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Guidance to Facilitate Decisions for Sustainable Nanotechnology

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Notice

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

Abstract

Products that incorporate materials manufactured at the nano scale (i.e., nanoproducts) offer many potential benefits to society; however, these benefits must be weighed against potential "costs" to the environment and public health. This document was developed to provide a broad guidance for assessing the sustainability of nanoproducts and is intended to lay the groundwork for developing a decision-support framework through continual updates as research in this area progresses. At the very least, it will aid stakeholders when navigating the various choices that must be made to foster the development of sustainable nanotechnology. Given the all-encompassing nature of sustainability, this work should be of interest to stakeholders in all areas of nanotechnology, including research, product development, consumer use, and regulation. The aim of this work is not to make decisions for stakeholders, but to help frame the pertinent issues that must be addressed to properly assess emerging nanotechnologies and to provide information on the various tools that may be used to address them. The foundation of this approach is to consider existing standards and methods for environmental, economic, and social assessments using a life cycle perspective and offer guidance by relaying first-hand knowledge of applying assessment tools to nanotechnologies, whenever possible. Brief overviews of the various assessment methodologies are provided to help stakeholders make informed choices when selecting tools appropriate for their goals. For specific details of a method, readers are directed to the referenced standards and guidance documents supporting the application of these tools. The key steps to be included in the evolving framework include: characterizing a nanoproduct and identifying potential risks and impacts; identifying relevant stakeholders; defining the goal and scope of an assessment; assessing environmental, economic, and social impacts; evaluating sustainability criteria; developing and evaluating alternatives; and selecting and implementing a decision to support sustainability. Given that the field of nanotechnology is relatively new, there are significant uncertainties regarding its potential human health and ecological risks and impacts. Hence, methods developed to address these uncertainties are also explored. Moreover, since the field of nanotechnology is changing rapidly, this document will be reviewed and updated as additional information becomes available to continue working towards the end goal of sustainability.

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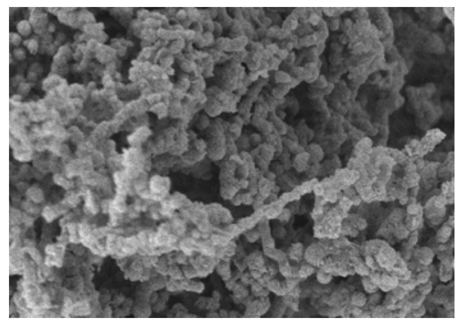
Figures and Tables

1. Managing Sustainable Nanotechnology

1.1 Nanotechnology Overview

The U.S. National Nanotechnology Initiative (NNI) defines a technology as nanotechnology **only if it involves all of the following**:
- Control or manipulation of matter at dimensions in the 1 to 100-nanometer range.
- Creation of structures, devices and systems that have unique properties and functions at the nanoscale leading to novel applications.

Nanotechnology relates to the ability to create materials and devices through the manipulation of individual atoms and molecules (up to 100 nanometers). Further, it involves integrating these structures into larger systems (Bhushan, 2007). Similar to information technology, nanocomponents (the nanoscale building blocks of nanotechnologies) exhibit a diverse array of characteristics that may be used for a wide range of beneficial applications and have the potential to generate significant improvements to existing technologies (Palmberg et al., 2009). These applications include medical, food, clothing, defense, national security, environmental clean-up, energy generation, computing, construction, and electronics (Davies, 2009; EPA-SPC, 2007). Consequently, according to a recent publication from the Organization for Economic Co-operation and Development (OECD), the field of nanotechnology is rapidly expanding (Wiesner et al., 2006) and is anticipated to emerge as a key engine of growth for the 21st century (Palmberg et al., 2009).



Throughout this framework, the diverse products and materials that are made using (engineered) nanocomponents will be collectively referred to as nanoproducts.

> *"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."*
>
> Neal Lane
> Former NSF Director
> Assistant to President Clinton
> for Science and Technology

Nanotechnology is being touted as a profound technological advancement capable of transforming society as we know it. Accordingly, the investment in nanotechnology initiatives have skyrocketed (Roco, 2009). However, the potential for explosive growth in nanoproduct markets should be viewed with cautious optimism. Without question, knowledge of the physical world at the nanoscale opens a world of possibilities to enable the development of products and systems with great precision and intricate properties that could improve our overall quality of life. Systematic control of the production of products at the molecular level could enable the development of eco-friendlier products and services. The projected trillion-dollar nanotechnology market is expected to provide new markets, create jobs, and greatly increase profits for businesses. However, caution must be applied to temper these expectations when considering the growing concerns regarding the unforeseen impacts of nanotechnology deployment. For example, with many nanotechnologies requiring energy intensive processes and rare materials, it is unclear how large-scale deployment will affect the environment. In addition, the cost needed to retrofit production and incorporate nanotechnology may be more than some existing companies can afford. This could lead to a radical shift in the make-up of the various application markets, resulting in the emergence of corporate monopolies and destabilization of the global economy. In addition, the more advanced manufacturing processes will require workers with greater knowledge and expertise, thereby putting pressure on the existing workforce to adapt mentally or risk unemployment, a problem that can quickly alter societal dynamics. Perhaps the greatest concern with nanotechnology is the potential threat that nanocomponents pose to human health and ecosystems. NSF's increasing investment in the safety and societal implications of nanotechnology (Roco, 2009) stems from recognition that the unique properties that define a nanotechnology and make it novel are the same properties that could eventually pose the greatest health risks. These various concerns transcend the science of nanotechnology and raise the issue of its sustainability.

1.2 Towards Sustainability

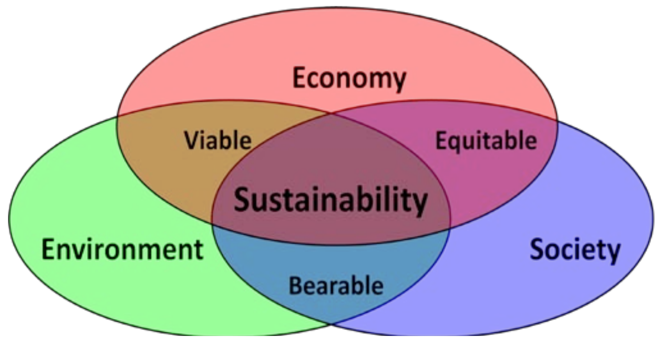


Figure 1-1. A Holistic View of Sustainability

The National Environmental Policy Act of 1969, a precursor to the establishment of the Environmental Protection Agency, formalized a growing understanding of the importance of the relationship between humans and the environment. Further its language, "…to declare a national policy which will encourage productive and enjoyable harmony between man and his environment; to promote efforts which will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of man….", foreshadows ideals soon to be of great importance on a global stage. Nearly two decades later, the World Commission on Environment and Development (WCED) coined the term sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (ONGO, 1987). Thus, sustainability may be viewed as using resources and developing products and processes in a way that ensures and promotes a legacy of economic viability, social equity and environmental responsibility for current and future generations.

Many researchers recognize that traditional growth and development practices are contradictory to shifting to a sustainability paradigm (2003). While there is great interest in this area, some believe that economic progress and sustainability are mutually exclusive (Davidson and Julie, 2001). This idea is birthed from the concept that sustainable development inevitably translates into benefiting one facet to the detriment of another. However, in truth, it is about balance and optimization and entails evaluating the intricate elements of sustainability (Berkel, 2000; Eason et al., 2009). Built on a foundation of economic, social and environmental indicators, sustainability-based decision making is a highly complex challenge and is predicated on the ability to reconcile both disparate and integrated aspects of the product, process, or system under study. Given the magnitude of its anticipated impact, nanotechnology should therefore be produced and utilized in a manner that is environmentally, economically, and socially sustainable to fully realize its potential (Helland et al., 2007; Klopffer, 2008).

Years after the WCED definition was accepted, researchers have continued to struggle with reaching a consensus on how sustainability should be measured. However, one key development and widely accepted convention was to establish what is termed the three pillars of sustainability:

environment, economy, and society (Figure 1-1). Each of these pillars denotes particular aspects of the product, process, or system that may be assessed via observable and measurable criteria (i.e., metrics). While there are tools available that may be used to evaluate characteristics within a particular pillar, the difficulty lies in making decisions based on information gathered from various tools and disparate criteria.

The challenge of sustainability begins with an understanding of the holistic nature of the world in which we live. Traditional Newtonian thinking views the world as isolated subsystems and seeks solutions to problems within each system with little regard to how the various systems interact. In contrast, holistic thinking examines how changes within a subsystem can affect the system as a whole through interactions across subsystem boundaries, recognizing that the world is an integrated sum of its parts. This holistic approach has inspired the field of industrial ecology, a systems-based, multidisciplinary approach to understand the emergent behavior of complex integrated human/natural systems. With nanotechnology, it is important to understand how the various world systems (i.e., ecosystems, societies, etc.) will be impacted by its existence throughout its full life span (i.e., from cradle to grave). The life cycle concept identifies five key stages where impact may occur, including:

Systems Thinking

In his landmark book, The Fifth Discipline, Peter Senge wrote, "From a very early age, we are taught to break apart problems, to segment the world. This apparently makes complex tasks and subjects more manageable, but we pay a hidden price. We can no longer see the consequences of our actions; we lose our intrinsic sense of connection to a larger whole." For Senge, the answer lay in systems thinking. Applying systems thinking helps creative individuals to see wholes, perceive relationships, uncover connections, expose root causes and master complexity. Senge argued that systems thinking integrates what might otherwise be considered separate management disciplines, preventing them from becoming "gimmicks or the latest organisation change fads." *(Smith, 2005)*

- **Raw materials extraction**: Activities related to the acquisition of natural resources, including mining non-renewable material, harvesting biomass, and transporting raw materials to processing facilities.
- **Materials processing**: Processing of natural resources by reaction, separation, purification, and alteration steps in preparation for the manufacturing stage; and transporting processed materials to product manufacturing facilities.
- **Product manufacture:** Manufacture of product and transport to the consumers.
- **Product use:** Use and maintenance activities associated with the product by the consumer.
- **End-of-life disposition:** Disposition of the product after its life span, which may include transportation, recycling, disposal, or incineration.

The Daly Rules for Sustainability

Working from theory initially developed by Romanian economist Nicholas Georgescu-Roegen, Herman E. Daly (University of Maryland School of Public Policy professor and former Chief Economist for the World Bank) , laid out in his 1971 opus "The Entropy Law and the Economic Process") suggests the following three operational rules for defining the condition of ecological (thermodynamic) sustainability:

1. Renewable resources such as fish, soil, and groundwater must be used no faster than the rate at which they regenerate.
2. Nonrenewable resources such as minerals and fossil fuels must be used no faster than renewable substitutes for them can be put into place.
3. Pollution and wastes must be emitted no faster than natural systems can absorb them, recycle them, or render them harmless.

Accordingly, each stage during product development should be optimized to minimize the impacts within the three pillars. However, it is important to remember that changes to one stage can lead to impacts in another stage. Thus, the holistic approach is needed to achieve sustainability. True sustainability, as described by Daly (text box above), may never be fully achieved during a product's life cycle in the short term. Subsequently, the goal of sustainable development would be to help identify the most desirable option based on available technologies and current industrial practices. However, it is beneficial for decision makers to remain open and continually explore alternative solutions for a product function by periodically revisiting the design and manufacture of a product. Potential product alternatives can provide a comparative basis to better understand assessment results. In some cases, the alternative may be an existing product or process and in others, after the initial design, it may be worthwhile to generate alternatives encompassing other available technologies.

1.3 Document Overview

This document presents guidance for integrating sustainability into the evaluation, management and development of nanoproducts. The material is presented while keeping in mind the long term goal for this work to eventually be refined into a decision support framework. It is intended to support Goal 4 of the NNI's Strategic Plan "to support the responsible development of nanotechnology"(NNI, 2011). Efforts in this area are coordinated by the Nanotechnology Environmental and Health Implications (NEHI) working group of the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee that maintains the Environmental, Health, and Safety (EHS) research strategy. Since the original EHS research strategy was written in 2008, the NEHI has collaborated with stakeholders from government agencies, industry, academia, non-governmental organizations (NGOs) and the general public to determine how best to update and improve EHS research (NNI, 2010). One of the primary results of these actions was the recognition of the stakeholders to incorporate life cycle considerations for sustainability into risk management for nanocomponents and nanoproducts. Therefore, the preliminary framework of this guidance represents a reasonable approach to sustainability assessment rooted in a life cycle perspective.

Since anyone involved with the life cycle of a product may constitute a stakeholder (Freeman, 1984; Mitchell et al., 1997), the guidance that follows is intended to provide researchers, product developers, NGOs, policy makers, and consumers with an understanding of the various choices that must be made to ensure the development and sustainable use of nanoproducts. While some may argue that control of product sustainability is ultimately in the hands of researchers and product developers, it is important that stakeholders throughout the product life cycle have a common understanding of the benefits and challenges associated with sustainability in order to better work together to achieve it. Further, this guidance helps stakeholders understand the tools that may be used to assess aspects of sustainability and identifies current approaches in the literature to attempt to integrate data from these disparate evaluations to make quality decisions. At present, integration of assessment tools is a key challenge for sustainability assessment in general with no clear consensus choice of method available. As an additional benefit to stakeholders, discussions of potential pitfalls and areas of concern that may arise during assessment are included. Moreover, whenever possible, the authors relay first-hand knowledge of the application of specific assessment tools to nanoproducts.

The guidance offered in this document may be applied to both new and existing technologies. An existing nanoproduct can be a complete product redesign, a modification of an existing nanoproduct, or the incorporation of nanotechnology into a traditional consumer product. However, the large number of unknowns regarding the use and disposal of nanomaterials makes it more challenging to successfully address the critical sustainability concerns within the life cycle of a new nanoproduct or concept prior to full-scale implementation. Therefore, researchers and product developers must integrate sustainability considerations into subsequent modifications to correct for unforeseen issues as the nanoproduct evolves and develops. For the sake of discussion, guidance is presented for the case of new technology development with the understanding that any issues that may arise when dealing with product redesign can be addressed using the same principles.

Before presenting the preliminary framework that will guide the discussions in this document, it is important to first recognize a key contribution to life cycle based sustainability assessment in the open literature to provide readers with an understanding of why this work has chosen to adopt a different approach to accomplish decision making for sustainable nanotechnologies. Kloepffler (2008) has proposed Life Cycle Sustainability Assessment (LCSA) as a tool to evaluate the sustainability of products. The tool integrates the existing methods of Life Cycle Assessment (environment), Life Cycle Costing (economy) and Social Life Cycle Assessment (society) to perform a sustainability assessment using the existing indicators of each method for the respective pillars. While this approach is a viable option, it presupposes the ability of these three tools to account for all potential implications of a product. As will be presented in this document, there are many challenges associated with assessing nanotechnology that may fall outside of the scope of these three tools. Therefore, this work will focus on developing a framework that is more readily adaptable for nanoproducts by allowing for a customizable selection of indicators, and therefore tools to be made by those with first-hand knowledge of the product/system to be studied. This should lead to more relevant decisions regarding the development of sustainable nanotechnologies.

Figure 1-2 demonstrates how the preliminary framework presented in this guidance document can be deployed during product development. Experts can include risk assessors, economists, public health experts, or other scientists that may offer important advice in assessing impacts and selecting approaches for mitigating these impacts. The people who will guide the overall application of the framework are a group of decision-makers typically comprised of experts and stakeholders. The key steps of the framework include:

1. **Characterize product and identify potential health and environmental (toxicity) risks.** At the outset of developing the initial idea or product concept, product developers should conduct an initial characterization of the potential health and environmental (toxicity) risks of the chemicals contained in the product. This would allow the team to identify and mitigate potential chemical hazards early on in the product design stage.

2. **Identify stakeholders.** Stakeholders should be identified early and engaged at the outset of sustainability assessments, as they provide important input in defining the goal and scope of the study, as well as helping to develop appropriate sustainability metrics, evaluating and interpreting impacts, and selecting alternative approaches to mitigate impacts.

3. **Define assessment goal and scope.** Establish the goals and objectives of the analysis and determine the appropriate methods and models to meet the assessment objectives. This step involves translating the broad concept of sustainability into concrete, measurable goals, which can be assessed in step 4.

4. **Assess environmental, economic, and social impacts:** Apply methods for assessing environmental, economic, and social impacts across the life cycle of the nanoproduct. These impacts include, but are not limited to: energy and material use, costs to the manufacturer, greenhouse gas emissions, and wages. Uncertainty should be assessed and a sensitivity analysis may be conducted as part of this step.

5. **Evaluate sustainability criteria.** Normalizing the inventory of impact results into pertinent categories related to the sustainability criteria and eliciting stakeholder valuations of criteria to interpret and compare results.

6. **Develop alternative approaches to mitigate impacts.** The results of the assessments and evaluations can help developers identify improvements to the product system that will mitigate impacts (e.g., modification to the manufacturing process or use of alternative nanomaterial in an upstream process).

7. **Assess the environmental, economic, and social impacts of the alternative approaches.** Each alternative approach developed should be assessed to determine the impacts for each pillar. The results will then be used to compare different alternatives. As part of this step, additional alternatives may need to be developed and assessed if the initial designs are found to be inadequate for improving the sustainability of the product.

8. **Select most sustainable alternative.** Once the environmental, social, and economic impacts for each alternative are assessed, decision makers work together to select the best alternative approach for mitigating impacts and achieving a sustainable product design.

9. **Implement production of sustainable nanoproduct.** Following selection of the preferred alternative, the product should be manufactured and continually monitored for further improvements using the sustainability framework.

Although these steps are discussed with regard to a new product development, we re-emphasize that the framework may also be applied to products in any development stage, including those that are already commercialized. As noted above, achieving sustainability is an iterative process in that products should be continually assessed and updated as new information becomes available. The guidance in this document will be given through detailed discussion of each step of

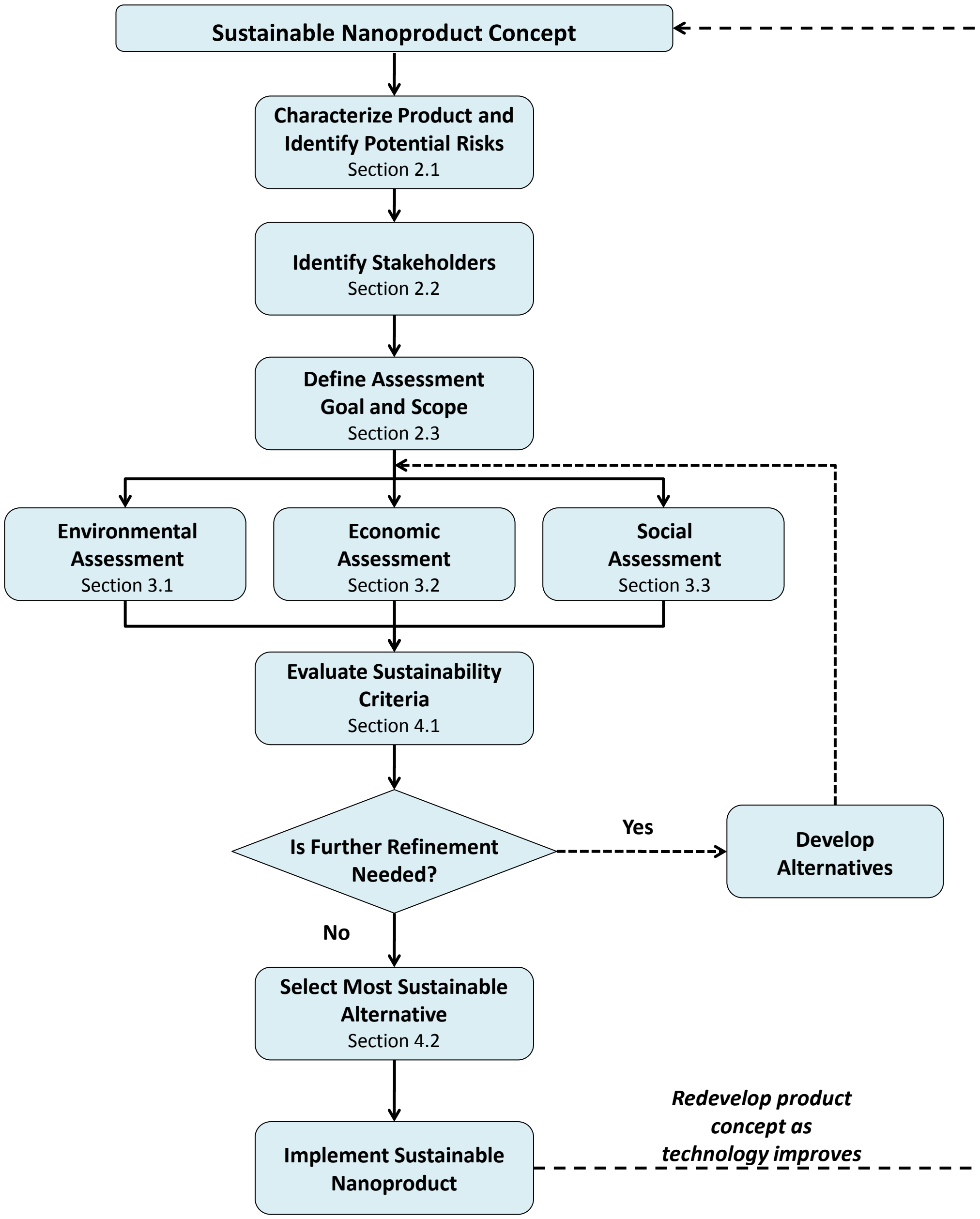


Figure 1-2. Overview of a Preliminary Framework for Sustainable Nanotechnology

the preliminary framework and is presented in **Sections 2-4**. **Section 5** presents overall conclusions of this work and how they can be applied to refine the proposed framework. Finally, the **Appendix** includes a list of additional resources that may be useful in conducting sustainability assessments of nanoproducts.

