Environmental and Economic Assessment of Manufacturing Carbon Nanotube Products

L. J. Dahlben and J. A. Isaacs
Department of Mechanical and Industrial Engineering
Northeastern University, Boston, MA, USA
ldahlben@coe.neu.edu

ABSTRACT

Carbon nanotubes (CNT) have significant potential to enhance the microelectronics industry. However, prior to full-scale manufacturing of CNT products, the environmental and economic impacts of such an implementation must be assessed. Using life cycle assessment (LCA) techniques, environmental attributes are assessed for fabricating CNT transistors and CNT-polymer composites used for electromagnetic interference (EMI) shielding. Manufacturing cost will also be determined for these using process-based technical cost modeling. Such information on both cost and environmental impacts will enable more responsible nanomanufacturing.

Keywords: Carbon nanotubes, CNT, LCA, environmental impact, industrial economics

1 INTRODUCTION

With nanotechnology moving from development to commercialization at a rapid rate, so too are calls for a more comprehensive understanding of the production costs and environmental impacts associated with various nanomanufacturing processes. The integration of carbon nanotubes (CNT) into applications such as transistors, sensors, interconnects, low-mass/high-strength structures, and EMI shielding is a promising venture. This is because CNTs have unique electronic semiconducting properties and high thermal conductivity, tensile strength, and elastic modulus. However, as with any new emerging technology, identifying its environmental impact and manufacturing costs is critical to its commercial success. To analyze the environmental footprint of nanomanufacturing processes involving CNTs, life cycle assessment (LCA) is utilized. In order to assess the economic impact of manufacturing CNT products, process-based cost modeling is applied.

The CNT product manufacturing processes under investigation are those of current research projects at the NSF-funded Nanoscale Science and Engineering Center for High-rate Nanomanufacturing (CHN) at Northeastern University. The CHN houses facilities for micro and nanofabrication, and includes the manufacturing and assembling of nanoparticles for various potential applications. The specific processes analyzed in this study are the fabrication of CNT transistors and CNT-polymer composites designed for electromagnetic interference (EMI) shielding, both of which are still in the developmental phase. Through examining the resource inputs, outputs, and associated costs of these promising processes in their early stages, interpretation, optimization and sensitivity analysis can be performed. In turn, more environmentally benign and economical process alternatives can be determined prior to full-scale manufacturing.

2 METHODOLOGIES

The methodology of this research consists of using LCA for environmental assessment and process-based technical cost modeling for economic assessment.

2.1 Life Cycle Assessment

LCA is a methodology that investigates the environmental impacts associated with a product's life cycle. LCA has 4 distinct phases: goal and scope, life cycle inventory, life cycle impact assessment, and interpretation [1]. The goal of LCA is to provide comparison of environmental footprints for processes and products. Life cycle inventory consists of collecting input data (i.e. raw materials, energy, and equipment used) and output data (i.e. emissions to land, water, and air), describing this data, and modeling the product system using functional unit processes. Impact assessment involves characterizing the environmental impacts, evaluating the contributions to each category, and weighting to determine relative importance. Interpretation includes analyzing the major environmental impacts of the product and performing sensitivity analysis. These 4 phases are illustrated in Figure 1. Using the LCA technique, a "cradle-to-grave" model of the product is developed.

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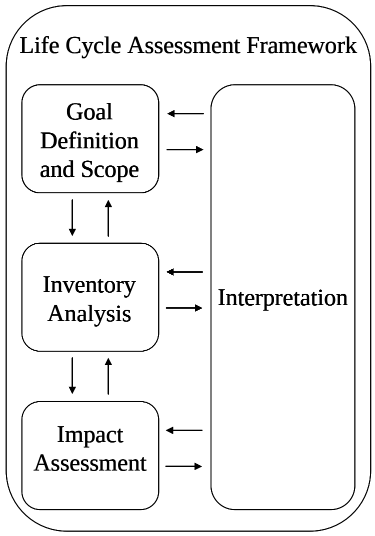

Figure 1: Phases of a life cycle assessment [1].

The impact analysis will be performed utilizing SimaPro software (although impact data for CNT is as yet unavailable), which is a tool that allows a first order prediction of the processes' environmental footprint. Using SimaPro with Eco-Indicator 1999 methods, emissions from each CNT product process will be categorized into areas such as impact on the ozone layer, minerals, and climate change. After the SimaPro results have been generated, improvement analysis will be enabled to minimize the environmental impacts while furthering other objectives.

