the results of each indicator between a reference and a prospective system, and also see aggregated results, where the combined impact of each dimension is also compared.
	OECD Sustainable Manufacturing Toolkit	No	Y	Y	N	N	N	N	N		$ to $$$	+ to +++	+ to +++	Is flexible; can be started without a lot of data.	A general description and indicators of the environmental impacts caused by the manufacturing process. The more data included, the more valuable the information.
	LICARA nanoSCAN	Yes	Y	Y	Y	Y	Y	Y	Y		$	+	+ to ++	If unknown, then assumes worst case scenario.	Simplified risks vs benefits comparison that takes into account many dimensions of sustainability and is specific to nanoproducts.
	GRI	No	Y	Y	Y	Y	Y	N	Y		$ to $$$	++ to +++	+ to ++	Not stated	A description of the significant aspects and their potential impacts related to the company's processes.

4.3 Identifying trends and tradeoffs

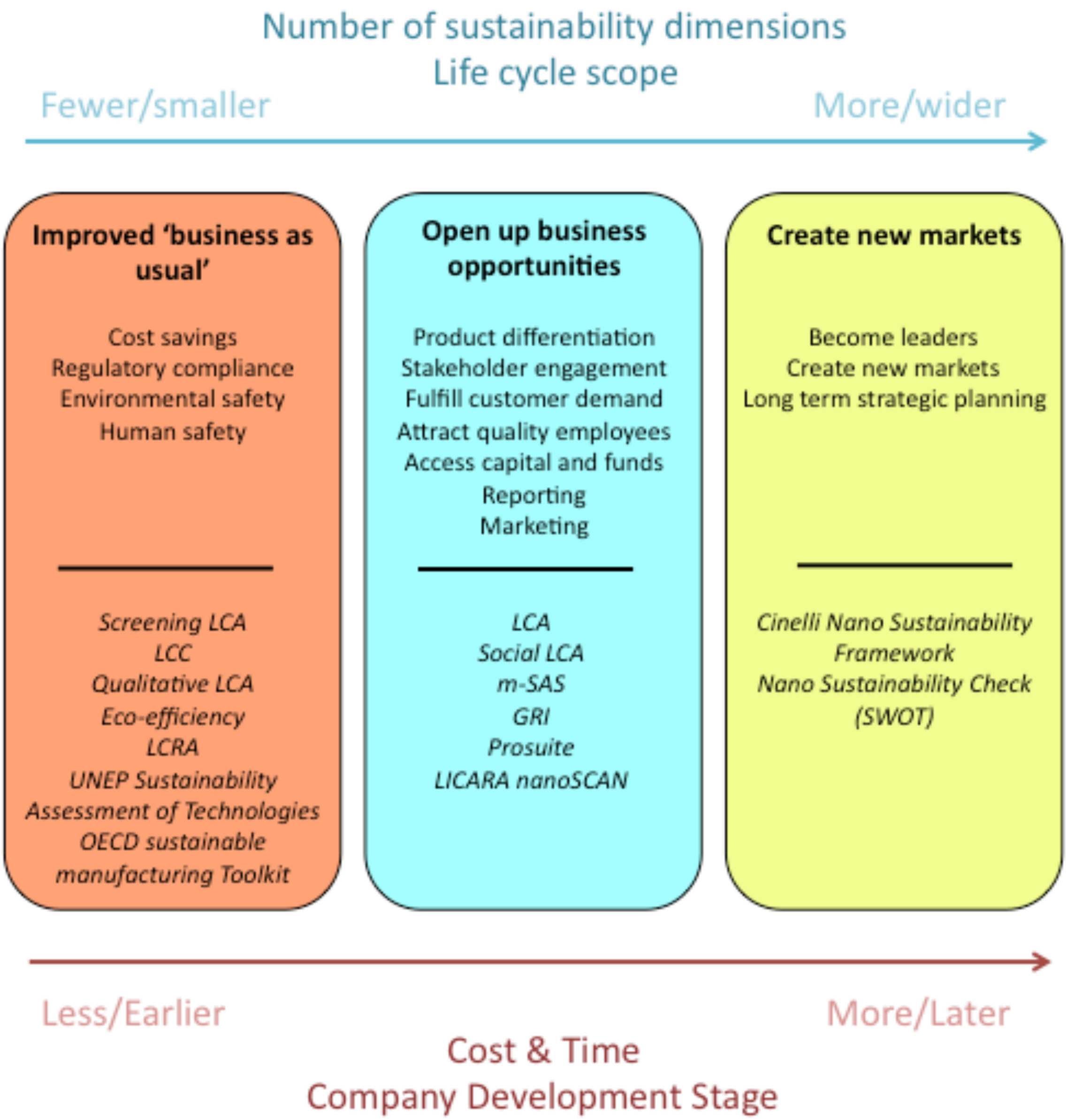
4.3.1 Categorizing SAs based on benefits

SAs that can help achieve *benefits from improved 'business as usual'* involve a general screening of impacts that can be used within the company will help nano-companies gain an understanding of the business' hotspots that can lead to cost savings and regulatory compliance. In addition, it addresses the basic human and environmental safety of a product. There are defined by their smaller scope (*e.g.* limited part of the life cycle, only one sustainability dimension), lower costs and shorter time requirements to perform the SA.

SAs that can help achieve *benefits that open up business opportunities* involve more complex analyses that can be used externally, to encourage stakeholder interaction, and can achieve also all targets achieve in "internal use". These are characterized by addressing at least two sustainability dimensions, cover the whole life cycle, and are intermediate in relative costs and time requirements.

SAs that can help achieve the benefits from *creation of new markets* involve more comprehensive and holistic assessments that can fulfill all the goals of the SAs of internal and external use, in addition to creating new markets for a company's products. They take a long-term view of operations into account. These are characterized SAs that address all sustainability dimensions, cover the whole life cycle of the product, are the highest in relative costs and time requirements, and are specific to nano.

Table 4-5 Potential benefits of sustainability assessments



4.3.2 Trends and tradeoffs

Companies face different barriers and therefore may be limited in the value they can achieve from sustainability assessments. For example, holistic assessments that cover all dimensions of sustainability and cover the whole life cycle will require more in terms of resources and expertise. Some trends were observed amongst SAs that can be considered in terms of tradeoffs. Therefore, companies will need to consider the trade-offs associated with performing the different assessments in order to gain the maximum value given the barriers they face.

Benefits vs cost and time – For companies to get maximal benefits (*i.e.* internal, external, and new market creation benefits), they will have to use the most expensive and most time-intensive assessments. These tend to have the higher number of dimensions, the largest life cycle coverage, and are specific to nano. However, if a company has less money or time, then it can still perform SAs that will bring internal or external value. These can still be valuable in terms of cost savings, lowering risks, improving reputation through reporting or stakeholder engagement, and provide a good base for having a stable, reputable company.