1.4 Key Benefits to the Intended Audience

As previously described, this document is anticipated to primarily assist nanotechnology researchers, developers, engineers, and product manufacturers in addressing potential environmental, economic, and social implications throughout the life cycle stages of a new or developing nanoproduct. It can also be useful to other decision-makers, including government agencies and NGOs by providing a better understanding of the pertinent issues that must be addressed to properly assess the sustainability of a nanotechnology.

Industry and government stakeholders can realize many benefits from conducting and supporting sustainability assessments of nanoproducts. A sustainability assessment can contribute to research that will aid current efforts to promote health and safety when manufacturing nanoproducts as well as in their public use or consumption. This will not only help minimize risk, but also reduce unsubstantiated or nonscientific claims of risks or benefits of nanoproducts. Further, if nanoproduct developers can demonstrate that they are serious about developing a sustainable product that presents minimal long-term risks to human health and the environment, then their products may be viewed more favorably. Such an effort will help avoid an inaccurate perception of risks among the general public similar to those that arose for genetically modified organisms (Bell, 2007). Upon completion, this process will aid in establishing a protocol toward the development, management and assessment of sustainable nanoproducts. Additionally, it will provide life cycle data (material and energy flows) that may be used as a benchmark for future sustainability assessments of nanoproducts and technologies, to measure improvements, and evaluate the impacts of possible design changes.

Other benefits include:

- Placing human health risk assessment in perspective with other environmental concerns across the life cycle of nanoproducts.
- Quantifying energy and resource intensive processes and minimizing their impact.
- Identifying cost savings for the manufacturer and consumer.
- Developing an evaluation of impacts and risks to human health, the environment, and society from the local to national and global scales.
- Demonstrating a commitment by manufacturers to stakeholders for the responsible development of nanoproducts.

<u>Notice of Use</u>

Any comparisons discussed in this document refer to *internal* comparisons within a company's own processes or alternatives. Internal comparisons can help a company to improve an existing product line, but do not make any claims in regards to other companies' products. **Comparing products against similar products from other companies and making a public statement about results, known as a comparative assertion, requires a thorough review process, which is not presently addressed.**

2. Initializing the Path Forward to Sustainability

Before offering detailed guidance based on the preliminary framework, it is important to articulate how sustainability can be integrated into existing models of product deployment. Product deployment is comprised of two stages, product development and product management. Traditionally, product development can be broken down into a series of steps including:

- Idea Generation: Use brainstorming to identify potential products and markets.
- Idea Screening: Eliminate impractical ideas and select most promising alternative.
- Concept Development and Testing: Establish engineering and marketing details.
- Business Analysis: Use stakeholder feedback to estimate pricing and profitability.
- Beta Testing and Market Testing: Produce prototype and evaluate typical use.
- Technical Implementation: Develop quality guidelines for manufacturing; compile product data sheets; prepare supply chain for product deployment.
- Commercialization: Product launch into consumer markets.

At the onset of commercialization, product management is invoked to oversee the product life cycle. In this case, the term “life cycle” from a business perspective is different from what is defined for sustainability and describes the four stages involved with marketing a product: (1) Introduction, (2) Growth, (3) Maturity, and (4) Decline. These stages track the market penetration of a product and its consumer acceptance. Upon entering the Decline stage, businesses can either discontinue a product or seek to redevelop it to make it commercially viable.

To achieve development of sustainable technologies and products, careful consideration must be given to the issues of sustainability prior to commercialization and product management. However, this is not as simple as inserting a “Sustainability Assessment” step into the product development concept above. Instead, the steps of the sustainability framework described in this document will have to move in tandem with the steps of product development as the needed data become available. This will help insure that sustainability is achieved for a product in a manner that maximizes its benefits to a company while minimizing its impact on the process of product deployment.

The overlap of sustainability with product deployment is shown in Table 2-1. Sustainability concerns are not considered during the generation of ideas to avoid stifling creativity. As a product idea develops, sustainable design begins with consideration of the basic risks and eventually grows into full assessment of the three pillars. However, the various pillars can and should be considered at multiple times throughout product deployment to maximize the potential for sustainability. For example, the environmental impacts of manufacturing and distributing a proposed product can be examined during concept development and testing using pilot scale data and engineering estimations. Once beta testing is initiated, this assessment can be revisited and expanded to include the use and disposal phase based on testing results. The data can be updated using realistic manufacturing data during technical implementation. Finally, the environmental impacts can be reassessed during product management using real market data to identify any potential concerns that did not manifest themselves during design. This approach is intended to provide companies ample opportunity to amend a product to achieve sustainability goals prior to large scale commercialization through early detection and action. Thus, sustainable design from a business perspective is both iterative and cyclic in nature. By keeping this in mind, it will be easier to understand the discussions of assessment and decision-making tools that follow.

Table 2-1. Traditional Product Development and Sustainable Design proceed in tandem and entail overlapping steps

Product Development	Sustainable Design
Idea Generation	Initial Risk Screening
Idea Screening	
Concept Development and Testing	Product Characterization, Risk Screening, Stake Holder Identification, Environmental Assessment
Business Analysis	Economic Assessment and Social Assessment
Beta Testing and Market Testing	Product Characterization, Risk Screening, Environmental Assessment
Technical Implementation	Risk Screening, Environmental Assessment
Commercialization	Economic Assessment and Social Assessment
Product Management	Risk Screening, Environmental Assessment, Economic Assessment, Social Assessment

2.1 Initial Product Characterization and Identification of Potential Risks

Defining the Nanoproduct Concept

1. What is the function of this product?
2. What is the anticipated target market?
3. What are the necessary materials?
4. Is there more than one approach?

One of the first steps of the framework is to appropriately characterize the nanoproduct. This includes an understanding of how the product will be used along with a general description of the intended materials and characteristics (e.g., chemical composition, physical form/shape, solubility, state of aggregation or agglomeration, etc.), and physical and mechanical properties. Characterization of the product should be detailed enough to provide sufficient guidance for conducting an analysis throughout the product's life cycle stages. When characterizing the nanomaterials, the reader can refer to the International Organization for Standardization's report on the classification and characterization of nanomaterials (ISO, 2010).

Before undertaking a full sustainability assessment, it is appropriate to determine whether easily identifiable risks are present and whether they can be mitigated (Figure 2-1). This action is not intended to be a full risk assessment as defined in Chapter 3. Instead, it should be a quick screening-level identification of known risks. For example, if a proposed electronic product will involve lead or other toxic metals as part of the circuitry, the known risks related to exposure to these materials should be addressed before continuing. A benefit of this type of screening-level risk identification is that it can lead to the development of better products that are more sustainable. However, this may be more a challenging task when quickly considering nanoproducts because of the general lack of knowledge regarding the associated risks of nanomaterials. Although the toxicity and risk related to nanomaterials and products continues to be investigated, recent studies have found a correlation between certain physicochemical properties of nanomaterials and their potential toxicities. For example, the size and shape of a nanomaterial influences deposition patterns in the human respiratory tract. Nanomaterials that are deposited in the respiratory tract may cause symptoms similar to those caused by asbestos (e.g., immune-system malfunction, lung disease, and cell inflammation) (Olapiriyakul and Caudill, 2008). Other characteristics of nanomaterials that may affect toxicity include the chemical composition, aspect ratio, crystal structure, surface area, surface chemistry and charge, solubility, adhesive properties, and emergent properties (Klöpffer et al., 2007). It has generally been found that if nanomaterials are embedded as part of larger objects (e.g., nanocomposites and nanocrystalline solids) they are less dispersive and present lower risk than if they are used as free nanoparticles, nanorods or nanofibers (Ostertag and Husing, 2008). In addition, recent research focused primarily on airborne pathways has examined the hazards associated with exposure to nanomaterials in the workplace. These studies have found that some nanomaterials damage lung tissue after inhalation (Wiesner et al., 2006). The potential risk of such exposure will depend on how the nanocomponents are produced and handled while being incorporating into nanoproducts. A study by Sengul, et al. (Sengul et al., 2008) provides a comprehensive review of techniques used to manufacture nanoproducts, a description of the technique, key processes, materials used, primary energy consumption, and environmentally significant aspects. These techniques include top-down approaches where nano-scale dimensions are achieved through carving or grinding (e.g., lithography, etching, electro-spinning, and milling), or bottom-up methods in which nanomaterials are developed at the atomic scale using vapor-phase, liquid-phase, and self-assembly techniques (Sengul et al., 2008).

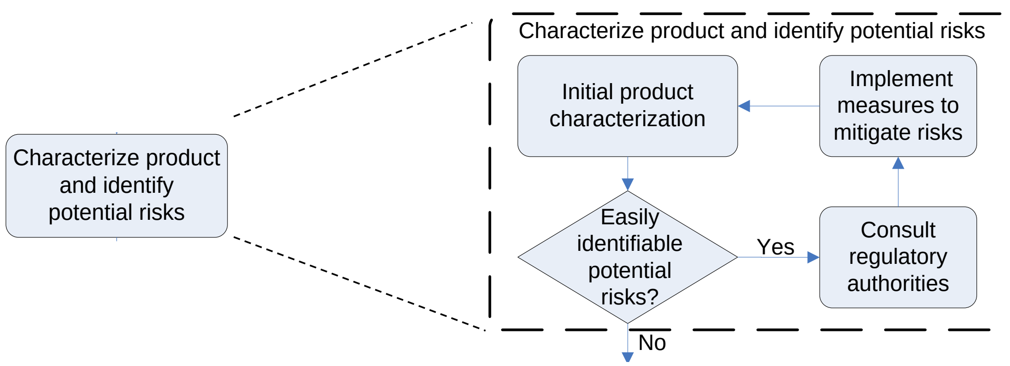


Figure 2-1. Identifying Risks Early in the Process

As shown in Figure 2-1, if easily identifiable potential risks are found, the product developers should consult the appropriate regulatory authorities to determine whether there are any compliance issues relevant to the nanomaterial or nanoproduct. In 2007, EPA convened a workgroup to discuss and document the science needs associated with nanoproduct. The resulting "Nanotechnology White Paper" (EPA-SPC, 2007) includes an overview of environmental statutes that may be applicable to nanoproducts (e.g., Toxic Substances Control Act (TSCA), Clean Air Act (CAA), and Clean Water Act (CWA)). EPA policies and regulations are evolving as research on nanotechnology and its impacts continue and additional information becomes available. However, measures should be taken to mitigate any easily identifiable risks and ensure compliance with the current and appropriate regulations before taking further steps in sustainability assessment. Examples of preliminary data needed to characterize early stage risks of nanoproducts are given in Table 2-2. Although many sources are working to provide an understanding of the potential toxicity of nanomaterials, nanomanufacturers should be encouraged to incorporate toxicity studies if possible into their product development because the

Table 2-2. Identifying Risks Early in Development

Stage	Preliminary Data Needs
Nanomanufacturing	• Are data available on the toxicity of the nanomaterials to human health or organisms in the environment? • Are data available (pilot plant) on potential air emissions, waste discharges and amounts of solid waste generated? • Is any risk issues associated with release of these waste streams? If yes, can the risk be contained with state of the art treatment protocols available to treat air pollutants/ liquid waste and solid waste?
Nanoproduct Use	• Is there an anticipated release and transport of nanomaterials from the nanoproduct during use?
Nanoproduct End Of Life (EOL)	• What is the likely frequency of waste generated? • Is nanomaterial encapsulated, semi dispersed or loosely formulated in the product at its end of life? • What are the effects of nanomaterials on environment when incinerated or landfilled?

A Case Study in Early Intervention

In the early 1980s, I was working in the plastics industry as the head of health, safety, and environment for a major business division of a parent company. Researchers at the division had just discovered a thermosetting catalyst that was unlike any previously available. Epoxy-type resins begin curing at the moment they are mixed with standard catalysts. This new catalyst remained inactive until a very specific and desirable temperature was reached.

This catalyst had enormous potential, and the marketing department immediately began distributing samples of it in order to encourage commercial trials. But there were also indications of problems with the substance. Both my department and the division's medical department recognized that the catalyst contained small amounts of a material that potentially could be toxic under certain circumstances.

Jointly, we formed an internal task force consisting of toxicology, environmental, industrial hygiene, and medical professionals. Our work was supported by an outside toxicology lab and a prestigious occupational medicine institute. In relatively short order, we discovered that the material was not just toxic (as suspected), but in fact so biologically active that it was attracting interest from external physicians as a possible pharmaceutical because of its radical effect on the circulatory system.

Executive management at our division could have attempted to brush off the preliminary test results as insufficient and inadequate to justify withdrawal of the material from full-scale commercialization. They could have rationalized away the risk and limited funding for what eventually became very expensive and sophisticated testing. Instead, they fully supported our efforts and allowed the toxicological testing and evaluation to proceed unhindered and in an unbiased manner.

Ultimately, the division decided to withdraw the catalyst from all future commercial trials. As a result, no one was ever seriously injured by the material.

If the toxicity of the catalyst had been fully understood in advance, the material might have been introduced successfully into a highly controlled, specialized niche market where its unique properties could have been utilized fully and safely. But the mainstream market was not equipped to handle the material. The division considered it too likely that customers would use the substance as they did other, relatively safe commercial catalysts, without proper safeguards.

By Richard MacLean (MacLean, 2009).

numerous variations that occur from batch to batch and product to product may lead to unique toxicity characteristics for a given nanomaterial

2.2 Stakeholder Identification

Stakeholder participation is an integral element of sustainable decision making (Kiker et al., 2005). Given the fact that the sustainability of a product may be viewed differently by different stakeholder groups, it is important to obtain their input and value judgments in conducting a sustainability assessment. In broad terms, a stakeholder includes any group or individual who can affect or is affected by any aspect of a product (Freeman, 1984; Mitchell et al., 1997). These stakeholders may include those that have a direct or indirect stake. For example, direct stakeholders may include those with a vested financial interest in the company developing the product or customers that will eventually use the product. Indirect stakeholders may include those with the ability to influence the product development (e.g., regulators) (Young, 2008).

All groups or individuals that are likely to be affected, whether positively or negatively, by the product throughout its life cycle should be listed through a brainstorming session. When listing the stakeholders, it is often helpful to group them into different categories (e.g., workers, management, customers, community, etc.). However, depending on where a product is in its development cycle, the product uses, target market, and associated stakeholders may be difficult to identify. Therefore, the list of stakeholders may expand and need to be updated and revised as a product is further developed and commercialized.

Engaging all the identified stakeholders is often unrealistic and resource intensive. Accordingly, decision-makers must narrow the list of stakeholders to those that seem the most appropriate to engage for the assessment. To assist in this effort, stakeholders may be "mapped" based on their level of interest, legitimacy, influence, or other factor relevant for the project (Bryson, 2004; Young, 2008). Figure 2-2 includes an example stakeholder mapping approach.

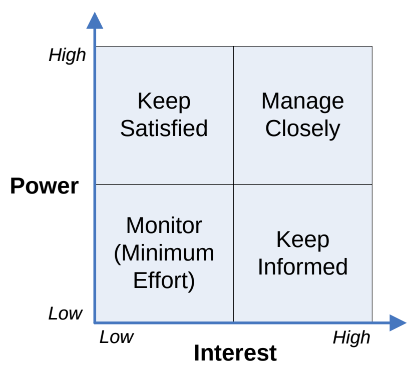


Figure 2-2. Example of Stakeholder Mapping (Bryson, 2004; Young, 2008)

Stakeholders are typically engaged in the goal definition and scoping phase, evaluation and interpretation of impacts and selection of final alternative approaches to mitigate impacts (steps 3, 5, and 8 of the framework). Participation strategies for soliciting stakeholder input may include individual surveys, public meetings, workshops, interviews, or a combination thereof. The appropriate participation strategy should match stakeholder preferences, which may be influenced by the level of trust participants may have of each other, scientific and technical experts, and the product developers. Furthermore, as the level of trust evolves, the participation strategies may need to be adjusted as appropriate (Anex and Focht, 2002). In addition to the level of trust between participants, the selected strategy may also reflect other factors such as the decision context and available resources for the study (Kiker et al., 2005). Ultimately, the specific involvement of individuals or groups will depend on how closely a particular issue is of interest and may affect them (Anex and Focht, 2002). For more discussion on the identification, engagement, and analysis of stakeholder input, the reader is referred to Reed and coworkers (Reed et al., 2009), Cuppen and coworkers (Cuppen et al., 2010), and Aaltonen and coworkers (Aaltonen, 2011), all of which provide useful insight based on case studies.

Involving Stakeholders

As indicated in section 1.4, a key step in the decision framework is to identify and engage stakeholders who can provide input in defining the goal and developing sustainability metrics, evaluating and interpreting impacts and selecting alternative approaches to mitigate impacts. This is especially important when working in a collaborative manner, such as in a private-public partnership, or in an industry consortium. As mentioned previously, stakeholders include any group or individual who can affect or is affected by any aspect of the nanoproduct (Freeman, 1984; Mitchell; 1997), and may also include experts such as LCA practitioners, risk assessors, economists, or public health experts, or other scientists that may offer important advice in assessing impacts and selecting approaches for mitigating these impacts.

A diversity of perspectives should be used to inform the project goals and scope, identify the functional unit and alternatives (if a comparative assessment is to be conducted), refine the methodology, monitor its implementation, and facilitate use of the information generated by the study to make product improvements and, if a comparative assessment is conducted, to choose safer materials and processes. Involvement throughout the project helps to ensure that stakeholders contribute to, understand and support the outcome, enhancing credibility and promoting product improvements. Stakeholders are drawn from the entire supply chain and all life-cycle stages of the product. In addition to the experts identified above, typical stakeholders may include: chemical and product manufacturers and suppliers; product users and retailers; waste and recycling companies, government agencies; academics; and non-governmental organizations. Those developing new technologies in the area of study (that may be analyzed as potentially safer alternatives) should be included in the stakeholder group.

Early in the study, researchers and product developers should identify, contact, and inform potential stakeholders of the proposed project goal and scope, methodology, and potential benefits, to gain the expertise needed to conduct the study and representation of the broadest-possible points of view. Stakeholders can be identified via industry conferences, trade groups, academic institutions, or industry contacts. When proposing a collaborative effort (either by sending out an invitation to a group, or making individual contacts), it is important to point out the mutual benefits and potential savings that will result from sharing the cost of the study, and from making product improvements that result in the use of less energy and materials and provide the competitive advantages associated with generating fewer environmental impacts. When contacting potential stakeholders, it is also important to consider and explain how confidential business information will be protected, and to make clear that confidential data will not be made public.

Kathy Hart, EPA LCA Project Leader (Hart, 2009)

2.3 Goal and Scope Definition

The goal definition and scoping phase of a sustainability assessment should include information on the focus of the study, including the research questions to be answered, system boundaries, and functional unit (quantified reference flow) of the product system. The term functional unit is most often associated with LCA because it can provide a basis for comparison across the life cycle stages of dissimilar products having the same use. For example, a study examining antimicrobial foot treatment for diabetics might be based on the amount of product needed for one treatment, such as a pair of socks containing nanoscale silver or the prescribed quantity of an antimicrobial ointment dose. Other assessment tools may require a different reference such as the mass of a product unit or its monetary value. These simpler reference flows are also applicable for LCA when considering a single product or similar products (i.e. silver socks made by different manufacturers). The key point to remember going forward is that once a reference flow is established, it can easily be converted into equivalent forms to meet the needs of the various assessment tools.