2.2 Process-Based Technical Cost Modeling

Process-based technical cost modeling is a method of cost estimation in which the manufacturing costs are separated into fixed costs (i.e., main equipment, overhead labor, investment) and variable costs (i.e., raw material, direct labor, energy), which combine to form the total production cost for a device, as seen in Figure 2.

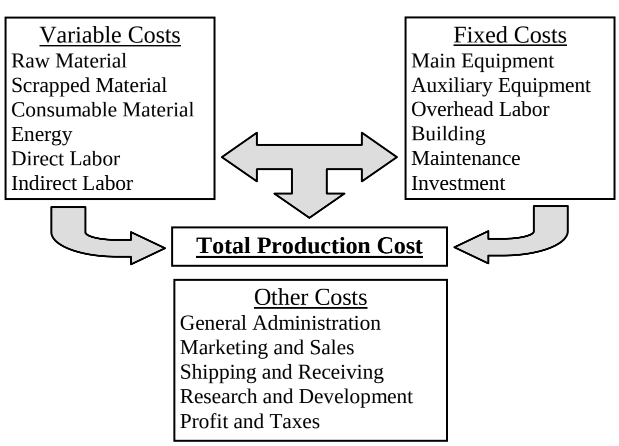

Figure 2: Costs included in process-based technical cost modeling.

The information from the life cycle inventory analysis taken from the manufacturing processes at CHN and other process assumptions will serve as the foundation for the models. These models will then be scaled-up to represent high-rate industrial manufacturing.

Results from the cost model are expected to provide critical insights for improving nanomanufacturing processes, and moreover, to track the inventories of materials, effluents and emissions generated in each process step. By understanding all of these costs and environmental aspects involved in developmental processes for CNT transistors and CNT-polymer composites, technology developers and researchers will be able to optimize their manufacturing conditions.

3 CARBON NANOTUBE PRODUCTS

3.1 Process Path for CNT Transistors

The integration of CNTs into the semiconductor industry is promising venture. Specifically, single-walled nanotubes (SWNT) can be used in the industry as inter-connects and active devices (transistors). An example of such a transistor can be seen in Figure 3, which shows how the SWNT bends to complete the circuit and remains in that position without the addition of more energy (this is referred to as being non-volatile). This transistor, which is presently under development at CHN, has significant potential to replace the current silicon-based switches because of the distinct properties and non-volatility of CNTs.

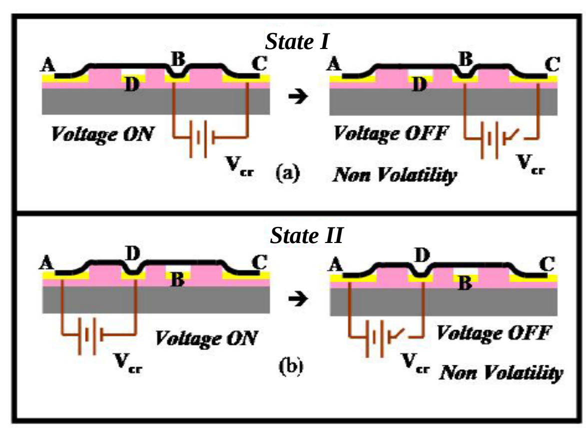

Figure 3: Schematic of SWNT switch in States I and II.

In order to assess the environmental impact of manufacturing this CNT product, the process steps, materials, and energy used need to be collected. This data is gathered at CHN, and the resulting CNT transistor manufacturing process steps are detailed in Figure 4 below. By understanding this process flow and its associated inputs and outputs, a comprehensive life cycle inventory can be collected and applied to the cost model.

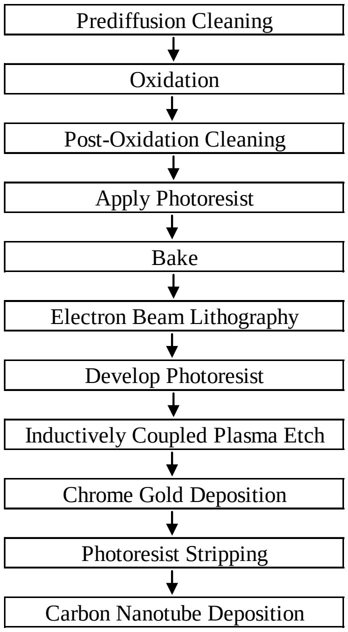

Figure 4: Process flow of synthesizing CNT transistor on silicon wafer substrate.