Benefits vs company development stage – As a company develops and grows, the resources (cost, time, skill base) available to it will also increase. Therefore, they will be able to access more benefits, starting with improving internal processes for cost reductions, and eventually being able to assess future markets and even create new markets for their product.

Wider scope of assessment vs cost and time - In general, assessments that are classified as methods only look at one to three dimensions of sustainability; this results in generally lower time and cost needs in relation to guidances and frameworks. In addition, companies earlier in their business strategy may choose to limit the scope of their assessment to smaller parts of the life cycle. Companies that wish to save time or money may consider only looking at one dimension and a smaller scope to start, with the realization that this does not fully capture sustainability. As the company develops, then more complex assessments can be made and these starting data can be slowly built upon, thereby allowing a company to continually develop its sustainability profile.

Adaptability It should be noted that many of the SAs could be done at a basic level, or an advanced level. Therefore, they could be tailored to a company's available finances, time, or expertise. They are adaptable for companies who are growing and would like to start an assessment and build upon it over time. Simplified versions of assessments, such as screening LCA, can be performed with less cost, expertise, time and data, and be further developed into a full LCA when these resources become available. The OECD Sustainable Manufacturing Toolkit allows for beginner, intermediate, and advanced assessments that can are appropriate for different stages of development and expertise, and could in theory help access more advanced benefits, as well.

Expertise Expertise was evaluated in such a way to show the minimum level of expertise needed, in comparison to an LCA. It was assumed that each company had a financial expert, therefore SAs purely based on cost (*e.g.* LCC) would likely already be possible to be done by experts within the company. Expertise is difficult to evaluate – even for assessments that required only qualitative data, was relatively cheap, and required less time, the required expertise still varies. In general, SAs based on qualitative data require less expertise to collect the data, but more expertise to interpret the data and identify issues for sustainability improvement purposes. However, for nano-companies, good quality and reliable quantitative data may be harder to collect, but once these data are collected, the results may be easier to interpret. It should be emphasized that the more expertise an assessor has with a particular sustainability dimension (*e.g.* environmental safety, social issues, financial experience), the more reliable the assessment will be. For example, Van Harmelen et al. (2016) found that having some experience with occupational health hazards improved the results of the LICARA nanoSCAN. Expertise is not only needed to collect data for a SA, but also to interpret and apply the results. The danger for both types of assessments is that a failure to capture the 'correct' or representative values can lead to incorrect conclusions. In addition, many assessments do *not* give suggestions on how to deal with uncertainty; therefore, expertise will provide an additional level of added value to these methodologies. Even methods that are "simplified", like the screening LCA, will require someone with expertise to identify areas of priority; this can likely be someone within the company, but a third party may be able to give a more objective and thorough assessment.

5 Discussion

Although sustainability issues have come more to the forefront of manufacturing the industry, there is still an overall lack of awareness or perceived value of the benefits of 'sustainable actions'. Here, the potential value that SAs can create for companies has been highlighted, including benefits ranging from cost savings to improved stakeholder relations to new market benefits. However, there are many limitations that can keep users from accessing these benefits and gaining value. In general, SMEs are resource-poor compared to larger companies, and may also find less benefits from performing a SA. Given their barriers, it is likely that they will not be able to perform comprehensive SAs, but may have to do more screening assessments that focus on one or two sustainability dimensions. Nano-companies face even more unique barriers related to data scarcity, a lack of methods for nano-products, uncertainty regarding their unconventional processing methods, and an insecurity in the future risks associated with nanomaterials. Therefore companies that are both 'nano' and 'SME' face the highest barriers, being both resource poor and dealing with the unique issues related to nanotechnology.

There are consistent features between SAs that prevent users from achieve maximum value from SAs. Some of these features limit the value of SAs to all users, and some that particularly apply to nano-companies.

5.1 General weaknesses of SAs

All of the SAs evaluated suffer from some inherent challenges that were common amongst the methodologies. These were not specific to nano nor SMEs, but instead would provide challenges to any assessor trying to perform a product SA, that would prevent them from attaining the full value of the SA. These challenges are related to their ability to address sustainability as a whole, their reliability, their applicability at different product development stages, their need for difficult-to-get data, their user-friendliness, and their accessibility.

5.1.1 Incorporating the "triple-bottom-line"

The accepted concept of sustainability encompasses the environmental, social, and economic domains. In accord with research showing that integration of these aspects into the 'triple bottom line' is not well researched (Hahn & Kühnen, 2013), few SAs were found to include all dimensions here in their SAs and integrate them well. The methods tended to focus on only one or two dimensions, but some could be used in combination with others following a similar methodology (LCA, social LCA, and LCC), but then how to interpret these individual results in an integrated manner is less clear.

While the C-NSF, the Nano-Sustainability Check, the LICARA NanoSCAN include all dimensions of sustainability, the majority of SA are based on, or have a larger focus (*i.e.* weighting or more indicators) on environmental or human health. Some justify this due to the fact that these are the outstanding issues, and focus on environmental and climate protection goals require special attention (*e.g.* Nano Sustainability Check). Furthermore, as evidenced by the interviews, companies may overlook social aspects, or not think of this as part of sustainability. Therefore, they may not necessarily look for SAs that evaluate social aspects, or put as much value in the social indicators.

Assessing the social aspects of product sustainability can be difficult and often plays a secondary or lesser role in SAs. The social assessment differs drastically between SAs. Some focus on occupational indicators (*e.g.* m-SAS), others chose to use criteria more relevant to society as a whole (*e.g.* Nano-Sustainability Check), and some combine both (*e.g.* C-SNF). Quantification of social aspects can difficult, and most relied on semi quantitative data, or quantification of social data based on subjective ratings (*e.g.* m-SAS, Prosuite, Nano-Sustainability Check). A basic problem is that many of the social aspects – such as peace promotion, symbolic benefts, provide opportunities to improve human health, etc. are highly subjective qualitative aspects, rather than quantitative measures that can be attributed to individual products. Usually, data on environmentally or economically relevant inputs and outputs can be found in databases, but so far there are no databases or standardized measures for social aspects.

The methods of integration and weighting of the different sustainability dimensions based on relative importance, varied vastly. Some do not give any integration advice (*e.g.* frameworks, Nano-Sustainability Check), some suggest that value-based weighting methods can be used (*e.g.* m-SAS, EU PEF, UNEP Sustainability Assessment of Technologies), other suggest that giving equal weight is the most appropriate analysis method (*e.g.* LICARA NanoSCAN), while others leave it up to the user to decide what works best for them (*e.g.* Prosuite, Cinelli et al. 2016, UNEP Sustainability Assessment of Technologies, EU PEF).