The overall goal of a sustainability assessment is to select and/or develop a product, process, or service that is sustainable. To make this a more practical goal, the concept of sustainability should be broken down into criteria for each pillar (environmental, economic, and social), paying special attention to any criteria and indicators that are pertinent to the product in question. If the manufacture of a nanoproduct is particularly energy-intensive, then impacts associated with energy use might be particularly critical to the overall sustainability of the product. Energy-related criteria and indicators could include, but are not limited to, air and water emissions from upstream power plants, material resources used for energy production, electricity costs, power plant working conditions, and the impact of power plants on local communities. However, impacts not related to energy use (ozone depletion, acidification, material costs, etc.) must not be excluded a priori because they may actually be the more severe impacts for the product based on other phases of the life cycle. Ultimately, the product developers should work with the stakeholders to select relevant criteria that accurately encompass sustainability (Azapagic et al., 2006). Table 2-3 provides a list of example sustainability criteria for each pillar. Some criteria such as noise may not fit uniquely with one pillar. In such cases, the criterion in question should be assigned to a pillar during goal and scoping to avoid (if possible) double counting the impact. The list provided is by no means authoritative with the understanding that ultimate placement of criteria within the pillars may depend on the indicators and metrics needed to measure them and what tools are available to assess these metrics and indicators.

Table 2-3. Examples of Sustainability Criteria (adapted from Azapagic et al., 2006)

Environmental	Economic	Social
Energy use Resource use (renewable and non-renewable) Emissions (air, water, land) Global warming Ozone depletion Acidifications Ecotoxicity impacts Human toxicity impacts Water eutrophication	Macro-economic - Environmental liabilities - Taxes Micro-economic - Capital costs - Operating costs - Consumer costs - Profitability	Provisions of employment Health and safety of: - Employees - Customers - Public Nuisance - Noise - Odor Public Acceptability

A list of complete sustainability criteria is too numerous to include here and would pose a daunting challenge if stakeholders tried to account for the entire set. Therefore, stakeholders must select relevant criteria from each pillar to adequately capture sustainability. The selection process is not trivial based on the varying preferences of stakeholders with regard to sustainability. For insight, readers are encouraged to read the work of Hirschberg and coworkers (Hirschberg et al., 2007) who have studied the selection process and offer guidance on what to consider when building a criteria set to insure it is scientific, functional and pragmatic. For example, a manageable number of criteria should be selected equally from the three pillars for balance while capturing essential technological characteristics of products and process to allow differentiation amongst them. With a defined selection process, stakeholder preference can be incorporated in a way that minimizes the subjective nature of sustainability. To illustrate the concept of balance, a sustainability assessment for a given product might examine energy and resource use, global warming, toxicity impacts, profitability, environmental liabilities, health and safety, and public acceptance. It is also possible that certain criteria can only be evaluated qualitatively, such as social issues. These approaches are permissible provided such choices are clearly defined and justified in the scope of the assessment. These decisions may be based on the resources available for the study, data availability, or the product development stage (EPA, 2006).

Preferences in Sustainability Criteria: The Case of Antimicrobial Textiles

Consider the growing use of nanoscale silver in antimicrobial textiles. A group of stakeholders for a product in this application might include the product manufacturer, textile groups, government agencies overseeing environmental and public health, consumer advocate groups, and residents of the communities surrounding the manufacturing site. For the manufacturers, profitability is obviously the most important criterion. However, profitability is directly related to both operating cost and public acceptance. The operating costs will depend on energy and resource use, potential emissions and environmental liabilities, taxes, and employee safety. These criteria are all easily quantifiable based on an understanding of the manufacturing process and workplace risk. The other concern for profitability, public acceptance, is not readily quantifiable and may be evaluated qualitatively based on an understanding of the market for the intended product. This might involve simple yes/no questions to determine if a large enough consumer base exists or more detailed analyses of factors that could create a potential negative public perception. Government agencies will care more about the impact on the public and environment. Criteria for these needs will include climate change (global warming, ozone depletion, acidification) and toxicity impacts to humans and ecosystems. Again, these are all quantifiable criteria. However, as opposed to the manufacturer, who might only focus on its own operation, government agencies will want to know about the impacts associated with the entire life cycle of the product. In a similar manner, consumers groups and local residents will be concerned with the potential health effects associated with product manufacture and use. For these criteria, a quantitative measure of health effects will be needed to satisfy the needs of the stakeholders. This will not be easy for most nanoproducts given the lack of available toxicity data for nanocomponents. In addition, consumers will also consider product cost when making a decision. What benefit will the product be to the consumer if it is unaffordable? Again, until the manufacturer can fully quantify the costs associated with the product, how can they provide an associated consumer cost? This example should illustrate the complex nature of decision making for sustainability. Each stakeholder will not only have his/her own important criteria that must be satisfied, but will have differing scopes and boundaries when beginning the assessment process that must be reconciled. Ultimately, the rules for selection (Hirschberg 2007) and data availability will be detrimental when prioritizing the criteria for assessment.

It is critical to recognize that a product is sustainable only if it is sustainable with respect to each of the three pillars. Accordingly, if one or two pillars are excluded due to practical constraints (i.e. resources, data availability, etc.), the resulting study must be identified as a partial sustainability assessment, and the interpretation of results must discuss the excluded pillar(s) and any known potential impacts associated with the pillar(s). While practical considerations cannot be ignored, a lack of data or resources cannot be confused with the absence of impacts. The level at which the criteria will be measured must also be considered. For example, the product developers and stakeholders may be interested in impacts at the product (micro) level, an industrial sector (meso) level, or an economy-wide (macro) level (Zamagni et al., 2009). These distinctions are chosen based on the perceived ability to impart change on connected systems within each level. Thus, little change to space, market, and time is anticipated for perturbations at the product level while changes at the economy-wide level will affect all systems. Generally, it is advisable for emerging technologies to start analyses at the product level and expand to the economy-wide level as the product is brought to market and additional information becomes available (Zamagni et al., 2009). In the absence of accurate data, possible macro-level considerations can be included during the initial assessment if desired using qualitative evaluation of criteria. Such evaluations can lead to greater insight during interpretation of results.

When defining system boundaries, it is important to include every step that could affect the overall interpretation or ability of the analysis to address the issues for which it is being performed. The system boundaries not only refer to processes, but include the geographical and temporal boundaries in which the nanoproduct will exist. These last two factors will help identify suitable data quality criteria and provide a context to interpret results. In determining the system boundaries, it is helpful to develop a system flow diagram, as shown in Figure 2-3, to depict the activities and direction of flow of products and materials. This will also be useful later on in guiding the efforts to gather data for assessment. Each system step should be represented individually in the diagram, including the production steps for ancillary inputs or outputs such as chemicals and packaging.

For a sustainability assessment, the functional unit has been defined as a basis to normalize data using equivalent use (or service provided to consumers) to provide a reference for relating impacts across life cycle stages as part of an improvement assessment. The functional unit is also useful for comparing alternate product systems or technologies. However, as discussed previously, any comparisons discussed in this framework are *internal* to a company's own processes or alternatives. Given that nanotechnology is an emerging field, the eventual function of the product and service level to the customer may not be known. As a result, it may not be possible to develop a functional unit, especially if the product is still in development (Klöpffer et al., 2007). In such cases, the product developers should determine whether reasonable assumptions may be made about the eventual product use and anticipated service provided to the customer. If it is not possible to develop a service-based functional unit and the assessment does not compare product systems, the product developers should determine another basis for organizing the data and results into context.

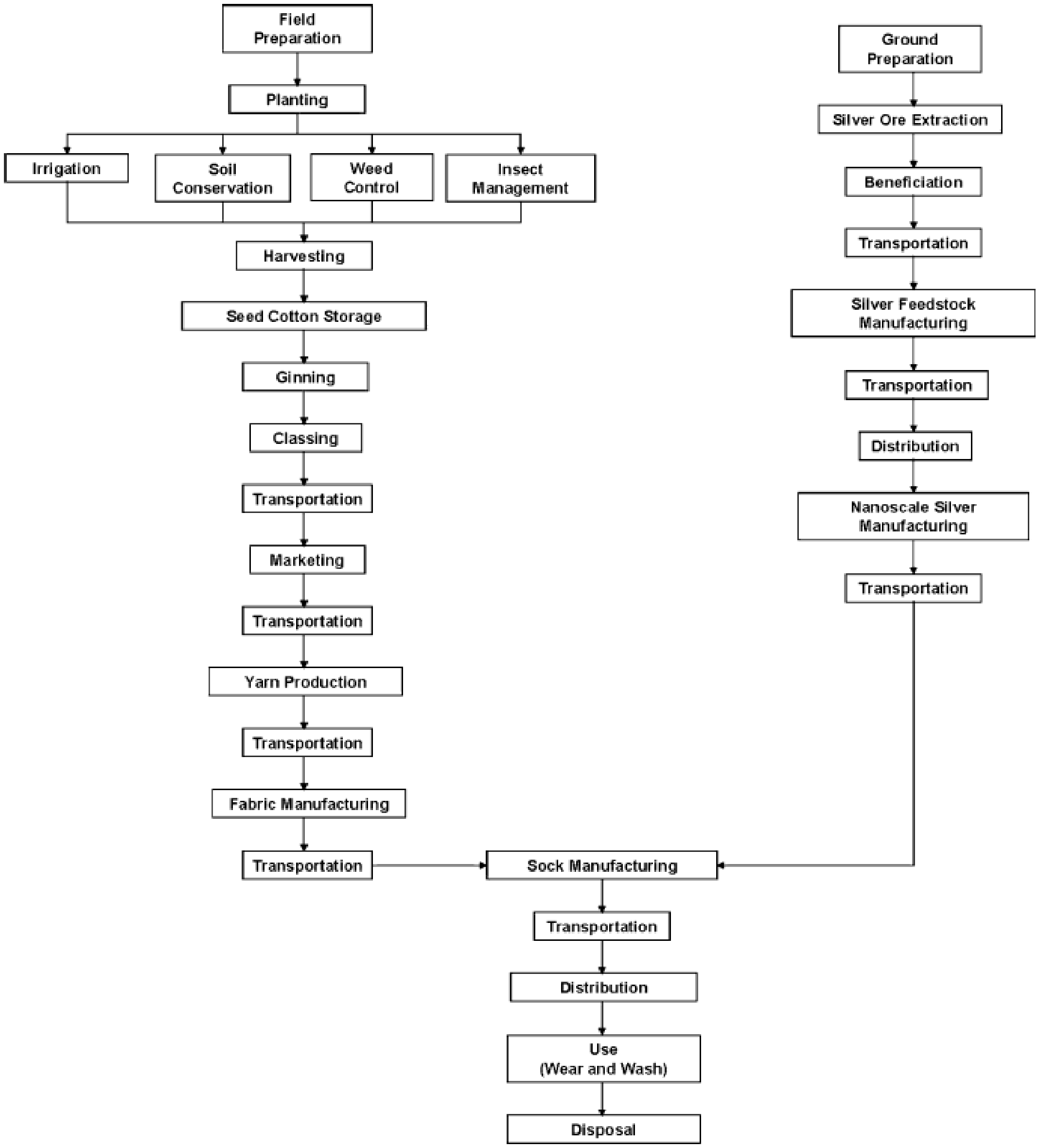


Figure 2-3. Sample Goal and Scope definition: The life cycle of a pair of cotton socks containing antimicrobial silver**.**

3. Assessing Environmental, Economic, and Social Impacts

The following section presents a summary of methods for assessing the environmental, economic, and social impacts of a nanoproduct. These assessment methods largely reflect methods that are commonly used by industry and LCA practitioners. They were selected because they can be applied to holistically assess nanoproducts and are based on citable standards and guidance for application. Qualitative as well as quantitative assessments may also be used, if needed. For example, the EPA's Comprehensive Environmental Assessment (CEA) method is being developed as a semi-quantitative tool based on expert judgment to identify information gaps and research needs (EPA, 2010).

In most cases, it is not necessary (or practical) to apply all of the available methods (Zamagni et al., 2009). The determination of which methods are most appropriate will depend on the applicability of the technique, whether the method will respond to the research questions and criteria, and the available resources for conducting the sustainability assessment. In addition, given the uncertainty associated with nanoproducts, any tool selected should address uncertainty and how it may affect the assessment given the nature of nanotechnology. The work by Schepelmann et al. (CALCAS, 2008) may be a helpful resource to aid in selecting methods as it provides an assessment of the strengths and weaknesses of various model and tools which support sustainability analysis.

Given the nature of nanoproducts and nanomaterials and the fact that they are a new and emerging technology, there are many issues and data gaps that may arise when assessing environmental, economic, and social impacts. Although some issues are applicable for overall aspects of a sustainability assessment, certain issues may be relevant for specific life cycle stages and sustainability pillars. As described in Section 1.2, the key life cycle stages include:

1. Raw materials extraction,
2. Materials processing,
3. Product manufacture,
4. Product use, and
5. End-of-life disposition.

Some of the common issues and data gaps, and possible methods for addressing them, are explained in detail below.

3.1 Environmental Assessment Methods

Many of the environmental protection strategies in which we have become accustomed can be viewed as short-term or quasi-environmental fixes. We now understand that environmental problems are rarely contained within a single resource area or within a single product's life cycle. Instead, they require longer term strategies that extend across geographic regions and timeframes. It has become obvious that a more integrated, systems-based approach is required to meet the needs of today while maintaining the prospects for the same quality of life for tomorrow's generation. As a result, many methods and tools are being offered to assess the environmental impacts of a product throughout its life cycle (see Table 3-1). For more detailed information about applying the methods, please consult the references listed on the right-hand side of the table. As discussed in Section 2, the method or tool selected should be based on the goal and scope of the sustainability assessment.

Table 3-1. Key Environmental Assessment Methods

Method	Description/ Benefits	Scope/ Stage	Impacts Measured	Reference
Life-Cycle Assessment (LCA)	Evaluates potential environmental impacts associated with a product, process, or activity. LCAs consider multi-media, multi-attribute impacts by quantifying energy and materials used and wastes released to the environment from cradle to grave.	Product to regional/national level All life cycle stages	• Natural Resource Use (e.g., water, nonrenewables, etc.) • Global warming • Ozone depletion • Smog Formation • Acidification • Eutrophication • Human Health • Ecotoxicity • Land Use • Etc.	(Baumann and Tillman, 2004; EPA, 2006; ISO, 2006; SETAC, 1992)
Carbon Footprint	Both GHG Life Cycle Analysis and Carbon Footprinting aim to account for the release of greenhouse gases that contribute to global climate change. The principal gases are carbon dioxide, methane, nitrous oxide, and fluorinated gases, such as chlorinated fluorocarbons (CFCs).	All life cycle stages	• Carbon • Greenhouse gases • Global warming • Climate Change	(BSI, 2008; WRI, 2010)
Environmentally-Extended Economic Input-Output (EEIO) Life Cycle Analysis	Assesses the economy-wide environmental impacts of a product throughout its life cycle stages. Note that this method may also be used to conduct an economic assessment (see Section 4).	Product/ micro level to economy-wide level All life cycle stages	• Economic activity generated • Natural Resource Impacts (e.g., energy use, fuel use, ores, etc.) • Abiotic Ecosystem impacts (e.g., green house gas emissions, ozone depletion, smog, etc.) • Toxic releases by sector and chemical	(CMU, 2008a; Klöpffer et al., 2007; Wiedema, 2010)
Life Cycle Risk Assessment e.g., Nano Risk Assessment	Characterizes the nature and magnitude of health risks to humans (e.g., residents, workers, recreational visitors) and ecological receptors (e.g., birds,	Product/local and meso level All life cycle stages	• Health hazards (e.g., neurotoxicity, skin absorption, genotoxicity, etc.) • Environmental (e.g., aquatic,	(EPA, 2010; Walsh and Medley, 2007)

Method	Description/ Benefits	Scope/ Stage	Impacts Measured	Reference
	fish, wildlife) from chemical contaminants and other stressors that may be present in the environment. Risk assessments are composed of two sub assessments: an exposure assessment and a hazard assessment.		terrestrial, avian, etc.) • Safety (e.g., explosivity, reactivity, corrosivity, etc.)	
Ecosystems Services LCA (ECO-LCA)	Expands upon traditional LCA and quantifies ecosystem services over the life cycle of a product.	Product/ local, meso All life cycle stages	Ecological services (e.g., land-use).	(Zhang et al., 2010b; Zhang et al., 2010c)
Sustainable Materials Management	Quantifies the relative magnitude of material flows in the global economy. Methods of material flow accounting, such as Material Flow Analysis (MFA) and Total Material Requirements (TMR), are used.	All life cycle stages, with a focus on material extraction and end-of-life management (recycling).	Flows (Kg)	(Fiksel, 2006)

Life Cycle Assessment

The most comprehensive method to assess the environmental impacts of a product, process, or activity throughout its life cycle stages is environmental life cycle assessment (LCA). A LCA accounts for the physical flows, i.e. the inputs and outputs, across the full life cycle of a product system, from materials acquisition to manufacturing, use, and final disposition (see Figure 3-1). As outlined in the International Standards Organization (ISO) 14040 series, an environmental LCA study has four major components: goal definition and scoping, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results (ISO, 2006).

Inventory data are subjected to life cycle impact assessment models, which seek to establish a linkage between a system and the potential, related impacts. The impact models are often derived and simplified versions of more sophisticated models within each of the various impact categories.

Although work is ongoing to reach consensus on which impact categories to include, the International Reference Life Cycle Data System (ILCD) Handbook (JRC, 2010) provides the following list of commonly used categories:

- Ozone Depletion
- Global Warming
- Human Health
- Ecotoxicity
- Eutrophication
- Acidification
- Smog Formation
- Fossil Fuel Use
- Land Use
- Water Use
- Land Use
- Resource Depletion

These simplified models are suitable for relative comparisons of the potential to cause human or environmental damage, but are not indicators of absolute risk or actual damage to human health or the environment. For that, a risk assessment is needed. In the case of a traditional risk assessment, it is possible to conduct very detailed modeling of the predicted impacts of the chemical on the population exposed and even to predict the probability of the population being impacted by the emission. In the case of LCA, hundreds of chemical emissions (and resource stressors) which are occurring at various locations are evaluated for their potential impacts in multiple impact categories. The sheer number of stressors being evaluated, the variety of locations, and the diversity of impact categories makes it impossible to conduct the assessment at the same level of rigor as a traditional risk assessment. Instead, models are based on the accepted models within each of the impact categories using assumptions and default values as necessary.

LCA is a well-established methodology for evaluating the environmental impact of products, materials, and processes. By including the impacts throughout the product life cycle, LCA provides a comprehensive view of a product's environmental aspects. It is also valuable in evaluating the many interdependent processes that are involved in a product system. A change to one part of this system may have unintended consequences elsewhere. LCA identifies the potential transfer of environmental impacts from one medium to another (e.g., eliminating air emissions by creating a wastewater effluent instead) and/or from one life cycle stage to another (e.g., from use and reuse of the product to the raw material acquisition stage). If an LCA were not performed, the transfer might not be recognized and properly included in the analysis because it is outside of the typical scope or focus of product design and selection processes.

A workshop comprised of international experts from the fields of both LCA and nanotechnology concluded that the LCA ISO-framework (ISO 14040:2006) (ISO, 2006) is fully suitable to all stages of the life cycle of nano-components and nanoproducts (Klöpffer et al., 2007). However, the workshop attendees acknowledged a number of operational issues that need to be addressed, such as functional unit selection, inventory data collection and/or estimation, allocation, and toxicity assessment. Similarly, Bauer and coworkers have also pointed out that a suitable definition of the functional unit and system boundaries for nanoproducts will be necessary to facilitate comparative assessments (Bauer et al., 2008). A complete list of LCA services, software tools and databases can be found at http://lca.jrc.ec.europa.eu/lcainfohub/directory.vm.