3.2 Process Path for CNT-Polymer Composites for EMI Shielding

Current nanoscale directed assembly processes under development at CHN have the potential to produce carbon nanotube wires and meshes. These can be used in EMI shielding to prevent obstruction of local electromagnetic fields in numerous devices. One method of fabricating this mesh at CHN is through the directed electrophoretic assembly of SWNTs. The process flow diagram for this process is illustrated in Figure 4 below.

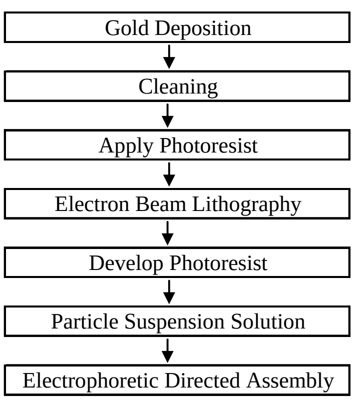

Figure 4: Process flow of directed electrophoretic assembly of SWNT [2].

Through collecting the materials and resources used for these process steps, life cycle inventory will be formulated.

4 EXPECTED RESULTS

This work is a continuation of previous and ongoing research involving the environmental and economic impacts of CNTs that have been in progress at CHN. Three SWNT processes were investigated [3] to assess the environmental attributes generated from production: Arc Ablation, Chemical Vapor Deposition (CVD), and High Pressure carbon monoxide (HiPco). The study provided a baseline for the environmental footprint of each process, which determined that HiPco is the most economically viable for bulk production of pure SWNTs and contributed the lowest environmental burden (Figures 5,6). The LCA and cost modeling techniques utilized in that study will be used in a similar manner for the assessment of manufacturing CNT transistors and CNT-polymer composite products.

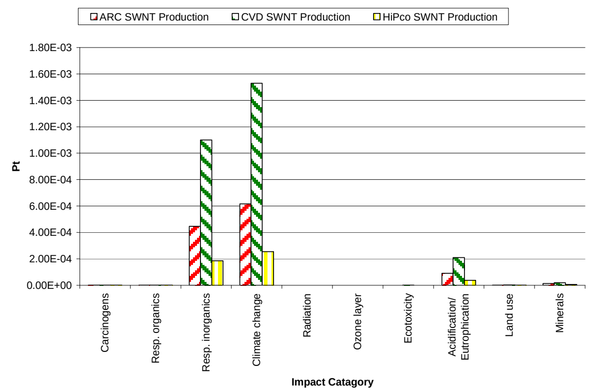

Figure 5: Arc, CVD, and HiPco base case production comparison using SimaPro and Eco-Indicator 99.

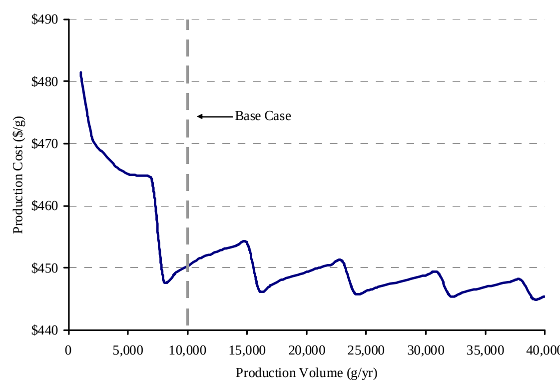

Figure 6: Production volume sensitivity for HiPco.

5 SUMMARY

While the processes of nanomanufacturing CNT transistors and CNT-polymer composites are still in the developmental stage, it is crucial formulate an understanding of their associated environmental footprints and costs. From their inventory data, process-based technical cost modeling, and impact and sensitivity analysis, detailed information on both cost and environmental impacts of manufacturing these CNT products will be achieved. In this manner, more responsible process alternatives can be determined prior to industrial manufacturing.

ACKNOWLEDGMENTS

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