Methods for integration, including weighting, analysis, and interpretation of these dimensions are challenging to provide. Giving equal weight to each category makes the final analysis easier, but then the developer must be careful in balancing the individual categories and indicators in the design of the SA. Van Harmelen et al. (2016) report that during their case studies, SMEs found weighting too complex and also thought that weighting would too easily influence the results. Therefore, they created their tool to give equal weighting to all six dimensions; they found that only very different weighting factors would change the output, therefore in most cases equal weighting would give a generally valid picture. For the SAs that provide weighting options, they can run from straightforward options (*e.g.* decision matrix, where criteria are ranked and weighted), to those including stakeholder consultations (*e.g.* the Delphi Method for Consensus building, which include multiple cycles of discussion and argument until a high degree of agreement is reached), to those reliant on expert opinion (*e.g.* Analytic Hierarchy Process, a structured and lengthier decision-making process that addresses complex problems, and results in a decision that best suits the needs of the evaluator). Weighting often requires the input of experts, but can also be based on cultural or political viewpoints, or economic considerations (EC 2013a). Regardless of the choice of weighting method, companies should be careful in interpreting the results, especially if using for comparative or marketing purposes.

The approach to weighting of different categories varied widely; for example, the LICARA nanoSCAN gives equal weight to all categories, whereas the m-SAS allowed the user to choose weights. Both approaches have issues; a lack of weighting assumes that all categories have equal importance to the company, but allowing for subjective weight distribution can skew the overall result. Sensitivity analyses showed that modification of different decision weights for economic, environmental, or social dimensions within the m-SAS analysis drastically skewed the decision as to which manufacturing process to choose (Othman et al., 2010). In contrast, the researchers developing the LICARA nanoSCAN determined that subjective weight assignment allow for results to be too easily manipulated (van Harmelen et al., 2016). In addition, the assessment was developed so that only very different weighting factors would change the results (van Harmelen et al., 2016). Therefore, expert knowledge and objective and transparent decisions are necessary when weighting these assessments, or the SA must be developed in such as a way that the assessment categories do in fact contribute equal weight.

5.1.2 Self-evaluation and expertise

As many SMEs indicated that they are not able to afford outside expertise, self-evaluation becomes an important topic of discussion. Interestingly, all the companies that had hired third parties to perform their SAs all mentioned that this was partially done to ensure that it was performed in an objective manner.

Many of the nano-companies were made up of highly technical personnel, such as engineers, chemists and product developers. While they may be qualified to develop the technical data, other areas, such as ecotoxicity or safety, nor are they necessarily qualified to make the subjective decisions necessary to complete most SAs. Through these subjective decisions, there is a high chance that an assessor can influence the results and the output may not be a legitimate representation of the company product. Some indicators such as "risk perception", or "symbolic benefits" (*e.g.* Nano Sustainability Check), require subjective judgment. Those SAs that require a relative comparison to a reference product may introduce biases from the users' end; they will likely tend to think their product is better than the reference product, especially given that they will probably have less information on the reference product. Indeed, this was seen by van Harmelen and colleagues (2016) when doing case studies for the LICARA nanoSCAN – one company gave too positive a result for their nanosilver antimicrobial cloth because they underreported the benefits of the reference product. Assessors must be aware of such issues and answer as transparently and honestly as possible. Some assessments, such as the Nano Sustainability Check, allow for a degree of uncertainty, and the final analyses and decisions are only performed on indicators that have sufficient information. In addition, many assessment require that all subjective decisions are recorded clearly so that a third party could assure objectivity, and also this will help any future employees wanting to build on these reports.

If the results of an assessment are to be public, then a company may be tempted to not report 'negative' results. Indeed, one company interview suggested that a major barrier to performing SAs may be that the organization knows that an LCA may reveal an relatively negative impact. While there would be no benefit to a company to produce 'false' data for internal purposes (*e.g.* technological improvements, product eco-design, employee awareness), any data produced for the public may be better off if performed by an independent third party. However, this is clearly a challenge for companies who cannot afford to hire these experts.

5.1.3 Suitable development stage for assessment

The decision as to when to perform a SA is particularly difficult; if a company performs the SA too early in the product development stage, then there may be little quantitative data on the processes and potential life cycle of the material, and the identification of potential future risks and opportunities is difficult, thereby not allowing a decisive analysis. But, if it is too late in the development process, then it will be very expensive to change already existing equipment, methods, etc. The Nano-Sustainability Check suggests that it should be performed on products that will shortly be launched, or just being launched, into the market, as this will be the time that information on the life cycle of the product will be available, but also allow for further development and optimization of the manufacturing processes (Nano-Sustainability Check, 2016). In addition, if done too early, the company risks wasting resources on assessing processes that might completely change. Many of the nano-companies interviewed were in early stages of development; almost all mentioned that they were unsure as to the final manufacturing process (hindering the ability to evaluate the manufacturing phase), and the final product (hindering the ability to evaluate the use and end of life phases). As companies progress, they generally get larger; determining how the manufacturing process will scale and its associated impacts can be a challenge. Larger scale processes tend to be more efficient than those used in the research and development stages (Kim & Fthenakis, 2012). Some SAs are designed to be performed prior to development (*e.g.* UNEP Sustainability Assessment of Technologies), and others as a reflective tool (*e.g.* GRI), but in theory all could be used at earlier stages for sustainable design purposes.

Ideally, a company can be flexible and start the SA process early, filling in as much data as possible, and continually adding data and decision categories, and assessing as they develop the product. Alternatively, the combination of more than one assessment with different goals could be used. For example, the UNEP Sustainability Assessment of Technologies could be done at the early stages, prior to final purchasing of the equipment needed for manufacturing, then the Nano Sustainability Check to ensure that the product and its intended uses are relatively sustainable, and finally perform GRI reporting to ensure that all categories are covered, and to communicate these data and information to stakeholders. However, doing so many different SAs may possible for SMEs – therefore, they must make careful decisions as to which SA they invest in.

5.1.4 Information sources for data collection

All of the SAs require that data is collected, and determining an appropriate information source can be a challenge. Information can be gathered by the company itself; for example for LCAs and LCCs, input and output data from the processing may be available through inventory, purchasing, or regulatory reports, or may be based on data collected by others. Information can come from other sources, including experts, internal employees, stakeholders, reports, and policies, risk assessments, financial reports, regulatory disclosure, simulations, published information such as academic journals, or trusted non-published information. For secondary sources, expertise will be needed to know whether the information is accurate, and also reflects the situation of the company. Many manufacturing processes use common technologies and methods, and there are many free and commercial databases that contain these data for life cycle inventory measurements of these flows. However, access to the databases that contain pertinent and comprehensive information can be costly (Table 5-1). The data extensiveness for some products are better in commercial databases than in free ones (Lehtinen et al., 2011), but users should check before purchase to see if the database fulfills their requirements. None of the free databases contained a significant amount of nano-specific information as of the writing of this thesis (Table 5-1).