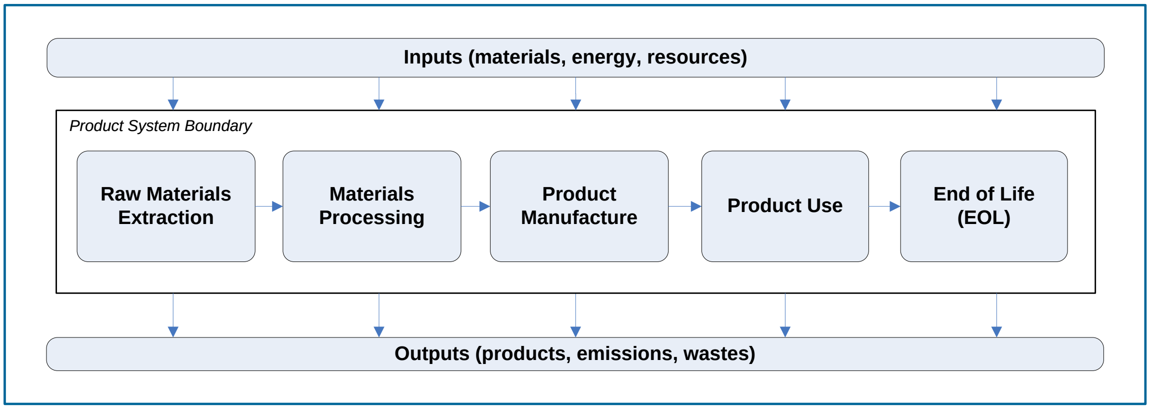


Figure 3-1. General Framework for a Product Life-Cycle Assessment (LCA)

Carbon Footprint

Carbon Footprint (CF) has become widely used in relation to the threat of global climate change. CF is the measurement of the overall amount of carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions (e.g., methane, nitrous oxide, etc.) associated with a product, a person, an organization or an event. For products, the boundaries include the supply-chain and sometimes use and end-of-life recovery and disposal. For simplicity of reporting, it is often expressed in terms of the amount of carbon dioxide (tons or kilograms), or CO_2- equivalents.

Two well-known accounting tools for quantifying and managing GHG emissions are the Greenhouse Gas Protocol (GHG Protocol) (WRI, 2010) and BSI's "Specification for the assessment of the life cycle greenhouse gas emissions of goods and services" (BSI, 2008). In 2006, the International Organization for Standardization (ISO) adopted the Corporate Standard as the basis for its ISO 14064-I: Specification with Guidance at the Organization Level for Quantification and Reporting of Greenhouse Gas Emissions and Removals.

Several CF calculator tools are available on-line (e.g., http://www.carbonfootprint.com/)

Despite its ubiquitous appearance there seems to be no clear definition of the term carbon footprint. There is still much confusion as to what it actually means, what it measures, and what unit is to be used. While commonly understood to refer to certain gaseous emissions that are relevant to climate change and associated with human production or consumption activities, there is no agreement on how to measure or quantify a carbon footprint. Questions remain regarding whether the carbon components should be weighted and normalized based on their potential effect in the atmosphere. Other questions that need to be answered include the following:

- Should the carbon footprint include just carbon dioxide (CO_2) emissions or other GHG emissions as well, e.g., methane?
- Should it be restricted to carbon-based gases or can it include substances that do not have a carbon atom in their molecule, e.g., N_2O which is another powerful GHG?
- Should the carbon footprint be restricted to substances with a global warming potential at all, since there are gaseous emissions that are carbon-based and relevant to the environment and health, such as carbon monoxide (CO) which can convert into CO_2 through chemical processes in the atmosphere?
- Should the measure include all sources of emissions, including those that do not stem from fossil fuels, e.g., CO_2 emissions from soils?

The Carbon Footprint approach is included in this guidance because of its widespread use in the management of GHG gas emissions. While developing strategies for mitigating climate change is indeed important, we must be mindful to not exclusively focus on one factor and discount other equally important environmental aspects, such those listed under LCA. Decision makers are encouraged to build upon the results of the carbon footprint approach toward a holistic examination of environmental impacts in order to identify potential unintended trade-offs between different environmental categories.

Environmentally-Extended Economic Input/Output LCA

In conducting an LCA, the creation of a life cycle inventory often follows a "process-based" approach in which the resource inputs and the releases to the environment are reported for all the processes within the life cycle system. Because finding such process data can be challenging (see Section 3.1.1) methodology developers created an approach that uses national economic input/output (I/O) models to help estimate the materials and energy resources required for, and the environmental emissions resulting from, activities in the entire economy (CMU, 2008b).

The process-based and the environmentally extended economic I/O based approaches have advantages and disadvantages, and it is possible to create hybrid models that incorporate aspects of both. As the name suggests, process-based LCAs model processes, such as the steps for manufacturing carbon nanotubes. Although process-based LCAs can provide detailed information about a nanoproduct system, they may necessitate artificial boundaries between the products of interest and the rest of the economy.

The disadvantage of input-output-databases is that processes are aggregated at the level of product groups rather than individual products. This disadvantage can be overcome by conducting a hybrid analysis, which essentially links the inputs and outputs of a process-based LCA into an input/output-database (Wiedema, 2010). For example, one could use process-based LCA techniques to model the impacts of the production processes at a given facility, but use EIO-LCA to model the supply chain impacts of the electricity purchased by the facility (CMU, 2008a). Three main ways of combining process-based LCA and I/O- based LCA are: tiered hybrid analysis, IO-based hybrid analysis and integrated hybrid analysis (CALCAS, 2008).

Several I/O databases are available, including a free database from Open IO that covers the USA in 430 industrial sectors, including emissions relevant to global warming. Open IO is jointly administered by the Sustainability Consortium and the University of Arkansas Sam M. Walton School of Business.

A well-known LCA-based approach that uses the economic input/output model was developed by the Carnegie Mellon Green Design Institute and is freely available on-line (www.eiolca.net).

Life Cycle Risk Assessment

Life Cycle Risk Assessment (LCRA) integrates the traditional risk assessment paradigm with a life cycle perspective. It attempts to examine potential human health and ecological impacts (both positive and negative) in a broad, systematic manner by stepping the decision maker through the life cycle of a material in identifying the pertinent exposure pathways and forms of a substance. This, in turn, can identify the need for more detailed evaluation at particular life cycle stages to characterize impacts (Shatkin, 2008). The life cycle nature of the approach indicates that it encompasses a cradle-to-grave framework while accounting for multi-media environmental fate and transport, exposure, and effects on both ecological receptors and human health. Other dimensions such as economic, political, security or societal factors are typically excluded.

In 2005, ED and DuPont entered into a partnership to develop a framework for the responsible development, production, use, and end-of-life disposal or recycling of engineered nanoscale materials, that is, across a product's life cycle. The resulting "Nano Risk Framework" (Figure 3-2) develops profiles of nanomaterials' properties, inherent hazards, and associated exposures throughout the material's life cycle (ED-DuPont, 2007).

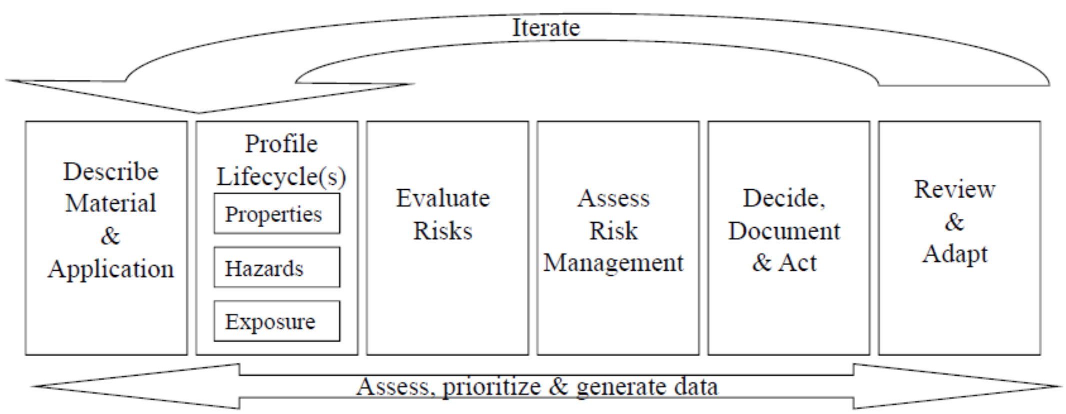


Figure 3-2. Nano Risk Framework (ED-DuPont 2007)

The ED-DuPont Nano-Risk Framework is not intended to be a full-scale life cycle analysis, in which one pays prominent attention to resource inputs. Instead, it is intended to help users assess, manage, and report the potential environmental, health, and safety risks associated with a particular material and application. It follows a traditional risk-assessment paradigm similar to the one used by the U.S. Environmental Protection Agency (EPA) for evaluating new chemicals (EPA's New Chemicals Program: http://www.epa.gov/oppt/newchems/index.htm). However, it does not present a "one size fits all" approach. Different organizations, depending their size and structure, will have differing ways of implementing the framework for maximum effectiveness.

Ecosystems Services LCA

Natural ecosystems provide us with a multitude of resources and processes from clean drinking water, to processes such as the decomposition of wastes, and other benefits such as pleasant aesthetics. Ecosystems and the valuable services they provide (e.g., soil, pollination, flood prevention and cropland) are often overlooked, but recently attempts are being made to include these aspects in environmental assessment tools. For example, the Ohio State University Center for Resilience developed a free, online tool called Eco-LCA (http://resilience.eng.ohio-state.edu/ecolca-cv/). Eco-LCA was developed to complement other LCA tools by showing how different products and materials have different impacts on nature.

Those services are divided into four areas: supporting services (soil, pollination, sunlight, hydropotential, geothermal, wind), regulating services (flood protection, disease regulation, carbon sequestration), provisioning services (fuels, ores, water, timber, cropland), and cultural services (spiritual and recreational benefits). Eco-LCA includes various aggregation schemes that are based on thermodynamic concepts (Zhang et al., 2010a).

Sustainable Materials Management

Sustainable Materials Management (SMM) is an approach to promoting sustainable materials use, integrating actions targeted at reducing negative environmental impacts and preserving natural capital throughout the life cycle of materials by taking into account economic efficiency and social equity (OECD, 2005). At this point, SMM is more a concept than a single methodology. Many suggest that the focus of SMM should be on *environmental impacts* of the materials flows, rather than simply on volumes or weights of materials alone (OECD, 2005). Material Flow Analysis, or Accounting, (MFA) is a complementary tool that tracks the amounts of a material as it goes into multiple products, as they enter and exit the economy through various types of transactions. Although there is no global consensus on MFA methodology, MFA can provide important background information and data for life cycle approaches and SMM.

SSM is especially applicable to nanotechnology because non-renewable metals and rare earths are often used to manufacture various nanocomponents. Although the application of nanotechnology could lead to significant reductions in the consumption of critical minerals compared to traditional technologies, the need to extract more metals, such as silver, gold, titanium and lithium, and other exotic rare earth metals, such as europium, cerium, neodymium, gadolinium, and terbium, will continue as the demand for nanoproducts grows. These natural resources are in limited quantities and there may not be enough supply of them in the near future.

The Need for Multiple Methods to Understand the Complexity of Nanotechnologies

The primary impacts associated with the development of Carbon nanotube (CNT) nanoproducts can be attributed to either the manufacture of CNTs and CNT nanoproducts or the release of CNTs into the environment throughout the life cycle. Manufacturing impacts are related to both the selection of raw materials, particularly the metal catalysts and carbon precursors, and the unit operations involved during the incorporation of CNTs into nanoproducts. For example, the popular chemical vapor deposition (CVD) process used to generate CNTs involves thermal pretreatment of the gaseous hydrocarbon to increase the feedstock purity (Journet et al., 1997; Sinha et al., 2006) and accelerate formation and growth of CNTs (Plata et al., 2009). Although beneficial to the process, this step can be responsible for the airborne release of greenhouse gases (GHGs), volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs) (Plata et al., 2009). Likewise, the formation and release of carbon soot as a byproduct upon heating the precursor during arc discharge processes is possible (Plata et al., 2009). Photo-reactive VOCs can cause additional impacts like smog formation and ozone depletion (Plata et al., 2009; Singh et al., 2008; USEPA, 1976). Certain PAHs can accumulate and persist in the environment, posing a threat to human health as a cancer risk (Plata et al., 2009). Carbon soot formation not only disrupts the radiative heat balance (Kauffman and Fraser, 1997) of the atmosphere but is a serious concern for public health (USEPA, 1977). Furthermore, Plata et al. (2009) observed a significant increase in the quantity of greenhouse gases emitted during CVD when the reactor temperature is only slightly increased. Similarly, the thermal pretreatment of ethane as a carbon precursor results in the formation of larger quantities of byproducts including GHGs such as methane, several photo-reactive VOCs, and toxic compounds such as benzene and 1,3 butadiene (> 36000 ppmv) (Plata et al., 2009). The acid purification step used to remove trace impurities of the metal catalyst from raw CNTs may result in the discharge of unconventional liquid waste to wastewater treatment plants (Singh et al., 2008). Some of the waste compounds such as molybdenum or cobalt chloride ($MoCl_2$, $CoCl_2$) are not completely treated by wastewater treatment plants and can pose serious risks to aquatic species if released into fresh-water bodies. Molybdenum compounds are known to cause anoxic conditions (Arnold et al., 2004; Gooday et al., 2009) while cobalt compounds support the growth of blue-green algae (harmful algal blooms) which can lead to eutrophication (Hansen et al., 1954).

The potential health risk of CNT nanoproducts is a function of their release probability and the inherent toxicity of the CNTs. The potential release of aerosolized CNTs at CNT and nanoproduct manufacturing sites greatly depends on the type of process and work place practices adapted to handle free CNTs (Kohler et al., 2008). The aerosolization of CNTs is a function of their size and rates of diffusion, agglomeration, deposition and re-suspension into the surrounding environment (Kohler et al., 2008). For example, the HIPCO method of CNT synthesis releases larger amounts of CNT aerosols than other synthesis methods. Similarly, gas phase product recovery of CNTs and unit operations such as mechanical milling and dry CNT powder mixing increase the probability of forming CNT aerosols (Kohler et al., 2008).

The probability of CNT release from nanoproducts during use and disposal will depend on the durability of the nanoproduct. For example, a window frame or automotive body panel made with a CNT-polymer composite material is expected to have a minimal chance of CNT release during use. On the other hand, products such as CNT textiles and CNT coatings may exhibit a larger potential for release, particularly when subjected to thermal degradation, photochemical oxidation and other harsh weathering patterns (Kohler et al., 2008). Furthermore, there are concerns that CNT-bearing waste will cause problems during conventional disposal processes. Incineration of CNT-laden waste may generate CNT aerosols if the operating temperature of the incinerator facility is less than the decomposition temperature of CNTs (Kohler et al., 2008). The presence of

CNTs in landfill leachate may affect the remediation efficiencies for other hazardous pollutants (e.g. PAH and Pyrene) by altering their fate and bioavailability in the environment (Petersen et al., 2009; Yang et al., 2006).

The release of CNTs is important because it is the first step in exposure to humans and biological receptors. Once CNTs are released into the environment, impact of exposure will depend on the toxicity of CNTs as determined by their physico-chemical properties. The extent of toxic damage will be influenced by both the bioavailability (uptake) and bioaccumulation of CNTs by biological receptors (Linkov et al., 2009). Bioavailability and bioaccumulation potentials are dependent on many factors including the quantity of CNTs released, the physical properties of CNTs (i.e. size and shape), surface functionality, dispersivity, the presence of impurities (Kushnir and Sanden, 2008; Linkov et al., 2009), and the environmental media for exposure (air, water or soil). Ultimately, the toxicity potential of CNTs is not only varied based on the physical properties of CNTs, but also based on the physico-chemical properties of the surrounding environment and biological nature of cells that are exposed to the CNTs.

If LCA is used exclusively to assess the environmental impacts of a CNT nanoproduct, it will adequately capture the issues related to resource management and climate change issues such as acidification and eutrophication. Shortcomings will arise from the models underlying the characterization of impacts to human and ecosystem health because they have not been proven with regard to their ability to account for the many factors discussed above that dictate the toxic risk of CNTs. These models have been developed using average environmental factors and lack site-specificity to account for the influence of the factors on the behavior of CNTs. Even the traditional risk assessment approach, which is based on dose-response studies, may not account for the cumulative risk of a CNT nanoproduct because it is typically a mass-based assessment and neglects the influence of chemical properties. However, it does provide the opportunity to better address the influence of local environmental factors. Thus, the incorporation of a modified risk-based health impact model accounting for chemical factors under site-specific conditions into the LCA framework would achieve a maximum understanding of the impacts of a CNT nanoproduct to guide decisions at the local level.

3.1.1 Data Sources for Environmental Assessments

The accuracy of assessment results obtained using the various methods listed in Table 3-1 will depend greatly on both the quantity and quality of data used to perform them. Although the required data sets vary from method to method, they generally fall into two categories, life cycle processes or chemical risk. Understanding where to obtain this information can greatly expedite the assessment process.

Detailed process flow data forms the basis for numerous techniques, including LCA, CF, EIO-LCA, Eco-LCA, and SMM. The best sources of data for these assessments are actual manufacturers and waste handlers. However, collection of data from primary sources can be time consuming. In the absence of this data, preliminary Life Cycle Inventories (LCIs) can be built using any of the following sources: existing LCI databases (e.g., U.S. LCI Database, Ecoinvent, Gabi, etc.), journal articles, patents, government reports, and manufacturers' websites. This data will be directly applicable for LCA, CF, and SMM. EIO-LCA simplifies data collection somewhat because LCI data can be taken directly from pre-existing databases built on the U.S. input-output tables. However, the most current version of this data represents 2002 and may not accurately capture nanomanufacturing processes. Eco-LCA requires thermodynamic conversion factors to express process data in a comparable form. The values should be available in engineering and physical chemistry reference books or scientific journals.

Chemical risk data is primarily used for LCRA, but is also necessary to some extent when calculating characterization factors for the human health and ecotoxicity impact categories tabulated in most LCA methodologies. LCRA data types include exposure factors, chemical toxicity, and transport model parameters. These data must be established through rigorous experimentation and require knowledge of site-specific environmental conditions. Pollutant release data can be obtained from government reports and databases (e.g., EPA's Toxic Release Inventory (TRI)). Toxicity, exposure, and transport data can typically be found in scientific journals. For existing chemicals other than nanocomponents, LCA characterization factors might already be available with suitable models such as USEtox (Rosenbaum et al., 2008). For nanocomponents, these factors must also be derived experimentally and may be found in scientific literature.

3.1.2 Issues Related to Environmental Assessment Methods

Limited life cycle inventory data. A critical issue with the assessment of any nanoproduct is the limited availability of inventory data throughout the life cycle of the product. Products still under development may have limited LCI data for the manufacturing stage. LCI data for this phase may also become outdated as the product and manufacturing technologies evolve (Klöpffer et al., 2007). Because many nanoproducts are only beginning to enter the market, LCI data may especially be limited for the use and end-of-life (EOL) stages. Furthermore, LCI databases (e.g., those available through Simapro and GaBi) are currently limited in scope and may not include appropriate secondary data for nanotechnologies, such as material inputs, natural resource inputs, and emission outputs (Khanna et al., 2007).

Based on the available data, a determination should be made as to whether it is possible to include all stages of a product life cycle, discussed in further detail below. Developing a flow diagram of the product system, such as that in Figure 2-3, can aid the data collection process. Such a flow diagram can help identify the data sources for each category and assist in making reasonable assumptions when reconciling missing LCI data. These assumptions should be consistent with those developed as part of the goal and scoping phase. In addition, the input and output data that are most likely to change as the nanotechnology or manufacturing process evolves should be identified. For example, there may be a decrease in energy required to manufacture on a per unit basis as production is scaled up. For existing technologies, data may already exist. However, for emerging technologies, it may be necessary to gather data from laboratory experiments, models, databases, or other studies.

Dynamic research environment. Since many nanoproducts are either in prototype development or pre-production stage, they are constantly subjected to research improvements. Accordingly, the LCI data with respect to a particular nanoproduct may lose reliability quickly because the nanoproducts may undergo a series of improvement iterations within a short period of time. For instance, Bauer et al. (Bauer et al., 2008), conducted an LCA (hypothetical study) on 15 inch carbon nanotube field emission display CNT-FED devices. In 2007 when the study was conducted, it was initially believed that the deposition of CNTs using chemical vapor deposition (CVD) presented the most attractive solution for fabricating the cathode substrate. However, further investigation indicated that the high temperatures of CVD did not allow use of glass substrates in place of silica, meaning the CNT patterning could not be done using CVD (Fink and Lee, 2005). Consequently, CNT cathode substrates are built using CNT pastes (Chu et al., 2006) or inks (Kordas et al., 2006). Since the process of manufacturing CNT-FED changed significantly, the LCA study conducted by Bauer et al. (Bauer et al., 2008) using CVD grown CNT cathode substrates lost its significance within three years.

