AC 2009-77: A LABORATORY- AND PROJECT-BASED COURSE IN LEAN SIX SIGMA NANOMANUFACTURING

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Laboratory- and Project-Based Course in Lean Six Sigma Nanomanufacturing

Abstract

This paper describes the implementation of the Introduction to Nanotechnology course developed for undergraduate Applied Engineering Technology (AET) students at the Goodwin College of Drexel University and its expansion into a hands-on laboratory- and project-based course organized on Lean Six Sigma principles. The development of this course represents an innovative new approach for integrating Lean Six Sigma methods and principles and hands-on laboratory- and project-based learning in nanotechnology. This unique combination of learning, training, and assessment will contribute to the knowledge base of undergraduate STEM (Science, Technology, Engineering, and Mathematics) education, research, and practice. AET students will be exposed to exciting discoveries and applications in the emerging field of nanotechnology by working with leading faculty members through classroom instruction, guest lectures, laboratory procedures, and field trips. The developed material will become available to community colleges collaborating with Drexel University as well as middle and high schools through activities organized by the AET faculty.

Introduction

The development of a hands-on, project-based nanotechnology manufacturing laboratory course based on Six Sigma quality methods and Lean manufacturing principles is described in this paper. The course will consist of two parts. The first part will emphasize the foundations of nanotechnology. In the second part, nanotechnology applications and techniques will be studied through experiments that closely simulate industry-relevant processes or scenarios in a pilot-scale manufacturing processes laboratory. The laboratory work will be supported and supplemented with lectures and seminars on Lean Six Sigma. Experiments and projects will focus on two key areas: nanobiotechnology, such as nanoparticles for diagnostic imaging and therapeutics, and nanostructured energy conversion devices such as solar cells.

The objectives of the project are to:

1. Attract students with an interest in nanotechnology to applied engineering technology and engineering programs by developing a laboratory- and project-based course, which simulates commercial nanotechnology processes in biomedical and energy applications using an in-depth case study approach.
2. Prepare students for employment in the emerging nanotechnology field in areas such as process development; scale up and control; product specification development; and raw material and capital costing including ethical, environmental, and sustainability concerns. Special attention will be placed on a breadth of manufacturing activities with emphasis toward developing an engineering and engineering technology employee with a valuable range of skills and expertise to the employer.
3. Train the students in the methodology of Applied Lean Six Sigma to provide an overarching theory to the students' approach to problems and solutions in the workplace.

4. Foster a team approach in the laboratory process simulation to develop skills and learn the importance of corporate results-based progress rather than individual advancement, especially in emerging technology fields.
5. Develop the laboratory- and project-based simulation from several nanotechnology areas with future commercialization potential. Provide engineering technology and engineering students with nanotechnology toolsets designed specifically for the needs of industry including co-op cycles for Drexel students.

The outcomes of this project will provide a needed component of practical nanotechnology education for engineering technology students destined for employment in manufacturing industries. Industry is becoming reliant on the effective application of nanotechnology, and the demand for specialists in this emerging field is increasing, since nanoscale education, research, and manufacturing issues become driving forces in academia and industry. Students in the proposed course are expected to gain:

- Hands-on experience with nanostructures, devices, and processes
- Hands-on experience with characterization methods appropriate for nanomanufacturing
- Competency in Six Sigma quality methods, particularly their application to nanomanufacturing
- Understanding of Lean manufacturing concepts and their relevance to nanomanufacturing.

This course represents a new innovative approach for integrating Lean Six Sigma methods and principles and hands-on laboratory- and project-based learning in nanotechnology for applied engineering technology (AET) undergraduate students. The course will expose students to typical nanomanufacturing processes from several nanotechnology fields, and will include characterization and statistical control methods applied to nanomanufacturing pilot-scale processes organized and operated according to Lean Manufacturing principles. The course material will be made available to community colleges partnering with Drexel University and also to middle and high schools participating in activities organized by the AET faculty. Specifically, the hands-on nanotechnology course will be offered to the students of Burlington County College (BCC), Delaware County Community College (DCCC), Montgomery County Community College (MCCC), and Pennsylvania Institute of Technology (PIT), which have dual degree programs with Drexel's AET program. In addition, the developed course material will be adapted for presentations at the middle and high schools to provide an introduction to nanotechnology with the aim of stimulating an interest in STEM areas.

The need for a large number of practical engineers with background in advanced and emerging technologies over the next decade has been clearly outlined.[1,2,3,4] Engineering education is changing with its focus shifting from the traditional theory-based curriculum to more team-based learning, problem solving with open-ended solutions, hands-on projects, and team-oriented communications.[5,6,7] Addressing the need for skilled technology workers is a required competitive and survival strategy for most manufacturers.[4]

Four components of the development process will be addressed and tested in this project:

- **Creating Learning Materials and Teaching Strategies**. The project will revise and exchange existing educational materials and teaching strategies based on the prior results of the Introduction to Nanotechnology course.
- **Developing Faculty Expertise.** The project will provide professional development for faculty of the collaborating community colleges and middle and high school teachers by organizing workshops during each year of the project, so that new teaching materials and strategies will be widely implemented.
- **Implementing Educational Innovations.** The results from this project will demonstrate the challenges to and opportunities for adapting innovations in diverse educational settings, such as community colleges and middle and high schools, including dissemination of the developed material through the workshops, publications, conferences, and websites.
- **Assessing Student Achievement.** Special emphasis will placed on assessment of student learning. The project will apply new tools to conduct broad-based evaluation of the developed material through a Lean Six Sigma approach.