Table 5-1 Examples of common inventory databases and their general characteristics

Database	Cost	# of data sets	Number of nano-entries and type	Reference
Ecoinvent v3	Free to see limited datasets; €3800 (then €500/year) to access full datasets	Unknown	3 – (in free dataset) all for nanoscale indium tin oxide powder	EcoInvent, (2016)
European reference Life Cycle Database	Free	503	0	EC JRC, (2016)
GaBi	Not free. May be possible for SMEs to pay reduced cost	11659	1 – for a catalyst to make carbon nanotubes	Thinkstep, (2016) (personal communication)
Open LCA	Free	922220	4 – all for a textile with a nano-TiO_2 primer	GreenDelta GmbH, (2016)
U.S. Life Cycle Inventory Database	Free	2526	0	USLCI, (2016)

5.1.5 Clarity and ease of use

Step-by-step instructions, as those provided in the UNEP Sustainability Assessment of Technologies, the OECD Sustainable Manufacturing Toolkit, make it much easier and faster for a user to understand and perform a SA. For most of the methodologies, there are a number of methodologies available, including international standards. The C-NSF evaluated here was still in developmental stages, without clear guidance on how to perform the tests. Some had very clear and detailed descriptions, but could benefit from the addition of a tool that would help a user perform the test. For example, the Nano Sustainability Assessment provides good guidance for performing the SWOT assessment; however, the document is very long and cumbersome (Nano-Sustainability Check, 2016), which may deter users. The document refers to an online Excel tool, but as of September 4, 2016, was not found.

5.1.6 Availability and accessibility – Updating & maintenance of tools

One of the biggest challenges encountered as this project progressed was coming across descriptions about tools developed for SA, but then full tool or software was no longer accessible, or the website went down and the tool became unavailable during the course of the thesis. Huge amounts of resources (*e.g.* financial, personnel, time) were put into developing many of these SAs. Each of these projects were granted millions of Euros, involved many partners and collaborators, and spanned over many years.

For example, the *Prosuite project was funded with ~6 million euro*, and was a large scale collaborative project (25 academic, SME, and industry pratners), funded by the EU 7th Framework Program 7 (FP7) from 2009-2013. Its aim was to provide free software for the evaluation of the sustainability of technologies (Blok et al., 2013). However, as of September 2, 2016, the website is no longer working (www.prosuite.org) (though it was accessible as late as August 23, 2016) and it is unclear as to whether the software will ever come available again. Attempts to contact the main contacts were unsuccessful, and a former collaborator on the project stated that they did not know the current status of the project.

Similarly, the *LICARA project was also funded by EU FP7 for ~2.5 million euros* over 2012-2014, and included at least eight partners, multiple workshops, and at least 20 case studies of SMEs (European Commission, 2014; Som et al., 2014; van Harmelen et al., 2016). The tool does not appear to be currently accessible. To access the tool, users must register an account – but after two attempts to sign up for the registration (May 18, 2016 and September 2, 2016), I was never granted access. There used to be workshops to aid users in performing these assessments, but they do not appear to be currently available. Without access to the tool, this SA is not possible to perform.

Another EUFP7 funded project, *G.EN.ESI, was funded for ~4 million euros from 2012 to 2015*, with the goal of developing a software platform that included eVerdEE, a web based simplified LCA tool specifically developed for SMEs for integration of green engineering design (Naldesi, Buttol, Masoni, Misceo, & Sßra, 2004). It the online tool was not available during the period of this thesis; one of the developers told me that there was a problem with the domain registration, and that it would hopefully be solved soon (P. Buttol, personal communication July 27, 2016).

Developing a full SA is complex, and requires expertise and input from many different collaborators, and benefit from feedback from potential users through case studies. Therefore, these large-scale research projects are valuable in developing SA frameworks and tools. However, the fact these three tools are not accessible brings to light some issues associated SA development performed in this manner. It is possible that once the project is over, there are no longer continued financial resources to keep working on these free platforms. In addition, the maintenance of the platform likely becomes a voluntary job – since the coordinators of these large projects are academics (*e.g.* Prosuite and G.EN.ESI) or contract research organizations (*e.g.* LICARA), this is probably not a priority for them. In fact, when emailing these coordinators for interviews, one of the developers told me that, "…all my hours should be financed by contractors. As the […] project is ended I do not have any hours on this project to work on" (Anonymous, Personal communication).

Finally, another reason that these projects may not continue may be related to whether or not they were deemed worthy or valuable enough to continue. Two of the final reports suggested that experts and case studies thought that the tools had a positive effect for users, (EC, 2013c; van Harmelen et al., 2016), but the report on the outcomes of LICARA's four case studies could not be found, therefore it is unknown if users thought they were useful. Even if the case study participants did find that the studies were helpful, it must be taken into account the researchers provided free support to these case study companies. In reality, companies will have to rely on the guidance documents and the instructions within the tools. In discussing this with a researcher who performs LCA clinics, they also suggested that many companies were only interested in joining these clinics if they were provided for free (J. Syke, personal communication, May 19 2016). Evidence from the literature suggests that not many SAs are being used in SMEs (Table 5 in Johnson & Schaltegger, 2015) – a literature review of papers published from 1991 to 2011 shows that product specific SAs (eco-efficiency, EPM Kompas, environmental cost accounting, LCA, VerdEE) were not often employed (10 total). However, this may have changed since 2011; only 3 LCAs were reported, and in the course of this thesis many more were found to be completed. Also, these were published in academic journals, though this is not necessarily representative of industrial use.

5.2 Nano-specific limitations of challenges to performing sustainability assessments

While there are many limitations that apply to all companies, it was found that nano-companies face unique challenges in gaining value from SAs. A lack of data, the general early stage of development for many nano-companies, being locked into technologies, a lack of nano specific indicators, the use of comparators, and a lack of customer demand are all issues. Many of these issues are related to being small, new, and innovative companies that do not have a stable or traditional market to work with.

5.2.1 Challenges in getting reliable data

One of the largest issues for nano-companies in terms of understanding the sustainability of their product is the lack of generalizable and available nano-specific data for their materials. Validated or standardized data is lacking for nanomaterial manufacturing processes (*e.g.* energy inputs, raw material use, emissions, etc), human health (*e.g.* inhalation of nanomaterials, effects in the most vulnerable populations, explosion characteristics of nanomaterials), environmental health (*e.g.* biodegradation characteristics, fate in soils, bioaccumulation effects), and potential social effects (*e.g.* job creation, public perception, technological improvements).

Manufacturing data gaps

Relevant data for manufacturing can be collected from measurements done within the company, published literature, patents, laboratory measurements, or from inventories (Kim & Fthenakis, 2012). However, data for nanomaterial-specific processes is lacking and progress on inventories and shared data sources do not appear to be improving (Hischier, 2013). The wide range of potential production pathways for each of these formulations prevent standard or common data sets from being widely applied, unlike common production pathways in sectors like building and construction, plastics, and textiles. Many LCAs for nanomaterials have chosen to use the input and output data for their conventional counterparts (*e.g.* (Meyer et al., 2010). This can result in flawed and misleading results.