Access to confidential business information (CBI) and proprietary data. LCI data may also be limited by concerns over confidential business information (CBI) and other proprietary data from firms upstream and downstream of the product developer. If this data is pivotal to an analysis, it may be more effective for a third-party or consultant to work with the companies in conducting the assessment. This way, the third-party could sign non-disclosure agreements to aggregate and protect any confidential data from the manufacturers. In addition, the extent to which upstream and downstream companies could provide aggregated data to the product developers that does not disclose confidential information should also be explored. Although this would generate additional uncertainty, it would provide a starting point for generating LCI data from all the life cycle stages. As noted above, LCI databases may also provide inventory data on upstream processes.

Anticipating the Challenges of Collecting LCI Data

One of the hardest parts of conducting an LCA is obtaining the necessary data because the most accurate data often requires direct knowledge of industrial products and processes. Unfortunately, this data is typically considered a "trade secret" by industrial sources and is not readily available. So how does one reach out to companies and persuade them to look beyond their initial fears and contribute their knowledge to a life cycle inventory (LCI)? I was forced to ask myself this same question when I decided to perform an LCA of a popular nanoproduct. The following is a summary of what I learned by going through the process.

The current climate of the nanotechnology industry is extremely cut-throat as nanomanufacturers seek to establish themselves as major players in the nanocomponent market. Their livelihood is dependent upon protecting their manufacturing processes because these processes are what define the company. In order to get companies to open up about their process, you as an LCA practitioner must first gain their trust. This can be a difficult process, but one that ultimately begins with the mindset of the practitioner.

Instead of viewing companies as mere sources for data, I tried to see the LCA process from their perspective and identify potential outcomes of my work that could benefit their day-to-day business operations (i.e. process optimization, waste reduction, etc.). I familiarized myself with their goals and achievements to better justify how my project fit with their business strategy (i.e. environmental stewardship, community interaction, etc.). This allowed me to put together a unique "sales pitch" for each company that invited them to be an active part of an exciting project and not just one of a dozen data sources for a technology assessment. In addition, I avoided solicitation through random contact and meticulously identified a member of senior management that would best serve as a point of contact (i.e. vice president of manufacturing, plant manager, etc.). As a final step in building trust, I offered to protect their data through agreements of non-disclosure. While not every company I contacted was willing to help, these efforts over time did allow me to identify enough sources to complete the LCI for my project.

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Uncertainty regarding service level to the customer. The eventual function of the nanotechnology and service level to the customer may not be known, which may limit the ability to develop an appropriate functional unit. As discussed in Section 2.3, reasonable assumptions may need to be made about the eventual product use and anticipated service provided to the customer to develop an appropriate functional unit. If it is not possible to develop a service-based functional unit and different product alternatives are not compared, then another basis for organizing the data and for putting results into context should be determined (e.g., amount of principle inputs and outputs).

Development of new decision rules. Decision rules commonly used for other technologies may not be suitable for nanotechnologies. Typically a mass-based cut-off is used to determine which materials to include in the product system. However, given the small scale and mass of nanomaterials, this may not be appropriate. Therefore, decision rules should also include materials that are of known or suspected environmental and energy significance regardless of size.

Uncertainty regarding upstream resource use. Nanoproducts are frequently high-tech devices that require rare metals for production. If there is reason to believe that scarcity will drive up material costs, this factor should be included in the sensitivity analysis. If the uncertainty is too great or is unknown, then a qualitative discussion of the potential impacts should be included. Removing a resource from a region also impacts resource availability for local inhabitants and typically is further exacerbated by low initial reserves. In such cases, both the impact of mining operations on the effected population, as well as any impacts caused by the loss of the extracted materials should be considered.

Limited toxicity data. There is very limited quantifiable data on the toxicity of nanotechnologies to human health and the environment (Khanna et al., 2007; Klöpffer et al., 2007). There are several options to consider when addressing this issue. Toxicity data may be gathered from laboratory experiments, models, databases, or other studies (Walsh and Medley, 2007). For example, a study by Sengul (Sengul et al., 2008) provides a comprehensive review of technologies used to manufacture nanomaterials and associated environmental impacts. Currently, the Organisation for Economic Co-operation and Development (OECD) is testing a representative set of manufactured nanomaterials for human health and environmental effects, including:

- Fullerenes (C60),
- Single-walled carbon nanotubes (SWCNTs),
- Multi-walled carbon nanotubes (MWCNTs),
- Silver nanoparticles,
- Iron nanoparticles,
- Titanium dioxide,
- Aluminium oxide,
- Cerium oxide,
- Zinc oxide,
- Silicon dioxide,Dendrimers,
- Nanoclays , and
- Gold nanoparticles

(OECD, 2008)

When considering data from toxicity studies, it is important to ensure data relevance and accuracy through the review of important qualifiers, key assumptions, and material properties (Bell, 2007). In addition, when extrapolating data from laboratory experiments, it is important to consider the limitations of the studies and whether they may be reasonably extrapolated (e.g., studies extrapolated from animals to humans) (Bell, 2007). Depending on the available data, it may also be appropriate to conduct a threshold analysis to determine the toxicity level at which the nanomaterial becomes a significant contributor to the overall impacts (Klöpffer et al., 2007).

Similarly, a scenario-based assessment or worst-case scenario assessment may be conducted, in which the impact potential of the nanomaterials is assumed to be as high as that of the most toxic materials (Klöpffer et al., 2007). If data are not available, a qualitative assessment based on physical and chemical properties that may influence toxicity may be conducted. For example, as discussed in Section 2.1, changes in the size and shape of a nanomaterial may influence deposition patterns in the human respiratory tract. Excluding human health and/or ecotoxicity impacts (e.g., aquatic ecotoxicity, human health cancer) as part of the assessment and only focusing on environmental impacts (e.g., energy use, global warming, ozone depletion) until additional data become available is also an option (Klöpffer et al., 2007), although this exclusion should be clearly identified in the final report.

Limited exposure data. Given uncertainty regarding the nature and extent of future commercial use of the nanoproducts, there is limited exposure data with which to conduct risk assessments (Ostertag and Husing, 2008; Walsh and Medley, 2007). Although toxicity is an important element of risk assessment, it is only half of the analysis; the analysis of risk requires information about both toxicity and exposure (Wiesner, 2006). Many studies have assessed different exposure pathways relevant to nanomaterials throughout the life cycle stages (EPA-SPC, 2007). As noted previously, if nanomaterials are embedded as part of larger objects (e.g., nanocomposites and nanocrystalline solids), they are less dispersive and present lower risk than if they are used as free nanoparticles, nanorods or nanofibers (Ostertag and Husing, 2008). Tools for exposure assessment include monitoring, sampling, and modeling. However, these approaches have limitations due to the unique characteristics of nanomaterials (EPA-SPC, 2007). For example, unlike typical exposure assessment, mass may not be the appropriate metric by which to characterize exposure. Instead, surface area may offer a better measure for assessing exposures (EPA-SPC, 2007).

Given these limitations, conducting an initial “screening level” exposure assessment to identify gaps and “priority starting points” for a thorough exposure assessment as data becomes available should be considered (Ostertag and Husing, 2008) . As part of this approach four key steps should be followed, including (1) defining system boundaries, (2) identifying relevant product parts, flows, stocks, processes and emissions throughout the life cycle, (3) characterizing the potential of generation, emission, and exposure for the areas identified in step 2, and (4) identifying priority points for the exposure assessment (Ostertag and Husing, 2008). To identify potential emission sources, relevant literature sources that have studied likely areas of exposure to nanoparticles throughout the life cycle should be reviewed (EPA-SPC, 2007; Park, 2009; Sengul et al., 2008).

In addition, a scenario-based or worst-case scenario assessment may be conducted (Klöpffer et al., 2007). For example, one study that modeled the exposure of different nanoparticles in the environment looked at a “realistic-exposure scenario” and a “worse-case exposure scenario” to develop a range of concentrations of the nanomaterials in the environment (Mueller and Nowack, 2008).

3.1.3 Challenges in Conducting Environmental Assessments

Like any other new technology under development, early application of nanotechnology is surrounded by uncertainties about the potential effects on environmental and human health and safety. Based on the current state of knowledge, the risk is real for some nanotechnologies, but as yet unquantifiable. Current information regarding the environmental effects and health risks associated with nanomaterials is limited and assessing their associated risk is not a straightforward process. Advances are needed to advance nanoproduct risk assessment and risk management. Meanwhile, efforts should be directed toward a better understanding of tradeoffs and finding superior risk management alternatives instead of setting a goal of estimating exact risks and benefits.

Nanoproducts have many potential benefits to society with their development and deployment in science, engineering and technology. Their benefits, however, need to be weighed against potential impacts to environmental and public health. Adequate risk assessment processes are needed to study these potential impacts, however, manufacturers need to realize that environmental assessments should not be limited to risk of exposure to nano-components. In addition, manufacturers need to understand how the manufacture, use, and waste management of the nanoproducts they make could potentially contribute to ongoing environmental problems during their life cycle from cradle to grave, including recycling. For example, is there the potential for nanomaterials to impact global warming, stratospheric ozone depletion, acidification (formation of acid rain) or eutrophication (the increase of chemical nutrients in water)?

LCA is a powerful tool for making holistic comparisons among possible or competing systems. At the same time, not many studies on LCA of nanotechnology have been conducted; therefore much of the needed information has to be extrapolated through experiences in other similar industries. Furthermore, the rapid development of nanotechnologies and limited availability of data makes full LCAs difficult to complete but easy to become outdated.

A two-day workshop on LCA of nanotechnological products (Klöpffer et al., 2007) concluded that the current ISO-standard on LCA (14040) (ISO, 2006) applies to nanotechnological products but also that some development is necessary. The following main issues were identified:

- There is no generic LCA of nanomaterials, just as there is no generic LCA of chemicals.
- The ISO-framework for LCA (ISO 14040:2006) is fully suitable to nanomaterials and nanoproducts, even if data regarding the elementary flows and impacts might be uncertain and scarce. Since environmental impacts of nanoproducts can occur in any life cycle stage, all stages of the life cycle of nanoproducts should be assessed in an LCA study.
- While the ISO 14040 (ISO, 2006) framework is appropriate, a number of operational issues need to be addressed in more detail in the case of nanomaterials and nanoproducts. The main problem with LCA of nanomaterials and nanoproducts is the lack of data and understanding in certain areas.
- While LCA brings major benefits and useful information, there are certain limits to its application and use, in particular with respect to the assessment of toxicity impacts and of large-scale impacts.
- Within future research, major efforts are needed to fully assess potential risks and environmental impacts of nanoproducts and materials (not just those related to LCA). There is a need for protocols and practical methodologies for toxicology studies, fate and transport studies and scaling approaches.
- International cooperation between Europe and the United States, together with other partners, is needed in order to address these concerns.
- Further research is needed to gather missing relevant data and to develop user-friendly eco-design screening tools, especially ones suitable for use by small and medium sized enterprises.

3.2 Economic Assessment Methods

Uncovering and recognizing environmental costs associated with a product, process, system, or facility is important for good management decisions. Attaining such goals as reducing environmental expenses, increasing revenues, and improving environmental performance requires paying attention to current, future, and potential environmental costs. How a company defines an environmental cost depends on how it intends to use the information (e.g., cost allocation, capital budgeting, process/product design, other management decisions) and the scale and scope of the exercise. Moreover, it may not always be clear whether a cost or a saving, such as adopting an energy efficient process, is classified as partly environmental and partly not. Whether or not a cost is "environmental" is not critical; the goal is to ensure that relevant costs receive appropriate attention (White et al., 1995).

Scale. Depending on corporate needs, interests, goals, and resources, environmental accounting can be applied at different scales which include the following:

- Individual process or group of processes (e.g., production lines)
- System (e.g., lighting, wastewater treatment, packaging)
- Product or product line
- Facility, department, or all facilities at a single location - regional/geographical groups of departments or facilities
- Corporate division, affiliate, or the entire company.

Scope. Whatever the scale, there is also an issue of scope. Scope refers to the types of costs that are included. An initial scope question is whether the economic assessment extends beyond conventional, internal costs to include potentially hidden, future, contingent, and often intangible costs, such as image/relationship costs. Another scope issue is whether a company intends to consider only those costs that directly affect their bottom line financial profit or loss, or whether they want to also recognize the costs that results from their activities but for which they are not directly accountable. These are referred to as external costs.

Environmental accounting terminology uses terms such as full, total, true and life cycle in order to emphasize the fact that conventional approaches may be incomplete in that they overlook important environmental costs (and potential savings). In looking for and uncovering relevant environmental costs, decision makers may want to apply one or more tools. As the scope becomes more expansive, firms may find it more difficult to assess and measure certain environmental costs.

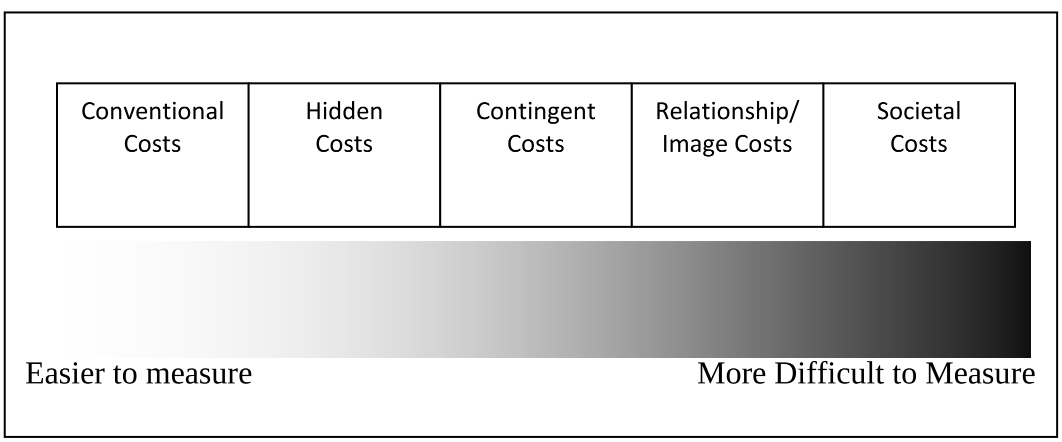

Figure 3-2. The Spectrum of Environmental Costs (White et al., 1995)

The discussion in this section concentrates on conventional costs (raw materials, utilities, capital goods, supplies, etc.) as well as environmental costs that are potentially overlooked in decision making (see Figure 3-2.) This is where companies that are starting to manufacture products in an environmentally sustainable way typically begin.

Examples of Environmental Costs Incurred by Companies

Potentially Hidden Costs		
Regulatory	**Upfront**	**Voluntary (Beyond Compliance)**
Notification Reporting Monitoring/testing Studies/modeling Remediation Recordkeeping Plans Training Inspections Manifesting Labeling Preparedness Protective equipment Medical surveillance Environmental insurance Financial assurance Pollution control Spill response Stormwater management Waste management Taxes/fees	Site studies Site preparation Permitting R&D Engineering and procurement Installation **Conventional Costs** Capital equipment Materials Labor Supplies Utilities Structures Salvage value **Back-End** Closure/ decommissioning Disposal of inventory Post-closure care Site survey	Community relations/ outreach Monitoring/testing Training Audits Qualifying suppliers Reports (e.g., annual environmental reports) Insurance Planning Feasibility studies Remediation Recycling Environmental studies R & D Habitat and wetland protection Landscaping Other environmental projects Financial support to environmental groups and/or researchers
Contingent Costs		
Future compliance costs Penalties/fines Response to future releases	Remediation Property damage Personal injury damage	Legal expenses Natural resource damages Economic loss damages
Image and Relationship Costs		
Corporate image Relationship with customers Relationships with investors Relationship with insurers	Relationship with professional staff Relationship with workers Relationship with suppliers	Relationship with lenders Relationship with host communities Relationship with regulators

(EPA 1995)

Life cycle costing (LCC) can be viewed as building on the ISO standards of LCA as a method for calculating costs throughout the life cycle of a product. LCC is based on the same physical product system used in LCA, and summarizes all costs associated with a product from inception, to development, use, and disposition (see Figure 3-3). However, it is pertinent to know the life cycle costs from different perspectives, and so costs are typically separated into two segments:

those paid by manufacturers and those paid by consumers or society (SETAC, 2009). There are three types of cost categories to consider when conducting an LCC:

1. **Internal costs** are those that are associated with real monetary flows. For example, it may include costs associated with raw material purchase, transportation, production, or incineration. Note that "internal costs" refers to costs that are directly covered by any stakeholder in the product system, including producers, consumers, end-of-life recyclers and landfill managers, and any other stakeholders involved in the product system. All internal costs should be included in a LCC.
2. **Anticipated internal costs** are costs that do not yet exist, but are anticipated in the future (e.g., future disposal costs from anticipated regulations). Depending on the study's goal, anticipated internal costs may be included in a LCC.
3. **External costs** are costs outside of the product system boundary, such as roadways for facility construction or maintenance of a port. These costs should not be included in a LCC.

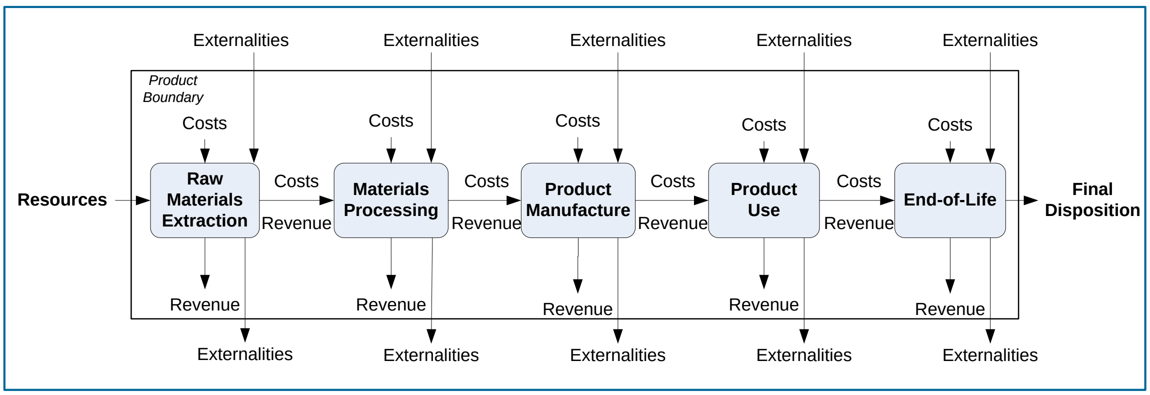

Figure 3-3. Life-Cycle Costing (as presented in SETAC (SETAC, 2009))

As with an LCA, LCC is a process-based method, accordingly boundaries must be set around the product system. To connect the analysis to the broader economy-level, LCC inputs and outputs may be combined with an economic input/output database. The resulting hybrid analysis allows the interconnections between the product system and the rest of the economy to be accounted for without compromising the level of detail.

Other methods such as total cost accounting (TCA) and total cost of ownership (TCO) may also be used to account for the costs of a product system. Although these methods do not consider both internal and external (societal) costs, they may be beneficial for estimating the costs for certain stages of LCC analysis. For example, total cost accounting may be used to estimate production costs for development of a nanoproduct from the manufacturer's perspective and total cost of ownership may be applied to estimate the costs incurred by a consumer during the use, maintenance, and end-of-life stages. As in LCA, LCC can be applied to specific stages of the product.

Total cost accounting (TCA) is concerned only with costs to the company itself and examines all the costs that go into making a product, including activities from R&D to sales. TCA can encompass any combination of business activities.

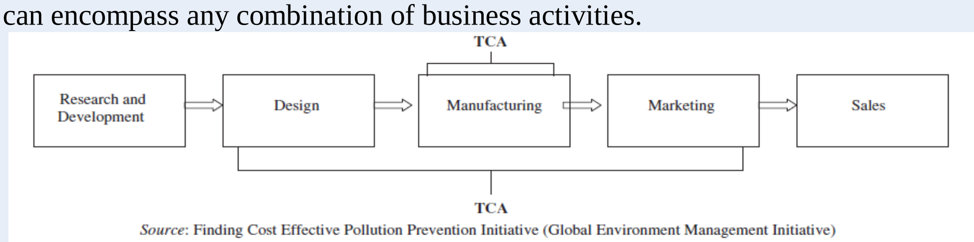

Table 3-2 summarizes the economic assessment methods most relevant to nanoproducts. The table does not include non-hybrid economic input-output models, general equilibrium models, or partial equilibrium models, because these tools primarily assess meso- and economy-wide changes, and are not as applicable to nanoproducts.

Table 3-2. Key Economic Assessment Methods

Method	Description/ Benefits	Scope/ Stage	Impacts Measured	Reference
Life Cycle Costing (LCC)	Assesses the comprehensive costs of a product throughout its life cycle stages. LCC may apply techniques such as Total Cost Accounting, Activity-Based Costing (ABC), or Total Cost of Ownership to estimate and allocate costs between manufacturers, consumers, and society.	Product/ micro level All life cycle stages	Cost to manufacturer and consumer per functional unit (service of product)	(Hunkeler et al., 2008; SETAC, 2009)
Eco-Efficiency Analysis	Combines Environmental Life-cycle Assessment with Total Cost of Ownership to draw a relationship between the economic value of a product and its environmental impacts.	Product/ micro level All life cycle stages	Ratio of economic value of a product (from a consumer perspective) to the life cycle environmental impacts (e.g., energy and material consumption, waste, air, and water emissions).	(Saling et al., 2002; White et al., 1995)

3.2.1 Data Sources for Economic Assessments

Life cycle costing requires data for not only the direct cost factors but also indirect costs, as well as costs related to liability and less tangible benefits. While it may be easier to obtain data on direct costs, it may be more problematic to estimate potential future costs. Following are ways by which these costs may be tracked.

3.2.2 Issues Related to Economic Assessment Methods

High research and development costs. Nanoproducts are an emerging technology, and involve a great deal of research and development. Even though material use during research and development may be low, the costs during this phase often constitute a large amount of overall product costs. As a result, the economic assessment may include the "knowledge" phase, e.g. research and development and acquisition via the supply chain. Other elements, such as marketing activities, might also be included in the assessment (SETAC, 2009).

Fluctuating manufacturing and capital equipment costs. Costs associated with a nanoproduct may fluctuate as the technology matures, depending on several factors, including changes in technology design and resources needed for capital equipment. Given the quickly evolving production processes for nanotechnologies, capital equipment may become outdated more rapidly than for other technologies. Furthermore, some costs may be sensitive to production volume due to economies of scale, while other costs are rather stable (SETAC, 2009). If capital equipment is included use of a hybrid economic input-output model would sufficiently capture impacts from capital equipment. Alternatively, instead of EIO data, if more precise data is available, an evaluation of capital equipment could be nested within the larger assessment when appropriate and feasible.

Limited consumer and end-of-life cost data. In many cases, there is a high degree of uncertainty for emerging technologies regarding future costs during the use and end-of-life stages. If cost data from the use and end-of-life stages are limited, it still may be possible to conduct an assessment solely from the manufacturer's perspective. Such an assessment would not be comprehensive, but could still provide valuable information for an LCC. Cost data on use and end-of-life could be incorporated into the assessment at a later date when the product goes to market or when additional information becomes available (SETAC, 2009). Identification of costs that may change over time or by region (e.g., energy costs) are also important as it may impact the economic value of the product for the consumer (SETAC, 2009). In addition, it is possible to estimate future costs based on costs for similar products. For example, the cost to recycle a nano-based lithium ion battery may be similar to the cost of recycling a lithium-ion battery that does not contain nanomaterials. Any information about the uncertainty surrounding the predictions of future costs should be incorporated into an uncertainty analysis.

Uncertainty regarding product lifetime and selecting an appropriate discount rate. Given potential uncertainties in the lifetime of the product and/or when a product may come to market, it may be difficult to determine an appropriate discount rate (SETAC, 2009). Discounting is used to account for the time-value of money and brings future costs to a present value. Therefore, selection of an appropriate discount rate is crucial for estimating future costs (SETAC, 2009). SETAC (SETAC, 2009) provides guidelines for selecting a discount rate depending on the stakeholder perspective (e.g., bond rate, lending rate, or weighted average cost of capital). In addition, a sensitivity analysis should be considered to assess the impacts of a range of appropriate discount rates.

Uncertainty regarding economic benefits/costs. Developing nanotechnologies may lead to great benefits for society, such as improved military or medical technology, more efficient use of resources, and more reliable devices. However, these benefits might be accompanied by negative consequences. For example, improved medical care could increase healthcare budgets, because money spent on healthcare ultimately succeeds only in shifting the expenses involved in keeping individuals alive to a later date. The longer people live, the more expensive it is to keep them alive. Moreover, years added to the end of life are likely each to be quite expensive (Sparrow, 2009). There is a great deal of uncertainty surrounding the potential effect that nanoproducts will have on the economics of medical devices and health care costs, which makes it difficult to incorporate these concerns into an economic or social assessment. However, if there is reason to believe that the nanoproduct in question will affect a segment of the economy (e.g., healthcare), it may be worthwhile to at least include a qualitative discussion of the potential impacts. A qualitative assessment may be enough to facilitate a discussion with stakeholders during the decision analysis phase of the assessment.

Delineation between external versus internal costs. Given the high degree of uncertainty regarding nanoproduct properties, potential environmental impacts, and future regulations, some costs may be difficult to identify and estimate, such as future costs of remediation, or the reclassification of waste produced by the firm to hazardous (SETAC, 2009). This issue is essentially one of externalities. Even though governments and society generally do not directly cover costs in the product system, sometimes they do indirectly cover them (e.g. costs to construct and maintain roads near a production facility, impact of air emissions on human health). These external costs should not be included in the economic assessment to avoid double counting impacts. However, if it's anticipated that an external cost may become internalized, either through taxes, fees, or new regulations, then it may be appropriate to include such costs in the study, and to conduct a sensitivity analysis around them (SETAC, 2009).

Uncertainty regarding impacts on other economic sectors. If the nanoproduct has the potential to develop into a general purpose technology, previous experience suggests that the effects on productivity and economic growth could be significant even though these may sometimes come with a more significant time lag (Palmberg et al., 2009). Given the high level of uncertainty regarding the potential of various nanotechnologies to be transformed into general purpose technologies, it may not be possible to quantitatively assess the broader economic benefits and impacts associated with a new nanoproduct. In other words, it is very difficult to predict if and how an emerging technology will enable the development of other technologies (Palmberg et al., 2009).

Even so, if there is some evidence that the nanoproduct in question will enable the development of other products, it may be worthwhile to at least qualitatively consider the potential economic implications, such as increased or new demand for certain materials, job creation, and economic growth. For example, increased demand for high-tech materials might increase the number of jobs available to the high-tech workforce. The bulk of nanotechnology firms are based in developed countries, particularly the United States, (Palmberg et al., 2009). Accordingly, many of the newly created high-tech jobs might also be located in developed countries.

Uncertainty regarding impacts on incumbent firms. Some nanotechnology-based advances will build upon or be readily integrated with existing technologies manufactured by "incumbent" firms. In such cases, adjustment to the new technology by incumbent firms is expected to be relatively smooth. Other nanotechnology based innovations will involve radically different processes, in turn destroying the competencies of existing firms with the potential of reallocation of economic activity to different firms and regions of the nation or globe (Shea, 2005). While it can be difficult to determine ex-ante the impact of an emerging technology on existing competencies, it may be possible to draw qualitative conclusions. Table 3-3 presents a summary of observations that may aid in providing qualitative assessments regarding whether a nano-based innovation is more or less likely to result in decline in economic performance of the incumbent firm (Shea, 2005).

Table 3-3. Example Factors Impacting Incumbent Firms

Factors *more* likely to negatively impact incumbent firms:	**Factors *less* likely to negatively impact incumbent firms:**
• Nanotechnology-based innovations that are complex or where only limited information is available. • Nanotechnology-based innovations that constitute a change to a process or component that is core to the whole product system. • Bottom-up fabrication techniques (e. g.,	• Incumbent firm's existing technologies are reaching the limits of their life cycle curve, resulting in increased incentive to adopt new technologies. • Incumbent firm has complementary assets to take advantage of the nano-based innovation. Complementary assets can range from technical knowledge to relationships with distributors and consumers. • Incumbent firm engages in inter-firm cooperation to keep

based on emerging chemistry techniques) as opposed to top-down techniques (e. g., use of existing lithography techniques).	abreast of nanotechnology-based developments. • Incumbent firm has a strong ability to exploit external knowledge relevant to nanotechnology-based innovations.

3.2.3 Challenges in Conducting Economic Assessments

The term 'economic assessment" has many meanings and uses. It can refer solely to the costs that directly influence a manufacturer's bottom-line (private costs) or it can be expanded to include the costs to individuals, society and the environment (total costs). Specific economic assessment issues or challenges vary depending on the scale of the application. Accounting for conventional, private costs is a fairly straightforward process. Life cycle costs which do not have a direct impact on a company's bottom-line, are harder to model. However, businesses will ultimately benefit from moving toward including probabilistic and difficult to estimate costs in their business decisions.

It is important to ensure that environmental impacts are not "double counted" when applying the impact models of LCA and LCC. To avoid double-counting costs, LCC avoids the monetization of external costs that are environmental impacts not paid for directly or indirectly by the product manufacturer (e.g., the potential monetary costs caused by losses due to greenhouse gas emission and the resulting global warming) (SETAC, 2009) . In addition, when conducting both a LCA and LCC, it is important to use equivalent system boundaries and the same functional unit (SETAC, 2009). However, it is possible that some components or processes of a product system would be included in one assessment and not another (or vice versa), because some aspects could have high costs but low material flow. For example, while the cost of research and development may be high, the material flow and costs may be relatively low once in full production mode. In this case, research and development costs might be included in the LCC, but research and development materials would not be included in the LCA.

3.3 Social Assessment Methods

While methods for assessing the social impacts of a product are not as mature as methods for assessing environmental and economic impacts, concerns about social responsibility are increasing and should not be overlooked (ISO, 2009; Jorgensen et al., 2008). Several initiatives and organizations, as well as the international community, have given thought to the underlying core values, principles, and standards that should guide social assessments, and researchers are actively developing methods for applying these principles and standards to products.

Given the nascent stage of social sustainability assessment and the lack of well-developed methods, this section describes principles and standards relevant to social sustainability, as well as the currently available methods for applying those standards. In addition, we describe potential issues and decision factors that may arise when applying these standards to nanoproducts.

The International Organization for Standards (ISO) is in the process of developing the Guidance on Social Responsibility, which "provides guidance on the underlying principles of social responsibility" (ISO, 2009). This document was released as a draft international standard in September 2009 and was advanced to a final draft international standard in March 2010. Other organizations have also developed internationally recognized standards for social accountability, which can be used in social sustainability assessment. These include Social Accountability International's facility level SA8000 standard (SAI, 2008), AccountAbility's AA1000 enterprise level series of standards (AccountAbility, 2008), and the Global Reporting Initiative's supply chain level reporting guidance (GRI, 2006). Researchers and analysts are currently working to incorporate these principles and standards into assessment methods, including existing life cycle assessment methods.

In an effort to create a central framework for adapting ISO 14040 and 14044 to social criteria, the United Nations Environmental Program (UNEP) together with the Society for Environmental Toxicology and Chemistry (SETAC) published the Guidelines for Social Life Cycle Assessment of Products through the Life Cycle Initiative (UNEP, 2009a). The UNEP/SETAC guidelines pull together and build upon much of the existing literature to provide a framework for Social Life Cycle Analysis (SLCA). These guidelines recommend that impact categories be based on internationally accepted standards, such as SA8000 (SAI, 2008) and AA1000 (AccountAbility, 2008). The UNEP/SETAC guidelines also suggest following the requirements of the Voluntary Quality Standard for SRI Research (CSRR-QS, 2010) to gather data on upstream suppliers.

The basic components of an SLCA are the same as for an LCA described in Section 3.1. There is a difference, however, in the type of data collected. As illustrated in Figure 3-4, whereas a LCA requires data on process and material flows, SLCA requires data on how companies in the supply chain interact with stakeholders, such as employees, local residents, the broader community, society at large, and other persons affected by the company's actions (Dreyer et al., 2006; Hauschild et al., 2008). Furthermore, SLCAs must typically include geographic information, because social assessments must take into account conditions specific to companies and geographic areas, such as worker safety, environmental justice, access to resources, etc (Dreyer et al., 2006; Swarr, 2009). The local/regional nature of some social impact pathways also creates a high degree of uncertainty when calculating impacts with methods built upon aggregate data, such as traditional LCA methods (Klopffer, 2008; Norris, 2006). As an alternative, certification systems, such as fair trade programs, may be used to determine whether materials in the supply chain meet certain standards, such as fair wages and safe and just working conditions (Norris, 2006). Norris introduced the Life Cycle Attribute Analysis (LCAA) to calculate the amount of output from a supply chain that has an attribute of interest. Attributes could be any quality relevant to the assessment, such as fair trade labels (Norris, 2006).

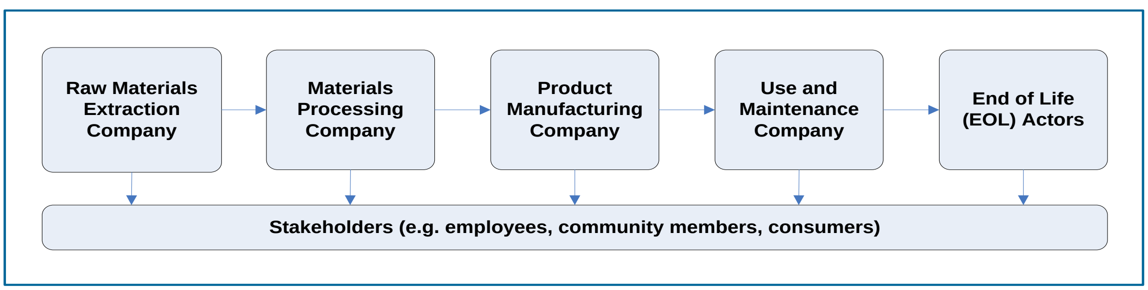

Figure 3-4. Social Life-Cycle Assessment (Dreyer and Hauschild, 2010)

Some impacts estimated as part of an environmental assessment may also be considered in a social assessment, but care should be taken not to double count impacts. For example, human health impacts (e.g., cancer human toxicity) for both the public and workers may be considered a social impact. If an impact is included as part of the social assessment, then it should not also be included as part of the environmental assessment.

Social Impact Assessment (SIA) and Social Assessment (SA) are other methods commonly used to analyze social impacts. However, these methods were developed to complement Environmental Impact Assessment, and apply more to larger scale meso and economy-wide projects. The United States Department of Agriculture describes SA as "the basis for identifying and forecasting consequences of possible projects or policies" (Alan et al., 2003). Similarly, the

SIA community describes SIA as a method for "analyzing, monitoring and managing the social consequences of development" (Vanclay, 2003). While the methods of SIA apply more to larger scale projects and interventions, the guiding core values and principles are equally applicable to products. These principles are laid out by Vanclay (Vanclay, 2003). Table 3-4 shows the social assessment methods most relevant to nanoproducts.

Table 3-4. Key Social Assessment Methods

Method	Description/ Benefits	Scope/ Stage	Impacts Measured	Reference
Social Life-Cycle Analysis (SLCA)	Assesses the social aspects of products and their impacts along their life cycle.	Product/micro level All life cycle stages	Defined by the stakeholders. For example: • Human rights • Working conditions • Cultural heritage • Poverty • Disease • Political conflict • Indigenous rights	(Dreyer et al., 2006; Jorgensen et al., 2008; Swarr, 2009; UNEP, 2009a; Weidema, 2006)
Life Cycle Attribute Analysis	Calculates the amount of total output that has the attribute of interest (e.g. fair trade certification)	Product/micro level All life cycle stages	Amount or percent of output that: a) Has the attribute of interest; b) Lacks the attribute of interest; or c) Lacks data on attribute status	(Klopffer, 2008; Norris, 2006)
SocioEco-Efficiency-Analysis	Provides an assessment of societal impacts, as well as environmental impacts and economic costs.	Product/micro level All life cycle stages	• Environmental • Economic • Social (e.g., number of jobs, number of working accidents occurring during production).	(BASF, 2011; Klopffer, 2008)

In addition to the methods presented, some computable general equilibrium (CGE) models and partial equilibrium models (PEMs) incorporate social aspects (Zamagni et al., 2009). However, these models address the meso and economy-wide impacts, and are not expected to be relevant to nanoproduct design and manufacture.

3.3.1 Data Sources for Social Assessments

Generally, practitioners of SLCA will need to incorporate a large share of qualitative data, since models for interpreting the numeric information related to the social issues being addressed are not well developed. When numeric data is useful—for example, in assessing the wages of a particular enterprise—additional data will still be needed to address its meaning. For example, compliance with minimum wage laws does not always mean that the wages are livable. Often, data may need to be collected to represent site-specific situations, since databases for specific social and socio-economic impacts are at a minimum (UNEP, 2009a).

The Social Hotspots Database, a project of New Earth, was created in 2007 by Catherine Benoît and Greg Norris (Benoit and Norris, 2007). The idea began during their work on the Guidelines for Social Life Cycle Assessment of Products, published by UNEP (UNEP, 2009b), when Benoît and Norris noticed opportunities for improvement in Life Cycle databases. Most LCA tools lack the ability to specify the geographical location of production activities -information that is essential for social impact assessments. The Social Hotspots Database can play a role similar to LCA databases in assessing product hotspots, but with the added benefit of geographical precision and potential social impacts identification. The development of the database started in September 2009.

The Social Hotspots Database allows for visibility in the supply chain by:

- Providing modeling of product life cycles by country specific sector.
- Providing estimates on where the people are in the product's supply chain and what specific risks and opportunities might affect them.
- Expressing quantitatively the share of a supply chain where specific hotspots are found.

It shows which country specific sectors represent the greatest share of worker hours in a given supply chain, which ones are the most at risk of human rights and social issues, and which ones can represent business opportunities to implement positive changes in livelihood.

3.3.2 Issues Related to Social Assessment Methods

Uncertainty regarding social impacts. Like all emerging technologies, it will be difficult to assess the social impacts of nanoproducts before they have been on the market. Nanotechnologies have the potential to deliver considerable benefits to society, but at the same time these products may pose great risks (Walsh et al., 2008). Much of the risks that have concerned researchers to date are issues of toxicity, yet there may be other risks, as well. For example, will disposal and/or recycling of the nanoproducts be associated with poor working conditions? This raises further questions regarding the scope of a social assessment done from the developer's and manufacturer's perspectives. For example, to what extent should such assessments take into account downstream practices that might be out of the manufacturer's control? Although the answers to the questions are not yet fully resolved, they should be considered even as part of a qualitative analysis (Dreyer et al., 2006).

Inadequate methods for addressing high levels of uncertainty. As described above, for nanoproducts, there are likely to be multiple layers of uncertainty. As a result, traditional approaches to quantifying uncertainty, such as Monte Carlo analysis, might be inadequate (Seager and Linkov, 2008). Probability distribution under conditions of extreme model and boundary uncertainty lack meaning (at best) or may lead to overconfidence (at worst). To address these uncertainties a scenario analysis could be conducted, thereby affording the ability to consider possible future activities, events or even policy decisions, such as market expansions, resource availability, use, technology improvements and production caps). This allows product developers to explore sensitivities and possibilities while gaining a feel for trade-offs (Seager and Linkov, 2008).

3.3.3 Challenges in Conducting Social Assessments

The conduct and implementation of social responsibility assessments is relatively new and poses complex challenges. The choice of which approach is appropriate will be application specific. Different contexts will represent different challenges and will need varying levels of assessment. Some developed countries may already cover many of Human Rights and Worker Rights indicators and the application of the law may be well executed. However, developing countries may not be at this same level. For example, in many cases, enterprises in developed countries are not allowing freedom of association. Therefore, as part of the assessment, screening for minimum compliance when thresholds exist, and possibly also to assess performance beyond compliance thresholds, is suggested. The elements that should be defined in the goal definition phase of the assessment and accounted for in the interpretation phase of the study. Comparative studies must be conducted with the same level of assessment (UNEP, 2009a).

4. Assessing Sustainability

In Section 3, we provided a summary of methods for evaluating the environmental, social and economic impacts of the product system over its lifetime. The result of these assessments is an inventory of indicators computed and compiled based upon the established sustainability criteria. The data alone can provide some insights regarding the nanoproduct to include identifying the processes with the greatest impacts, prioritizing approaches for impact reduction and improving the product system. However, it typically is very difficult to determine which approach is better due to complex tradeoffs. For example, a company may be considering three different synthetic processes for manufacturing silica nanoparticles, each of which are technically and economically feasible, environmentally sound and socially responsible. Hence, while data may be plentiful, critical knowledge to guide decision making is scarce (Klimberg and Miori, 2010). Further, note that while making decisions based on one facet alone is challenging, when coupled with the unique intricacies of handling multiple factors inherent in sustainability, the difficulty of decision making skyrockets. In this section, formal decision analysis methods are discussed which may be used within the context of sustainability to systematically organize information, make sense of the problem and select the preferred option.