There a number of free databases (Table 5-1), which have some data for energy and material flows for commonly used materials, products, and processes; however, these databases do not generally contain nano-specific data, and can suffer from incompleteness, a lack of verification, or are not kept up to date. Some may be valuable for nano-companies; some types of nanomaterials are produced using the same equipment as the conventional materials. For example, nanocellulose can be made using some of the same equipment as those used in pulp and paper mills or biorefineries. The majority of LCAs published to date on nanomaterials focus on the impacts related to electricity use and do not include the direct toxicological impacts of nanomaterials, as these data are more difficult to get (Kim & Fthenakis, 2012).

Safety data gaps

Most of the SAs require safety data. These types of data are available in published literature, but the papers can be hard or costly to access. Academic studies have different goals than those in industry; projects tend to be designed to look for 'unique' results, and as a result tests are not performed in a standardized manner, and the pressure to publish 'interesting' results also means that negative data (i.e those not showing any toxicity) tends to go unpublished (Matosin, Frank, Engel, Lum, & Newell, 2014). Furthermore, those publishing nanotoxicology tests continue to ignore the need to verify that their nanomaterials are not causing false-negatives or false-positives in their toxicity tests (Ong et al., 2014). Nanomaterials can interfere with the proper functioning of these tests, therefore published data needs to be assessed before it can be used. As such, it can be difficult for companies to get an unbiased and reliable set of data, and will likely need the advice of an expert to evaluate these data.

Despite thousands of published papers related to human and environmental nanomaterial effects, no consensus has been reached in most regulatory bodies or amongst nanoexperts as to how to assess nanomaterials. Nanomaterials should not be treated as one entity; there are a wide variety of nanomaterials, and even classification and grouping of these materials (*e.g.* on the basis of the size, of their core material, shape, charge, etc.), to aid faster risk assessment is proving difficult. Most regulatory bodies are evaluating them on a case-by-case basis such as in the E.U. (EC, 2012b) and the U.S. FDA (FDA, 2014). Nanomaterials can be altered with various surface coatings, shapes, sizes, charges, etc., called "physico-chemical (pchem) properties", and these can change dependent in different conditions (*e.g.* freshwater, saltwater, soil, presence of other particles, etc.) (Baalousha et al., 2016; Peijnenburg et al., 2015). In addition, it is difficult to find and measure nanomaterials once they have been released to the environment, thereby hindering exposure, fate and behavior measurements, and also development of models (Kammer et al., 2012). This makes it a challenge to reliably use these data for SAs.

Use and disposal data gaps

So far, assessments based on the full life cycle have been difficult to perform because the final use and disposal stages is limited, and information on manufacturing processes also has limited data. Miseljic et al. (2014) reviewed 29 published LCAs on nanomaterials and found that most relied on generic data from databases, and many had to make rough estimations, therefore leading to higher uncertainties. However, the available data does appear to be growing, and more companies and groups are publishing their primary data (*e.g.* Husgafvel, Vanhatalo, Rodriguez-Chiang, Linkosalmi, & Dahl, 2016, Grubb & Bakshi, 2010), and was supported by one of the companies interviewed, who will be publishing their LCAs soon.

A lack of reliable public databases

If comprehensive, transparently documented, and good-quality data are collected, and then made public or shared in an easy-to-understand format, then the ability to assess the sustainability of nanomaterials would be more straightforward. Collaboration and data-sharing has been seen to be key to producing sector-wide data on specific nanomaterials. Indeed, every nano-SME interviewed that had been successful at performing SAs had only done so in collaboration with partners. However, during the interviews, most companies admitted that they are hesitant to release their data. The processes to make nanomaterials are not homogenous amongst companies and these are still trade-secrets. Three interviewees did express an interesting to contribute to public databases, or to create private consortia, and one will be publishing their LCA data soon. Online repositories and databases could, in theory, help companies fill in the data gaps for their products. However, it must be noted that often in these public databases the data is not necessarily verified, performed with standardized tests, kept up to date, or detailed enough for other companies to use these data. Even large efforts, such as another EU FP7 funded project (~1.6 million Euros), called the "Nano health-environment commented database (NHECD)", running from 2008 to 2012, are not successful in providing a free, continually updated database. The project was supposed result in a "…novel and useful automatic database on the impact of nano-particles on health and environment, which will be hosted and maintained by a expert software company based in Europe….The proposed database will be automatically and manually updated with state-of-the-art information, which will be automatically understood and extracted into a relational database and data warehouse that can be accessed by the public and agencies through the internet" (EC, 2013b). As of September 4, 2016, this database was not found online.

Even if large amounts of information are made public, these must be released in a systematic manner. The OECD started a massive effort in 2007, which ended in 2013 and dossiers containing data on 11 different nanomaterials, voluntarily provided by government, industry, and academic groups were published in 2015 (OECD, 2016b). However, these dossiers are just PDF compilations of all the reports submitted, so are mostly massive chunks of written descriptions of the tests that were performed. The nano-TiO_2 dossier alone contains 8 parts (up to 238 pages in one part) and 39 Annexes. There is no ability to easily compare or extract data. The OECD itself has written a disclaimed on the site saying that the information is not be used as "…a reference, standard, or validation regarding the safety of the specific nanomaterials" (OECD, 2016b). While these dossiers may be useful for some research (*e.g.* OECD, 2016a), it is not likely that manufacturers doing SAs will be able to effectively use these data.

5.2.2 Unchangeable Technologies

Most of the SAs are based on comparing alternative processes to manufacture a product, or on the assumption that companies have the opportunity to make technological changes if a hotspot is identified, prior to moving to manufacturing phase. However, for nano-companies, this may not always be the case; for some of the companies interviewed, the transition to nanomaterial production arose from other traditional industries, with equipment modified for nanomaterials. For example, equipment from the pulp mill, food processing, or biorefinery industries can be modified and used to manufacture nanocellulose. Therefore, these are the machinery that the companies can afford to work with, and for a start up or SME, these are likely too expensive to change for sustainability purposes. In addition, since mass nanomaterial production is still relatively new, different options are being explored, and a standard list of equipment options are not necessarily available.

If a company has the ability to do a SA during the research and development stages, the SAs presented here (*e.g.* UNEP Sustainability Assessment of Technologies, OECD Sustainable Manufacturing Tool Kit), may help companies make more sustainable technological decisions that can also save them money in the long-run. Risks and restrictions on technologies that nano-companies can consider include their future stability or resilience, the eventual scale of the operation, the flexibility of the technology, the adaptability, the potential safety issues, and the skill levels needed (UNEP, 2012). The benefits of considering all options during development phase may seem to hinder the creativity of the production of nanomaterials; however, as two companies highlighted, drastic changes in equipment had to be made just prior-to or after scale up. After performing an LCA on an already existing process, one company discovered one step that was consuming a large amount of energy, and was able to make changes in that one process, which saved money and energy, and also has made their process unique to their competitors. When performing SAs at early stages, users should account for the differences in manufacturing processes at larger scales and how this will affect sustainability (Jiménez-González et al., 2011).