4.1 Evaluating Sustainability Criteria

To illustrate the complexity of decision making, we highlight some of the critical elements that are important for assessing nanomaterials. Key characteristics include agglomeration and aggregation, reactivity, physical form/shape, solubility, surface area, critical functional groups, contaminant dissociation, bioavailability, bioaccumulation potential and toxic potential (Tervonen et al., 2009). These elements are primarily related to risk, however when assessing the sustainability of nanoproduct production, information such as energy use, material use, environmental impacts, human health impacts and cost should also be considered. Based upon preferences, values and objectives, the criteria for comparing each alternative are established by stakeholders and decision makers. Figure 4-1 is a mapping of decision criteria considered by Canis et al. (Canis et al., 2010) in their comparative assessment of alternatives for single walled carbon nanotube (SWCNT) synthesis. Note that life cycle impact assessment (LCIA) score and health risks are proxy measures which compile multiple indicators related to environmental and human health impacts. In the study, data were gathered to populate the measures for each synthesis method by extrapolating from existing studies and expert opinion. Even with data in hand, making a decision also requires deciphering the views of stakeholders who typically have diverse goals, priorities and values. Hence, the question now becomes: How is one alternative selected over another?

There are numerous studies that evaluate sustainability based on multiple criteria (e.g., (Bailey et al., 2010; Eason et al., 2009; Halog and Manik, 2011; Hopton et al., 2011; Linkov et al., 2006; Sikdar and Murray, 2010)), yet not all utilized a formal decision strategy. Further, while decisions may be made from simplified approaches, such methods tend to minimize complexity and consequently lose some crucial details (e.g., uncertainty) necessary for making informed, high quality decisions (Linkov et al., 2004; McDaniels et al., 1999). Merkhofer (Merkhofer, 1999) describes the characteristics of quality decision making as decisions that involve the key stakeholders, contains relevant types and amount of information, identifies good alternatives, provides logically sound results and properly integrates the preferences of the decision makers. Accordingly, it is critical that methods be implemented that have the ability to integrate pertinent information and help guide decision making. Table 4-1 is a snippet of the list Merkhofer (Merkhofer, 1999) presented which displays the scope of various tools that have been developed to aid in evaluating, refining and selecting desirable alternatives. The scope is defined by the

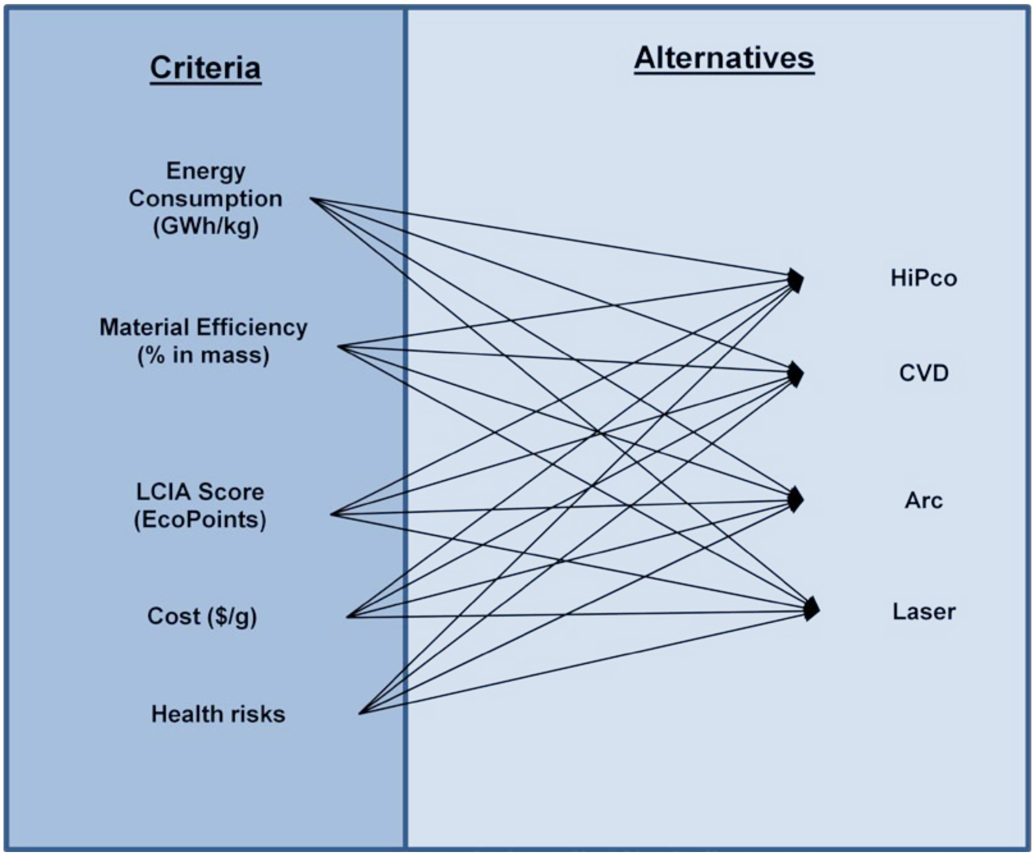

Figure 4-1. Mapping the Decision Criteria: Sample Criteria for Assessing Single-Walled Carbon Nanotube Synthesis Processes (Canis et al., 2010) HIPCO: High Pressure Carbon Monoxide; Arc: Arc Discharge; CVD: Chemical Vapor Deposition; Laser: Laser Vaporization.

Table 4-1. Sample Decision Making Tools (Merkhofer, 1999)

	Primary Uses									
Tool	**Problem Definition**	**Assessing health or environmental risks**	**Assessing other risks**	**Determining whether action is needed**	**Collecting information**	**Screening alternatives**	**Identifying alternatives**	**Evaluating Alternatives**	**Selecting Options**	**Communicating decisions**
Analytical Hierarchy Process										
Cost-Benefit Analysis										
Decision Analysis										
Environmental Impact Assessment										
Probabilistic Risk Assessment										
Structured Voting										
Classical Probability Models										

primary uses within decision making. For example, while cost-benefit analysis may be used for the full gamut of the decision making process from problem definition to communicating decisions, Analytical Hierarchy Process is typically only used to aid in problem definition, screening and evaluating alternatives and selecting options. Although, both decision analysis and cost-benefit analysis cover the scope of decision support needs, cost-benefit analysis only truly accounts for one of the pillars of sustainability, is primarily based on market prices and typically has very little stakeholder interaction.

4.2 Decision Theory

Decision theory is a field of study that aids in formulating hypotheses based on values, risk, uncertainty and tradeoffs. It relates to techniques to aid decision makers in determining the best option when the outcomes are uncertain and the decision environment is unpredictable (Parsons and Wooldridge, 2002). Decision theory is compartmentalized into two primary genres: normative and descriptive. While descriptive decision theory is rooted in experimental psychology and deals with determining how and why people make decisions, normative decision theory is prescriptive and relates to finding the best decision (Peterson, 2009). Decision analysis (DA) is under the banner of decision theory and is a systematic approach to evaluating complex problems and enhancing the quality of decisions (Clemen and Reilly, 2001). The basic steps of DA include: problem identification, information gathering, generating possible solutions, evaluating and selecting solutions. The DA flowchart provided in Figure 4-2 expands these basic steps to incorporate estimating baseline risk, decomposition and modeling, sensitivity analysis and a recursive step to account for further analysis when developing and analyzing new alternatives.

Many researchers have noted the benefit of applying decision analysis to life cycle approaches and highlight the similarities between the two structures (Seppala et al., 2002). Accordingly, when referring to Figure 1-2, note that rudiments of the decision analysis process are dispersed throughout the framework. Since Sections 2 and 3 contain elements of the initial steps of decision analysis, once we reach this section of the guidance structure, the product has been characterized and stakeholders have been identified. In addition, the objectives, goal and scope of the study and an inventory of indicator data have been compiled for each alternative. Hence, the focus at this point is to take the indicators and use them to make informed decisions. The DA approach was modified to reflect this aim and consists of evaluating and interpreting impacts, determining preferences and uncertainty, selecting the most sustainable alternative and sensitivity analysis (Figure 4-3).

At its core, DA aids in reconciling conflicting values, objectives and preferences with the aim of reaching a wise, informed decision (Keeney and Raiffa, 1976). More accurately, it relates to handling problems that are characterized by complexity, uncertainty, risks and tradeoffs. As described in Section 3, there is likely to be a great deal of uncertainty related to the sustainability of emerging technologies. Characterizing and dealing with these uncertainties will be a major challenge in any decision putting a premium on decision analysis methods that handle uncertainty in an explicit and transparent manner. The presence of uncertainty coupled with multiple attributes describes what Keeny and Raiffa (Keeney and Raiffa, 1976) denote as "the double dichotomy of decision problems." Uncertainty is discussed further in Section 4.4.

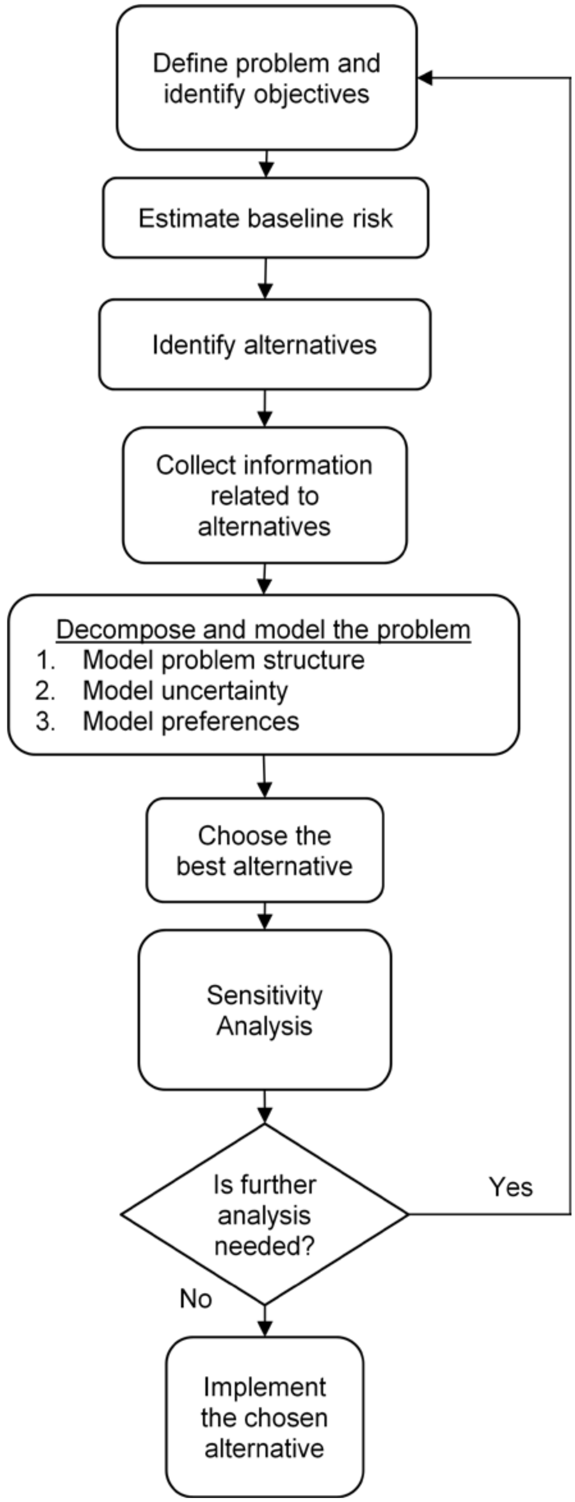

Figure 4-2. Decision Analysis Flowchart (Clemen and Reilly, 2001; Merkhofer, 1999)

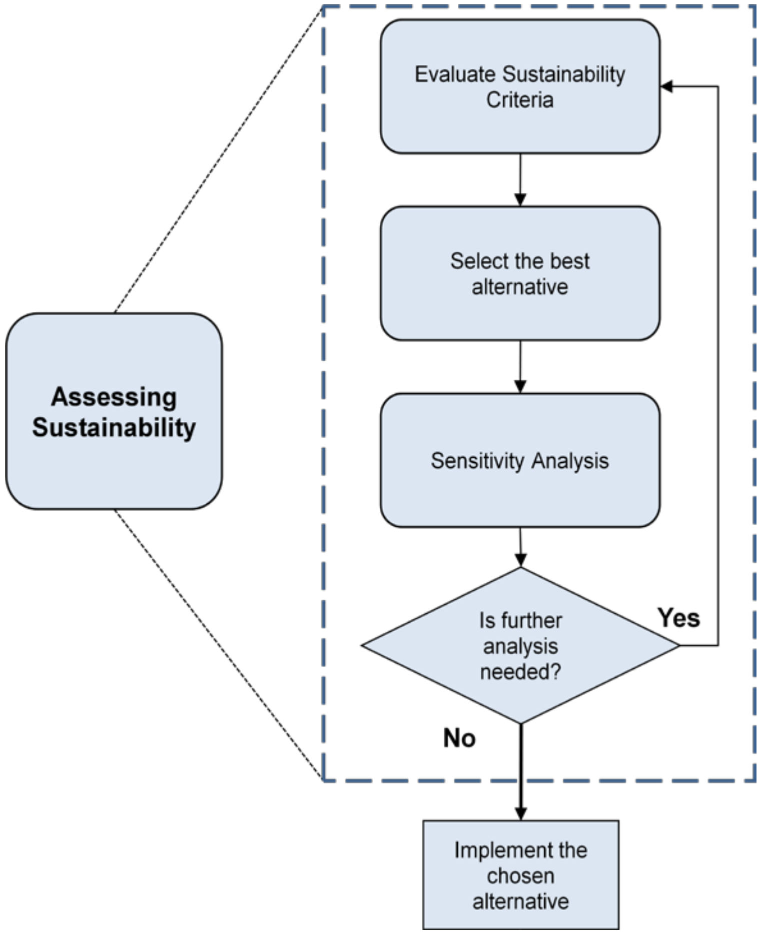

Figure 4-3. Modified Decision Analysis (DA) Approach

Table 4-2 provides information (to include stakeholder input) on some of the most common decision making strategies. *Ad hoc* approaches typically have very limited stakeholder input and contain criteria that often are not explicitly defined. In addition, alternatives are evaluated through qualitative or semi-quantitative measures and the final selection is often not transparent. Further, the weighting schemes are often developed by the decision maker and are not sufficiently justified. Cost-benefit analysis (CBA) and probabilistic risk assessment (PRA) have explicit evaluations schemes, a great deal of stakeholder input and are useful in many cases. However, these methods relate primarily to cost and risk respectively, but are limited in their ability to

Table 4-2. Comparison of Process Elements for Common Decision Making Tools (CALCAS, 2008; Linkov et al., 2006; Merkhofer, 1999)

Elements of decision process	Ad hoc decision-making	Probabilistic risk assessment	Multi-criteria decision analysis	Cost-benefit Analysis
Define problems	Stakeholder input limited or non-existent. Therefore, stakeholder concerns may not be addressed by alternatives	Stakeholder input collected after the problem is defined by decision-makers and experts. Problem definition is possibly refined based on stakeholder input.	Stakeholder input incorporated at beginning of problem formulation stage. Often provides higher stakeholder agreement on problem definition. Thus, proposed solutions have a better chance at satisfying all stakeholders.	Typically defined by decision makers
Generate alternatives	Alternatives are chosen by decision-maker usually from pre-existing choices with some expert input.	Alternatives are generated through formal involvement of experts in more site-specific manner.	Alternatives are generated through involvement of all stakeholders including experts. Involvement of all stakeholders increases likelihood of novel alternative generation.	Alternatives often generated by a limited group of stakeholders and decision makers
Formulate criteria by which to judge alternatives	Criteria by which to judge alternatives are often not explicitly considered and defined.	Criteria and sub-criteria are often defined.	Criteria and sub-criteria hierarchies are developed based on expert and stakeholder judgment.	Evaluation of total expected costs vs. total expected benefits; Criteria often based on various economic meausre to include: net present value, benefit, benefit to cost ratio, etc.
Gather value judgments on relative importance of criteria	Non-quantitative criteria valuation weighted by decision-maker	Quantitative criteria weights are sometimes formulated by the decision-maker, but in a poorly justified manner.	Quantitative criteria weights are obtained from decision-makers and stakeholders.	Preferences are not necessarily made explicit or considered
Rank/select final alternatives	Alternative often chosen based on implicit weights in an opaque manner	Alternative chosen by aggregation of criteria scores through weight of evidence discussions or qualitative considerations.	Alternative chosen by systematic, well-defined algorithms using criteria scores and weights.	Based upon costs and benefits
Strength	Simple and low cost	Systematic means of exploring and quantifying risk; good documentation,quantifies uncertainty, identifies threats	Ability to handle complex decisions with mutiple criteria and stakeholders with multiple viewpoints; Decision making in concert with stakeholder values and preferences; strong theorectical foundation; can handle soft issues (e.g., social) and uncertainty	Strong theoretical foundation with tools to aid in estimating (cost and benefits); common unit of measure; helps managers allocate limited resources; not everything can be monetized
Weakness	Inflexible, can not handle complexity or uncertainty, not reproducible, no logic or audit trail, limited stakeholder involvement; therefore, not all concerns considered	Difficult, expensive and time consuming; Possible inacuracies due to estimating and assumptions on mechanisms that are not well known leading to large uncertainties and misleading results	Typically time consuming	Often limited stakeholder interaction; deals with net impacts and not who pays the costs or reaps the benefits, typically based on market prices and not true preferences

handle the broad aspects of sustainability. On the other hand, multi-criteria decision analysis (MCDA) can handle the diverse elements of sustainability and affords the ability to make decisions based upon active stakeholder input from the beginning to include developing objectives, criteria and alternatives. Moreover, the weights are determined by querying both decision makers and stakeholders to determine their preferences and the final alternatives selected are determined systematically.

4.3 Selecting the Most Sustainable Alternative

It is expected that the development of sustainable nanoproducts will involve a finite number of alternative approaches. Accordingly, this section provides an overview of methods designed to handle the evaluation of multiple criteria (e.g., multiple impact categories) for multiple alternatives. These methods are commonly referred to as multi-criteria decision analysis (MCDA) (Cohon, 2003). The application of MCDA approaches has grown dramatically in the last twenty years, particularly in the environmental arena and has been used to support decisions in multiple areas including waste management, energy, sustainable engineering and manufacturing, natural resources, energy, product comparisons, policy decisions and remediation (Huang et al 2011). Hence, MCDA may provide a sound framework for assessing nanomaterials and products.

MCDA methods typically synthesize the criteria and select alternatives based upon techniques such as: ranking options, identifying a single optimal alternative, incomplete ranking, or differentiating between acceptable and unacceptable alternatives (Kiker et al., 2005). The primary MCDA approaches are: Multiple attribute decision analysis (MADA) and Multiple Objective Optimization (MOO). While, MADA is applied when the decision relates to evaluating a finite set of alternatives, MOO is an operations research approach and is often implemented when the possible solution set is infinite and/or contains continuous variables. Examples of these approaches may be found in Seppala (Seppala, 1999) and Azapagic and Clift (Azapagic and Clift, 1998). Since, the framework will involve the assessment of a finite number of alternatives, we will focus on MADA approaches. Further descriptions of these methods may be found in Stewart (Stewart, 1992), Chen and Hwang (Chen et al., 1992), Norris and Marshall (Norris and Marshall, 1995) and Guitoni and Martel (Guitoni and Martel, 1998).

Some of the most relevant MADA approaches are summarized Table 4-3 and include outranking, multi-attribute utility theory (MAUT) and analytical hierarchy process (AHP). These approaches not only aid in selecting an alternative, but all of them except outranking can be used to evaluate impacts. However, all of the methods are at least partially compensatory which indicates that low scores in one criterion can be compensated for by high scores in another. When performing a sustainability assessment, it is important to note that in order for a product to be sustainable, it must meet the established criteria within each of the three sustainability pillars – environment, economy, and society. Accordingly, some would argue that while components of sustainability are integrated, benefits in one aspect of sustainability do not compensate for detriments in another. Hence, care must be taken when using compensatory approaches. A list of some of the commercially available decision support tools is provided by Azapagic and Perdan (Azapagic and Perdan, 2005) and Kiker et al. (Kiker et al., 2005). Linkov et al. (Linkov et al., 2006; Linkov et al., 2004) provide an extensive record of studies that applied MCDA and decision support tools in environmental decision making.