5.2.3 Nano specific indicators

Using generic SAs for nanomaterials may result in important aspects of sustainability that are unique to nanomaterials to be missed. Three SAs tailored for nanomaterials (Nano-Sustainability Check, C-NSF, and LICARA nanoSCAN) were evaluated, and each had a different approach to addressing the needs of nano-companies.

Both the C-NSF and the LICARA nanoSCAN have nano-specific criteria and indicators. The C-NSF has a particularly large number of nano-specific indicators, but due to the fact that it is still a framework, it has yet to operationalize these criteria, and therefore it may turn out that they are not feasible or useful to include in a SA. For example, while they are important issues related to nanotechnology, it is not clear how criteria such as: "agreed-upon definition for a nano-product", "agreed set of assessment endpoint for eco-toxicity testing", "reduction of nano-divide" could be used in a product SA. The LICARA nanoSCAN deals with legislation and nano-product characteristics (*e.g.* individual particles or aggregates) as the first "go/no-go" steps to performing the assessment, which are specific to nano. After this stage, the user can continue to the main stage of assessment, where the developers have taken nano-considerations into account, with criteria like "gaps in knowledge about the background and future life of nanomaterials" and "product development stage". However, these main criteria and indicators could in theory apply to any technologies. The online tool that has been developed for this SA uses nano-specific software ("Stoffenmanager Nano Module") to assess occupational risks, and therefore only nano-related products can be assessed (BECO, 2016). The Nano-Sustainability Check, while developed specifically with nano-applications in mind, does address some areas of nano-concern such as legal framework and risk perception. However, it does not have any aspects that are unique to nanomaterials, and could be applied to any technologies, especially new technologies.

Only the Cinelli framework developed and prioritized criteria based on a thorough consultation with experts in the nano-field (Cinelli et al., 2016). Therefore, future and current developer of SAs for nano should consider incorporating some of these indicators into their assessments.

5.2.4 Comparisons based on function

A company may have the goal of using a SA to show that their nanomaterials are more sustainable than the conventional counterparts. Many SAs are designed to provide comparative information, so this type of comparison is possible. Given a lack of options, the default functional unit (the unit by which the products are compared), is mass (*e.g.* de Figueirêdo et al., 2012; Grubb & Bakshi, 2010). Many LCA studies show that, on a mass basis, the manufacturing of nanomaterials has an overall worse impact than their conventional counterparts (H. C. Kim & Fthenakis, 2012). In general, production of nanomaterials tend to have higher energy demands than their conventional counterparts, as they often start with the conventional material, then need added energy to continue to break them down (Kim & Fthenakis, 2012). For example, Middlemas et al. (2015) used the cumulative energy demand (CED) calculated per kg unit for nano-titanium dioxide (nano-TiO_2) in Grubb et al. (2010) (Grubb & Bakshi, 2010) to compare to a new method of production of conventional titanium dioxide and found it used 20% less CED than production of the nanoform. However, it is possible that less nano-TiO_2 is needed to provide the same functionality; therefore these data can be misleading. In general smaller quantities of nanomaterials are generally required to provide the same or better functionality, so if the study takes into account the functional unit, it will show that the nano-sized material has less impact to provide the same function (H. C. Kim & Fthenakis, 2012). Similarly, even comparison between different processes to make nanomaterials made of the same material, but different functionalities, are strongly dependent on the choice of functional unit. Pourzahedi and Eckelman (2015a) showed that LCA results based on mass versus function of antimicrobial nanosilvers produced by various methods resulted in different preference rankings for synthesis methods. Therefore, a functional unit or assessment based on weight, as is commonly assigned now, may not be a reasonable comparison (Hischier & Walser, 2012; Kim & Fthenakis, 2012). The use of nanomaterials in a product can result in energy savings or more sustainable functions; for example, the use of clay-polypropylene nanocomposites instead of steel or aluminum in vehicle body-panels results in reduced energy consumption and environmental emissions during the use phase (Lloyd & Lave, 2003). The challenge then is to determine the future functionality of these materials to be able to properly assess their impact in comparison to alternative materials. Also, nanomaterials may impart novel properties; in these cases it becomes almost impossible to do comparisons or define a functional unit (Pourzahedi & Eckelman, 2015b). Ensuring that the appropriate functional unit is used (which can be a challenge in the earlier stages of nanomaterial development), or incorporating some sort of measure for the future benefits of the nanomaterial is necessary.

5.2.5 A lack of customer demand

While market pull through customer demand for sustainability may be a driving motivator in many sectors, the literature review and the interviews suggest that customers do not often demand more sustainable products in the nanosector, and are not willing to pay more for a sustainable product. In the interviews, companies stated that, if customers demanded data, they would work to get these data in order to gain or retain customers. In the case of green chemistry, it is highlighted the consumers are often unaware of the chemical components of the products they purchase (Iles, 2008; Kümmerer & Clark, 2016), thus similarly, customer demand for sustainability in the nanomaterials sector may not by a strong driver. Furthermore, business-to-business nano-companies (*i.e.* those who manufacture chemicals rather than products) tend to report less on their CSR activities; this may be indication that these types of companies have fewer stakeholder demands (Groves et al., 2011). Despite this, institutional buyers in markets that are important for nano, such as the clothing, building, cosmetics, consumer product, electronics, health care, and retail fields, are developing chemical policies and standards that require more transparency, reporting, and safety testing (BizNGO, 2016), and therefore nano-companies may face more stringent sustainability requirements from these market players.

5.3 Conditions where a SA may not create value

Despite all the positive benefits that sustainability can bring, there are some situations where a company may want to reconsider doing a SA. While one does not want to discourage nano-companies to implement sustainability measures, it has to be recognized that doing a SA is not always in the best interest of a company. At this point, due to all the challenges outlined above, such as the lack of data, the barriers facing SMEs, and the newness emerging technologies and by proxy their constant development and process changes, comprehensive testing and SA of a company's nano-products is very difficult to do and a definitive result is difficult to provide. Currently, SAs are useful for screening purposes, where judgments based on value or standard indicators may be used at development phase of a material or product. In addition, many SAs run through a series of steps that help identify 'hotpots', or areas of concern, where the management might have missed major sustainability issues. This can be especially useful for tools that are more useful during the innovation and development stages – a SA can serve as an early warning system and help guide the development process. In addition, areas such as social aspects, or aspects related to risk have been overlooked within nano-companies; the indicators provided in some of the SA may raise the awareness and knowledge of the companies' sustainable impact. Furthermore, in the interviews done here, it was found that companies in early development stages, manufacturing at a very small scale, those working in business-to-business operations, and in companies that have sustainability already "embedded" in their DNA may not necessarily access the full benefits from doing SAs.

Many nano-companies in the *very early developmental stages* will not benefit from a full sustainability assessment across the life cycle; since processes are continually changing, materials and costs are fluctuating, and little data exists, they will find that they will have too much uncertainty to produce a reliable outcome (particularly a quantitative results). These companies should consider doing more general or qualitative assessments (*e.g.* qualitative LCA, LRCA), SAs that provide support for future sustainable improvements (Green Chemistry Checklist), and/or at least designate a person or group to read, understand, and start a full SA (*i.e.* determine sustainability goals, track regulations, map out the process, gather data as they progress), so that the principles of sustainability are embedded throughout the development process.

A company *producing very small volumes of nanomaterial* may not find benefit in performing a full SA for their product. If these nanomaterials have been found to not large negative impacts in small volumes/concentrations, and/or are incorporated into products as a small percentage of that product, then their relative impacts in comparison to the other materials may be negligible. Furthermore, if a company is not planning on scaling up its production processes, then its relative overall manufacturing impact may not be very high. Of course, there are some nanoproducts that, even at small volumes, have high toxicity and/or high risk of human or environmental exposure, use exceptionally high amounts of resources during production, use rare raw materials, etc.

While market pull through customer demand for sustainability may be a driving motivator in many sectors, the literature review and the interviews suggest that customers do not often demand more sustainable products in the nanosector, and are not willing to pay more for a sustainable product. In the interviews, companies stated that if customers demanded data, they would work to get these data in order to gain or retain customers. However, in the case of green chemistry, it is highlighted the consumers are often unaware of the chemical components of the products they purchase (Iles, 2008; Kümmerer & Clark, 2016), thus similarly, *customer demand for sustainability in the nanomaterials sector may not be a strong driver*. Furthermore, business-to-business nano-companies (*i.e.* those who manufacture chemicals rather than products) tend to report less on their CSR activities; this may be indication that these types of companies have fewer stakeholder demands (Groves et al., 2011). Despite this, institutional buyers in markets that are important for nano, such as the clothing, building, cosmetics, consumer product, electronics, health care, and retail fields, are developing chemical policies and standards that require more transparency, reporting, and safety testing (BizNGO, n.d.), and therefore nano-companies may face more stringent sustainability requirements from these market players.

It was found that for companies that *already have sustainability embedded in their DNA* (*e.g.* are part of a larger company that does many SAs, are actively involved in sustainable activities, already has a team of engineers trained in green chemistry, etc.) already perform informal assessments that pertain to sustainability. They appeared to have a good understanding of the principles of sustainability, and know a lot about their products. These companies have already implemented eco-efficiency measures, performed safety testing, and implemented occupational safety measures above and beyond regulatory requirements. Therefore, a SA might not be worth the resources to formally complete and record. However, it should be noted that since these companies have already collected these data, it may not be much work to complete a formal SA, which may help with stakeholder reporting, the ability to provide concrete sustainability claims, and it may highlight areas that they have overlooked.

6 Conclusions

This thesis set out to determine if existing product sustainability assessment methods are valuable for nano-companies. Little was known about the appropriateness of the current SAs the existed, and whether they could be used in a 'nano'-context. Furthermore, this research was an exploration of the benefits and costs that a nano-company could expect from a sustainability assessment.

There are many benefits associated to being sustainable, and sustainability assessments can help access these benefits. In performing SAs, companies can expect to *lower business costs and ensure compliance* through cost savings and risk management; *open up business opportunities* through product differentiation, stakeholder interaction, increased access to capital, and reporting; and, eventually, nano-companies may be able to *create new markets* and become leaders through long term strategic planning.

There are many barriers keeping nano-companies from performing SAs. *For all companies*, a lack of awareness of sustainability issues or a lack of perceived value could keep them from doing a SA. The development stage of a product was also a main factor; products in research and development stages were still undergoing changes that prevent a full assessment. *For all SMEs*, they tended to have less access to financial resources, time, and tools, and therefore face greater challenges in performing SAs. A lack of easily accessible expertise was a problem *for both SMEs and nano-companies*; SAs require expertise in many domains and while large companies may have access to departments and employees that only focus on sustainability, most small companies lack this, and also the ability to hire expertise. Finally, a lack of reliable data was identified as a challenge particular to *nano-companies*. Being a new field brings big uncertainties and challenges; a lack of public databases and intense competition means that there is a dearth of available data.

There are many different kinds of sustainability assessments and they range in complexity, outcomes, resource requirements and expertise needs. There are a few that are specific to nano. In general, they can all be adapted to assess nano products and all can produce different benefits. Due to constraints on companies, especially at different stages of growth, the benefits they can expect to achieve will vary. With fewer resources, companies can expect to only be able to perform SAs that achieve short term benefits and fewer long term benefits than those that can afford to spend more resources. In general, they all require financial, time, and resource investment, high data requirements, and extensive expertise. *Nano-companies face even more challenges due to their generally small size, early product development stages, and inability to access quality data.*

There are common limitations amongst all SAs that prevent companies from achieving the maximal value they could provide. Assessments *struggle to incorporate all dimensions of sustainability*, often struggling or ignoring social dimensions, and not considering nano-relevant dimensions such as regulation, technical performance, benefits, and risks. They rely heavily on *self-evaluation and expertise*, which can lead to highly subjective results and can be a prohibitive factor for many nano-companies. They have *value only during narrow periods of product development*; an assessment that is done too early will not have enough data and if it is done too late in the process then technologies and processes will be hard to change. One of the biggest problems discovered was that *the well-developed tools are not accessible*; huge amounts of funding have been spent on developing comprehensive and sound SAs, but often these projects do not continue after the funding period is over, and tools go obsolete or are no longer accessible by the public.

There are limitations amongst all SAs that prevent nano-companies from achieving the maximal value they could provide. In addition to the limitations discussed above, nano-companies also face additional challenges. *Getting reliable data related to the manufacturing, use, disposal, and safety* of nanomaterials is a challenge, and many data gaps exist. There are *few sources of updated and reliable information on nanomaterials*, and even the sources that exist are difficult to use. Many nano-companies have developed from old industries, and therefore *cannot afford to change their technologies or processes* to address sustainability issues. The importance of capturing *nano-relevant criteria,* like legislation, the definition of 'nano', or public acceptance are often not included in SAs, or are difficult to assess. Since some nano-products have novel functions, any assessment based on comparison to a reference product will be difficult.

Finally, it is recognized that there may be **some conditions where completing a full sustainability assessment may not create value**. Companies in early development stages will not have enough data or knowledge of their final product to properly perform an assessment. Those *manufacturing at a very small volume* may not have significant enough impacts to require a SA. Companies that already *have sustainability already "embedded" in their DNA* have likely already performed a series of informal assessments, and are going above and beyond regulation and compliance to satisfy their own intrinsic values.