Table 4-3. Summary of Common Multi-Criteria Decision Analysis (MCDA) Methods

Method	Description	Pros	Cons	Reference	Approaches
Elementary	Non compensatory method with no requirement for quantitatively evaluating criteria trade-offs; Ranking may be based upon: the strength of the weakest or strongest link, attributes meeting predetermined thresholds, or best performance on attributes with t	No weighting is required	Requires attributes to be on a common scale;	(Seppala et al., 2002; Yoon and Hwang, 1995)	Maximin, Maximax, Conjunctive, Disjunctive and lexicographic
Multi-Attribute Utility Theory (MAUT)	Compensatory method in which the overall score for each alternative is based on relative weights; Weights typically determined by surveying stakeholders and generated by utility functions	(1) Easier to compare alternatives whose overall scores are expressed as single numbers. (2) Choice of an alternative can be transparent if highest scoring alternative is chosen. (3) Theoretically sound — based on utilitarian philosophy (4) Many people p refer to express net utility in non-monetary terms.	(1) Maximization of utility may not be important to decision makers. (2) Criteria weights obtained through less rigorous stakeholder surveys may not accurately reflect stakeholders' true preferences. (3) Rigorous stakeholder preference elicitations are expensive.	(Baker et al., 2001; Clemen, 1996; Wolfslehner, 2008)	Multi-value utility theory (MAUT), Simple Multi-Attribute Rating Technique (SMART)
Outranking	Partially compensatory methods that determines the extent to which one alternative dominates another. It allows options to be classified as "incomparable"	(1) Does not require the reduction of all criteria to a single unit. (2) Explicit consideration of possibility that very poor performance on a single criterion may eliminate an alternative from consideration, even if that criterion's performance is compensated for by very good performance on other criteria performance (3) It is easy to explain.	The algorithms used in outranking are often relatively complex and are often not well understood by decision-makers.	(Kiker et al., 2005; Linkov et al., 2007; Naidu et al., 2008a; Seager and Linkov, 2008; Wolfslehner, 2008)	Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE), Elimination Et Choix Traduisant la Realite (ELECTRE) (Kangas et al. 2001) and Novel Approach to Imprecise Assessment and Decision Environments (NAIADE) software
Analytical Hierarchy Process (AHP)	Compensatory method in which the overall score for each alternative based on relative weights. Weights are generated by a series of pair-wise comparisons. . It is the most widely used approach of the MCDA methods.	Surveying pairwise comparisons is easy to implement	The weights obtained from pairwise comparison are strongly criticized for not reflecting people's true preferences	(Huang et al., 2011; Kiker et al., 2005; Linkov et al., 2007; Saaty, 1988; Seager and Linkov, 2008)	AHP

Additional details on applying MCDA approaches for assessment of nanomaterials can be obtained from literature (Canis et al., 2010; Linkov and Seager, 2011; Tervonen et al., 2009). Outranking and aggregated weighted approaches (e.g., multi-attribute utility theory and analytical hierarchy process) are discussed in the following sections.

4.3.1 Outranking

Outranking is the least compensatory of the methods presented and involves pair-wise comparison between alternatives (i.e., one criterion at a time) to determine the extent to which one alternative is preferred over the other. For example, outranking methods may select the product alternative that meets the minimum requirements and results in the greatest impact reductions for the greatest number of criteria. Outranking methods are most appropriate when the criteria are not easily aggregated, measurement scales vary over wide ranges, or units are incomparable (Kiker et al., 2005; Linkov et al., 2007; Seager and Linkov, 2008). Outranking methods include Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE), Elimination Et Choix Traduisant la Realite (ELECTRE) (Kangas et al., 2001) and Novel Approach to Imprecise Assessment and Decision Environments (NAIADE) software (Naidu et al., 2008b)). While outranking methods are easy to explain, they consist of complex algorithms that are often not well understood by decision makers.

Example – Outranking (Naidu 2008)

Sasikumar Naidu and other researchers from the University of Tennessee published a case study in 2008 that uses an outranking decision analysis method to select nanoparticle synthesis processes . Naidu, et al., evaluated the tradeoffs between three processes for silica nanoparticle synthesis: Sol-gel, a flame method involving tetraethylorthosilicate (TEOS) precursor and a flame method involving hexamethyldisiloxane (HMDSO) precursor. To facilitate the decision analysis, Naidu et al. (2008) used the Novel Approach to Imprecise Assessment and Decision Environments (NAIADE) software package. The analysis involves three steps: (a) pair wise comparison of alternatives, (b) aggregation of all comparison scores, and (c) ranking of alternatives.

a. Pair wise comparisons of alternatives

The outranking method begins by making pair-wise comparisons between alternatives, one criterion at a time. For a criterion j and a pair of alternatives i and i', the NAIADE software uses six membership functions to quantify the following comparisons:

- $\mu_{>>}(i,i')_j$ (i much better than i')
- $\mu_{>}(i,i')_j$ (i better than i')
- $\mu_{\approx}(i,i')_j$ (i approximately equal to i')
- $\mu_{=}(i,i')_j$ (i very equal to i')
- $\mu_{<}(i,i')_j$ (i worse than i')
- $\mu_{<<}(i,i')_j$ (i much worse than i')

These comparisons are scaled from 0 to 1, where 0 is not true at all, 1 is very true, and 0.5 is unclear.

Example - Outranking (continued)

b. Aggregation of comparison scores

The comparison scores for all criteria are aggregated into a single preference intensity index, $\mu_*(i,i')$:

$$\mu_*(i,i') = \frac{\sum_{j=1}^{m} \max\left(\mu_*(i,i')_j - \alpha, 0\right)}{\sum_{j=1}^{m} \left|\mu_*(i,i')_j - \alpha\right|}$$

Where * stand for >>, >, ≈, <, or <<, and α is the threshold value below which values are not considered . Determining the threshold (α) is important to the analysis and will likely involve input from experts who are familiar with the given criteria.

In addition to calculating the preference intensity index, the NAIADE software calculates the entropy of the intensity index, $C_*(i, i')$, which indicates the variance in the indices that are above the threshold and near 0.5 (maximum fuzziness) . An entropy value of 1 means that all criteria give an exact indication (definitely credible or not credible) and an entropy value of 0 means that all criteria give an indication biased by maximum fuziness ($\mu_*(i,i')$=0.5).

c. Ranking of alternatives

The intensity indices and associated entropies are combined to rank the alternatives. The final ranking is derived from two separate rankings, each one varying from 0 to 1. The first ranking, $\phi^+(i)$, indicates the extent to which *i* is better than all other alternatives, and the second ranking, $\phi^-(i)$, indicates the extent to which *i* is worse than all other alternatives:

$$\phi^+(i) = \frac{\sum_{n=1}^{N-1} \left(u_{>>}(i,n) \wedge C_{>>}(i,n) + u_{>}(i,n) \wedge C_{>}(i,n)\right)}{\sum_{n=1}^{N-1} C_{>>}(i,n) + \sum_{n=1}^{N-1} C_{>}(i,n)}$$

$$\phi^+(i) = \frac{\sum_{n=1}^{N-1} \left(u_{>>}(i,n) \wedge C_{>>}(i,n) + u_{>}(i,n) \wedge C_{>}(i,n)\right)}{\sum_{n=1}^{N-1} C_{>>}(i,n) + \sum_{n=1}^{N-1} C_{>}(i,n)}$$

4.3.2 Aggregating Weighted Impact Scores

As an alternative to outranking methods, the normalized and weighted impacts described previously may be aggregated. Some aggregation methods are multi-attribute utility analysis (MAUT) and analytical hierarchy process (AHP) and allow alternatives to be compared against each other on a single scale. These methods are essentially compensatory (Kiker et al., 2005; Linkov et al., 2007) (MAUT more so than AHP) and should be used with caution due to the non-compensatory nature of sustainability. Further, they can be used to elucidate stakeholder values and determine weights (Cohon, 2003).

While, both MAUT and AHP rely on stakeholder values to determine the weights, they differ in the way that they derive weights for the criteria. Weighting in MAUT relies on utility functions, while AHP utilizes pair-wise comparisons made by stakeholders. To elicit stakeholder values, the AHP method asks stakeholders to make pair-wise comparisons between different criteria, which are then translated into a weighting scheme via matrix algebra techniques. Stochastic Multiattribute Acceptability Analysis (SMAA) is another method for deriving weights from stakeholder values. Unlike MAUT and AHP, SMAA includes information about uncertainties in stakeholder values. As a result, SMAA can help to determine both a weighting scheme and the sensitivity of results to uncertainties in stakeholder values (Seager and Linkov, 2008). Analytic Network Process (ANP) is based on AHP, yet allows dependence between decision criteria. Once the weights are determined, they are then multiplied by normalized impact scores (see Box).

Aggregating Weighted Impact Scores for Nano Product X

In this example, an overall sustainability score is generated for three hypothetical synthetic processes by summing the normalized and weighted scores for all criteria (lower is better). While Synthetic process #2 scores lower than process #3 on economic considerations and process #1 on social considerations, it has the highest overall score. Note that these values are arbitrary, and for demonstration purposes only.

Selected Criteria	Synthetic Process #1	Synthetic Process #2	Synthetic Process #3
Environmental	**0.8**	**1.59**	**1.11**
Energy use	0.25	0.36	0.2
Greenhouse gas emissions	0.31	0.25	0.45
Potential aquatic toxicity	0.24	0.98	0.46
Economic	**0.53**	**1.03**	**1.11**
Consumer cost	0.35	0.46	0.53
Potential environmental liabilities	0.18	0.57	0.58
Social	**1.34**	**0.7**	**0.64**
Job loss	0.89	0.46	0.28
Worker harm	0.45	0.24	0.36
Overall	***2.67***	***3.32***	***2.86***

Figure 4-4 is a plot of the hypothetical weighting schemes constructed in Canis et al. (2010). As illustrated, the weighting systems are quite subjective and vary greatly based upon values and priorities. For example, note that while costs are the primary concern for the manufacturer with minor consideration of health risks, the environmentalist does not consider cost and assigned equal weightings to health risks, energy consumption and material efficiency. When these weights were applied in the MCDA, the order of the preferred options changed along with the reasons for the desirability of the alternative. Consequently, ranking of the alternatives is somewhat different for each scheme. The “Manufacturer”, “End User” and “Regulator” all preferred (ranked 1st) HIPCO, while the “Environmentalist” had a slightly higher preference for the Laser alternative. The rank of the remaining alternatives varied greatly (Canis et al., 2010). This exercise not only demonstrates the method but also highlights the fact that different weighing schemes may result in quite different decisions. Accordingly, care must be taken when evaluating alternatives and additional approaches (e.g., probabilistic method and/or sensitivity analysis) may be needed to compensate for stakeholder uncertainty.

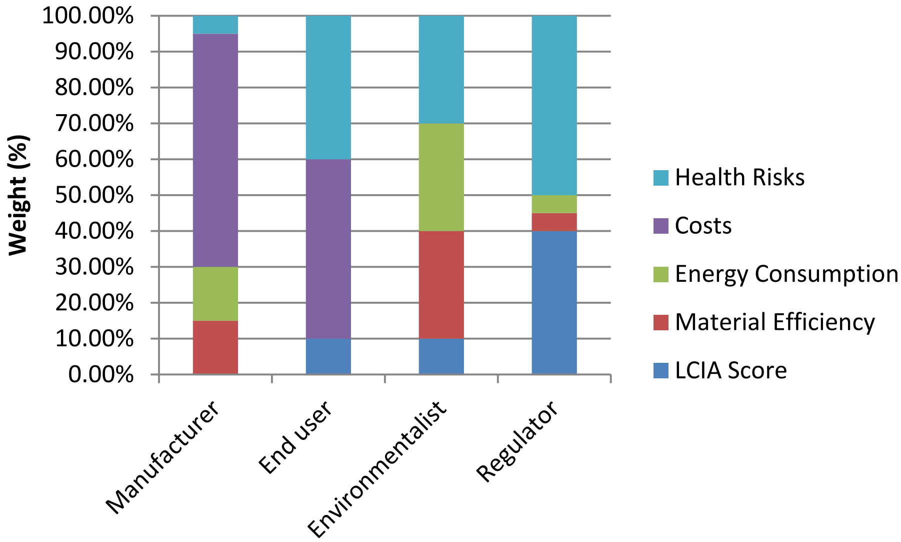

Figure 4-4. Comparison of Single Walled Carbon Nanotubes (SWCNT) Criteria Weightings (adapted from Canis et al. 2010)

4.4 Uncertainty Analysis

As described in Section 3, there is a great deal of uncertainty involved in the assessment of nanoproducts to include inherent uncertainty related to data quality and availability, costs and impacts. While some uncertainties are nearly impossible to estimate (e.g., level of market penetration), experts may be queried to get a qualitative sense of this variability (Seppala et al., 2002). In an attempt to capture uncertainty, researchers involved in the SWCNT assessment developed probabilistic estimations of the performance indicators (Canis et al., 2010). Data were primarily gathered from literature surveys and used to develop triangular distributions for the parameters. As in the case study, uncertainty is traditionally modeled by assigning probabilities through expert testimony, theoretical modeling, fitting empirical data and/or simulation (Clemen and Reilly, 2001; Keeney and Raiffa, 1976). While some level of uncertainty is present in any assessment, it is of particular importance for new and emerging technologies due to the many unknowns related to such issues as service level to the customer, upstream resource use, limited exposure data, market penetration, cost data, systematic impacts on other economic sectors, etc. As noted in Section 3, due to the multiple layers of uncertainty related to nanotechnology, traditional approaches may be insufficient (Seager and Linkov, 2008). Hence, sensitivity and/or scenario analysis may be more appropriate. Monte-carlo simulation is an approach not only for investigating the impact of uncertainty, but also exploring various management scenarios. This simulation approach is based upon altering variable values by selecting characteristic distributions and computing results to determine the impact of changes in underlying variables. Although sensitivity analysis provides insight on the impact of uncertainty, the range of possible outcomes and aids in determining and implementing management decisions, much work is needed on optimizing these methods (Basson, 1999).

4.5 Sensitivity Analysis and Scenario Analysis

Sensitivity analysis is a method of determining the effect changes in controllable variables have on output response variables. In the context of DA, the aim of sensitivity analysis is to identify the input variables and values that may alter preferences for different alternatives. Accordingly, it is crucial that the sources and types of uncertainties are identified and distinguished. While probabilities may be defined to characterize some variables, others may require the use of random sampling simulation and scenario analysis to get a sense of the range of uncertainty in the results. Using this approach, the impact of uncertainty in the variable on the viability of a particular alternative may be explored by varying key controllable variables.

Scenario Analysis is the strategic process of evaluating alternatives by considering possible future activities and can be used to assess what will happen (predictive), can happen (explorative) or how a specified target may be reached (normative) (Börjeson et al., 2006; Höjer et al., 2008). This technique enhances decision making by affording the ability to assess the performance and impact of alternatives given potential events and outcomes. For example, alternatives may be evaluated based upon various levels of market penetration, resource availability, production capacity or changing environmental regulation. Scenario analysis is used effectively in a number of arenas to include military intelligence, as well as finance to explore changes in the economy under several growth scenarios (e.g., rapid, decline or moderate). It is also used in long term planning and emphasizes the importance of systems thinking when developing and evaluating products, processes and systems. Because a system is typically comprised of many factors and subsequent interactions, scenario analysis may highlight outcomes that are counterintuitive, previously unknown or unexpected. The basic steps of scenario analysis include: determining which factors will be considered and the scenarios to be evaluated for each factor, estimating the outcomes and assigning the probabilities of various scenarios. Although estimating outcomes may involve adapting knowledge of existing systems, it typically entails some type of modeling or simulation activity. The resulting outcomes are compared for the alternatives across the scenarios. While scenario analysis is a valuable planning tool and is used to explore impacts as a result of what may happen, there are no assurances of what will happen; of course, this is true of any forecasting tool. Resources related forecasting and scenario analysis include, among others, Eriksson and Ritchey (Erikkson and Ritchey, 2002), Konsult and Nilsson (Konsult and Nilsson, 2005), Markham and Palocsay (Markham and Palocsay, 2006) , Eason et al (Eason et al., 2009), Hojer et al. (2008), and Borjeson et al. (2006).

4.6 Further Analysis

It is evident that the process of determining alternatives that satisfy the sustainability criteria will require an iterative approach. As such, there is no illusion that ideal options will be determined on first pass. Further, modifications due to technology enhancements, regulations, process alterations, changing supply horizon or energy security issues may demand the need to adjust viable options. Moreover, the results of the evaluation provide information on resources, stages or processes that may be candidates for redesign or replacement. However, making improvements with respect to one impact category of sustainability may adversely impact another category or pillar. For example, consider the case where a non-renewable feedstock or material is replaced with a renewable material that is processed in an upstream facility with a history of poor on-site worker safety. Although this substitution may improve the environmental sustainability of the product, it may have a negative impact on its social sustainability. Therefore, alternative approaches developed to mitigate impacts must be assessed according to the sustainability criteria and evaluated. While determining the impact of the substitution outlined above may require a full re-assessment, if replacing one material with the other does not affect other aspects of the product system, it may be appropriate to simply assess differences in impacts between the two materials.

Much like an adaptive management approach, developing more sustainable alternatives may occur several times over the course of a product's lifetime and the number of times this process is repeated depends on the need for and feasibility of developing alternatives. It is important to note that DA approaches are meant to facilitate decisions, not replace decision makers. As such, after conducting a decision analysis, it is advisable to discuss the results with stakeholders before selecting and implementing an approach.

5. Conclusions

By focusing on sustainability, product researchers, developers, and manufacturers can help ensure that as nanoproducts advance, they realize their potential benefits to society without jeopardizing the well-being of humans or the environment, in this generation and beyond. There are many unknowns surrounding nanotechnologies and nanoproducts, both in terms of performance and impacts on the environment, economy, and society. The preliminary framework presented in this guidance should aid in better organizing and understanding the known life-cycle impacts, as well as help product developers prioritize new research to better understand the unknowns. This document is intended to offer a *starting point* for assessing the sustainability of nanoproducts and provides a summary of existing methods for assessing various aspects of sustainability. Further, it highlights the critical elements needed for supporting sustainability based decision making. Feedback gathered from this report will be used for enhancement of the work, clarification of the approach and prioritization of future research. Moreover, given that the fields of nanotechnology and life cycle approaches are changing rapidly, this document will be reviewed and updated as additional information becomes available.

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Appendix: List of Additional Resources

Government Organizations

- EPA Life Cycle Assessment Research: http://www.epa.gov/nrmrl/lcaccess/
- ORD's Nanotechnology LCA website: http://epa.gov/nanoscience/quickfinder/lifecycle.htm
- EPA Lean Home: http://www.epa.gov/lean/
- ORD Sustainable Technologies: http://www.epa.gov/nrmrl/std/
- ORD's Nanotechnology website: http://epa.gov/nanoscience/
- EPA Sustainable Futures: http://www.epa.gov/oppt/sf/

Public-Private Partnerships

- Woodrow Wilson Center - Nano and LCA http://www.nanotechproject.org/file_download/files/NanoLCA_3.07.pdf
- PEN - The Project on Emerging Nanotechnologies (Woodrow Wilson Center) http://www.nanotechproject.org/publications/
- Life Cycle Initiative: http://jp1.estis.net/sites/lcinit/default.asp?site=lcinit
- CALCAS Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability http://www.calcasproject.net

Non-Profit and Professional Organizations

- International Society for Industrial Ecology: http://www.is4ie.org/
- AIChE Sustainable Engineering Forum: http://www.aiche.org/DivisionsForums/ViewAll/SEF.aspx
- SETAC site on LCA: http://www.setac.org/node/32
- American Center for Life Cycle Assessment: http://www.lcacenter.org/
- Athena Institute: http://www.athenasmi.org/index.html
- Global Reporting Initiative: http://www.globalreporting.org
- Ceres : http://www.ceres.org/
- Wuppertal Institute: http://www.wupperinst.org/en

Industry Organization

- Center for Environmental Assessment of Products and Materials http://www.cpm.chalmers.se/links.htm
- Nanotechnologies Industry Association: http://www.nanotechia.org/

Academic Institutions

- The Center for Environmental Implications of Nanotechnology (CEIN) http://cein.cnsi.ucla.edu/pages/
- Carnegie Mellon Green Design publications http://www.ce.cmu.edu/GreenDesign/publications/index.html
- Ohio State Center for Resilience: http://resilience.eng.ohio-state.edu/CFR-site/tools.htm
- Arizona State Center for Nanotechnology in Society: http://cns.asu.edu/
- International Council on Nanotechnology: http://icon.rice.edu/

Magazines and Journals

- Nanowerk Magazine: http://www.nanowerk.com/
- Nanotechnology Now: http://www.nanotech-now.com/
- Nano Magazine: http://www.nanomagazine.co.uk/