Based on these results, it can be concluded that SAs can bring value to nano-companies, provided that they can overcome the barriers to performing them. Companies will be able to access more benefits as they have more resources to be able to dedicate to the assessments. In general, there was an interest in sustainability amongst nano-companies, but many were unsure as to whether SAs would be of value to them. For nano-companies, where there are heightened concerns over human and environmental safety and uncertainties regarding future risk, doing a systematic SA will ensure that they have thought about all sustainability aspects prior to commercialization. 'Nano' is, and will continue to be, scrutinized more carefully than conventional materials; **it is imperative that the nano-sector moves forward in a safe and**

sustainable manner. This research has clearly laid out the benefits a company can expect to receive given the resources they are willing to provide, and therefore make it easier for companies to decide whether they see the value in pursuing a sustainability assessment.

6 Recommendations

6.1 For nano-companies

Nano-companies face many challenges and pressures from stakeholders. The nano-sector must move forward together in a safe and sustainable manner, as the large uncertainties mean that the chances of public opinion turning negative are higher than traditional companies. Negative media and news on any negative nano-product effects will be a detriment to the whole industry. Therefore, it is in the best interest of the industry to work together to improve the ability to do SAs that can ensure that companies make safe and sustainable products, and be prepared for extra scrutiny. Additionally, there is a unique opportunity here to address sustainability in the early stages of growth.

The keys to overcome barriers and perform successful sustainability assessments will include the development of collaborations and consortiums to develop reliable nano-specific data and databases. This includes working with universities, unions, suppliers, NGOs, competitors, and regulators. In addition, developing a base of employees that have 'green' chemistry backgrounds, or providing training for currently employees will build the expertise needed to do SAs. This will also encourage employees who recognize the impacts of using the equipment, think about supply chains, work collaboratively, etc.

This is the least expensive and onerous time to change processes, materials, and think about building a base for sustainability. Therefore, it is in the best interest of companies to approach nano-development with sustainable values in mind. While most SAs are too complex, comprehensive, or dependent on quantitative data for companies in the early stages to perform, a company could use them as a 'roadmap' for sustainability. That is, companies can take time to look at the criteria and indicators, and perhaps even start to fill them in, and continue to develop their assessment as their product grows. In this manner, sustainability will become the core of their company and also naturally integrate into the values.

6.2 For sustainability assessment developers and assessors

It is clear that the main barriers to performing sustainability assessments are related to the value-proposition. Either amount of resources needed is too high, or the benefits are not high enough. Therefore, those creating or performing the SAs should always consider how to make assessments cheaper, faster, and take advantage of existing expertise. Maybe more realistically, they have to play a larger role in actively highlighting the advantages of performing SAs, especially in areas where companies already assume that their products are 'sustainable'. In the case where companies do not want to do SAs in 'fear' of showing that their products are not sustainable, advantages such as an ability to change manufacturing processes and the associated cost savings and lowest health and environmental risks can be highlighted. Furthermore, the benefits conferred with doing a thorough examination prior to deciding whether or not to invest in the new technology through reflection on whether or not the risks are acceptable in comparison to the benefits may be invaluable in the long run. Having adaptable tools, such as the OECD sustainability manufacturing toolkit may encourage users to start early with little data, time, money, expertise, and build upon this. The tools and guidances associate with the SA should be made accessible and kept up to date; otherwise their value is reduced.

6.3 For academics and regulators

A lot of important data is developed in academic and government labs; these data can be crucial for nano-companies, but they may be difficult to access for these companies. The continuation of research on their toxicity, fate, and behavior is important, and these need to be disseminated to industry. Contrary to academic tradition, there is a particular gain in being able to see negative results (*i.e.* no toxic impact) published, too. Providing these data in open databases, or as easy-to-read reports will allow for better access and understandability.

Including sustainability aspects as part of funding or regulatory demands can encourage SA. However, it should be kept in mind that LCA is not the only type of SA available, and keep it realistic for nano-companies, especially smaller ones, to perform. While impacts are important, benefits should not be overlooked.

6.4 For funders and investors

Funding and investments are key to driving the nano-industry forward in a sustainable manner. Investors can encourage nano-companies to be more sustainable by demanding more information before investment, and have a minimum set of sustainability criteria. Funders supporting research projects that allow for research on how companies can become more sustainable is necessary. However in the case where funding is put towards something like developing a SA, funders should ensure that the resources and commitment are viable over the long-term to allow the project to continue running after the official funding period is over. This includes funding for personnel, maintenance costs, webspace, etc.

6.5 Recommendations and suggestions for future research

'Value', in a business context, is often linked to overall financial gains. This research suggested that these financial benefits could be reaped through development of products that can sell for higher prices, savings resulting from resource-efficiency, ensuring that products complied with regulatory requirements and were able to enter the market, avoidance of future financial risks related to occupational or environmental toxicity, or increased business through the fulfillment of stakeholder needs (*e.g.* demand for quantitative sustainability data). It would be interesting to quantify the gains/losses from performing actually performing SA. This could possible be measured by looking at cost of the SA *versus* overall financial gains. This could be measured through the change in sales, contingent valuation (customer 'willingness-to-pay' for more sustainable products), or through avoided future costs (*e.g.* implementation of PPE saves future occupational health costs). Furthermore, as nano-companies have specific challenges, then these measurements could also be performed to compare against traditional companies. I would expect that the costs would be higher for nano-companies, but their relative gains may be higher, as they have 'more to prove' to their customers (safety, functionality, etc.) than traditional companies.

In this study, it was not determined whether these are *perceived* or *real* barriers; for example, companies often cited cost, time, or expertise as a barrier to executing a SA, but there was no attempt made to quantitatively verify if this was true. No companies asked for actual numbers (*i.e.* "how long would a SA take, or "how much would it cost"), so either they were already aware of these values, which did not seem to be the case, or they were making assumptions that they could not afford it. Gathering these values and then asking companies if they have the resources to complete them would be helpful in identifying real barriers to performing a SA.

Finally, no single SA was perfectly aligned to the needs of a nano-company. However, there were components of each that would be valuable. Starting with the criteria from assessments like Cinelli's Nano-Sustainability Framework and other assessments, with the guidance of the lessons learned here and operationalizing them into a sustainability assessment guide and tool would be the next step of this research.

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Appendix I – List of unevaluated assessments

Sustainability assessment	Brief description	Reason for not including
Good Guide Ratings	Integrated sustainability assessment, each category scored between 1-10	Company cannot perform themselves,
eVerdee	Simplified LCA, free online tool	Domain down from beginning of thesis period
EPM Kompas	A tool that help measure the environmental performance of SMEs and help with decision making	In german
NanoMeter	Internet-based screening tool to assess applications using nanomaterials, with a focus on sustainability and success on the market.	www.observatorynano.eu/project/questionnaire/nanometer no longer functional. No in depth description of the method could be found (CORDIS Project 218528)
Nanoroad SME	A promising EU project - road mapping tool for nanomaterials, specifically focused on SMEs. Results based on a database with >100 nanomaterials.	Nanoroad.net no longer functional, no in depth description of the method could be found. (CORDIS 2011)
Sustainability Consortium Product Sustainability Toolkits	Scientifically rigorous toolkits looking at life cycle impacts for specific consumer products	Toolkits cost $699.