Course Overview

As nanotechnology moves from the research lab into the broader economy, a new generation of industrial engineers, manufacturing engineers, and applied engineering technologists must be educated and trained in the production and application of nanotechnology materials and devices. These degree-holders play a pre-eminent role in U.S. industry, providing the hands-on technical expertise needed to develop, operate, maintain, optimize, and trouble-shoot manufacturing processes in industries as diverse as microelectronics, automotive, aerospace, materials processing, biomedical, and energy conversion.[8,9]

There is already a significant amount of course, curricular, and laboratory development work occurring at U.S. universities and community colleges in an effort to introduce science, engineering, and technology students to nanotechnology concepts and applications. Also, there are currently programs to teach engineering technology students various nanoscale research tools, such as atomic force microscopy (AFM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and optical characterization, as used in R&D laboratories.[10] However, very little in the way of nanomanufacturing principles has been taught to the traditional cohort of students focused on manufacturing and industrial engineering and applied technology. Since there is no analogous dominant processing technology for nanotechnology, a broader and more flexible training is needed for nanomanufacturing including quality issues.[11,12]

The main thrust of modern quality engineering is to reduce process and product variability through statistical methods provided by Six Sigma programs. To date, there has been comparatively little activity in the application of classical statistical process control and Six Sigma quality methodologies to nanomanufacturing. Another major trend in manufacturing is the use of Lean principles, largely based on the Toyota Production System, to reduce waste and cut costs by eliminating non-value added steps in the manufacturing processes. Lean manufacturing was formulated for production in economic environments characterized by fragmented markets demanding many products in low volume, intense competitive pressure, fixed or falling prices, and rapidly changing technology.[13] Manufacturing engineers must be educated to work in environments with a large product mix and flexible production schedule. Waste reduction and materials utilization are closely allied to making manufacturing processes "green" and sustainable, which in view of the environmental and toxicity issues surrounding nanotechnology are certain to become paramount concerns to manufacturing and industrial engineers.

Nanomanufacturing as currently practiced has very low materials utilization efficiency and Lean structuring of nanomanufacturing processes could rectify this problem. It is clear that Lean Six Sigma (combining Lean manufacturing principles with Six Sigma quality control methods) manufacturing can address many of these crucial issues. Today's manufacturing, industrial, and applied engineering graduates have little classroom or laboratory experience with nanomaterials and nanomanufacturing processes, and in particular, there is generally no incorporation of Lean Six Sigma in current nanotechnology classes and laboratories.

Based on the course material, we seek to develop a workforce training program focused on Lean Six Sigma Manufacturing methodologies applied to nanotechnology materials and processes. The target audience for this program will include the workforce of industrial and manufacturing companies and AET students at Drexel University and collaborating community colleges. Course content will focus on applying Lean Six Sigma principles to the production of nanoproducts. The laboratory portion of the course will simulate production of a nanoproduct. The laboratory layout, operation, and analysis activities will be organized according to Lean principles. Students will apply Six Sigma statistical tools to processes for analysis, improvement, and control with the aim of replicating the application of Lean Six Sigma to commercial nanomanufacturing.

Lean Six Sigma

To achieve competitive, world-class quality products, manufacturers incorporate a rational, programmed system of process and product design, quality assurance and statistical process control methods broadly termed Six Sigma.[14,15] Six Sigma was originally developed in the 1980s by Motorola, Allied Signal, and GE for traditional manufacturing industries and subsequently adapted for service providers such as hospitals, banks, educational institutions, and government. For example, the U.S. Federal Government has instituted Six Sigma programs in many areas. Parallel to the development of Six Sigma, Toyota pioneered Lean manufacturing, including components such as Elimination of Waste, Just-in-Time Inventory and Production, Smart Automation, Rapid Set-Up, and Cellular Manufacturing.

In the last several years, manufacturing concerns have developed a "hybrid" Lean Six Sigma approach combining Six Sigma methodologies with Lean manufacturing principles.[16] Lean Six Sigma can be usefully applied to the following areas:

- Established manufacturing processes
- Development of new products and processes
- Laboratory settings[17]
- Educational institutions

The application of Six Sigma and Lean manufacturing to nanotechnology products presents new challenges and a need to rethink current manufacturing and engineering technology education. Traditional education for industrial engineering and technology students provides little or no exposure to nanotechnology materials and processes. Nanotechnology by nature makes setting specific quality metrics and applying statistical process control problematic. The developed course and the laboratory address these problems by emphasizing practical training to achieve economic and high quality production of nanotechnology products.

Course Structure

A 10-week (within the Drexel's quarter system) laboratory- and project-based course is under development. Seven weeks (21 hours) will be devoted to laboratory work and three weeks (9 hours) to lectures on the nano-process, Six Sigma topics, ethics and sustainability, and nano entrepreneurship. Guest lecturers are planned for the classroom sessions.

Students will replicate a pilot production process that turns a raw feedstock into a useful nanotechnology product, such as (1) nanoparticles for biomedical applications, and (2) a nanostructured solar cell. Each process step will be characterized, either by *in-situ*, real-time methods or by analysis of samples of intermediary or final product (Figure 1). These measurements will be used to generate data for Six Sigma analysis and statistical process control. We emphasize the production of a commercially useful product so that end-user quality issues and value-added features can be incorporated into the Six Sigma and Lean methodologies.

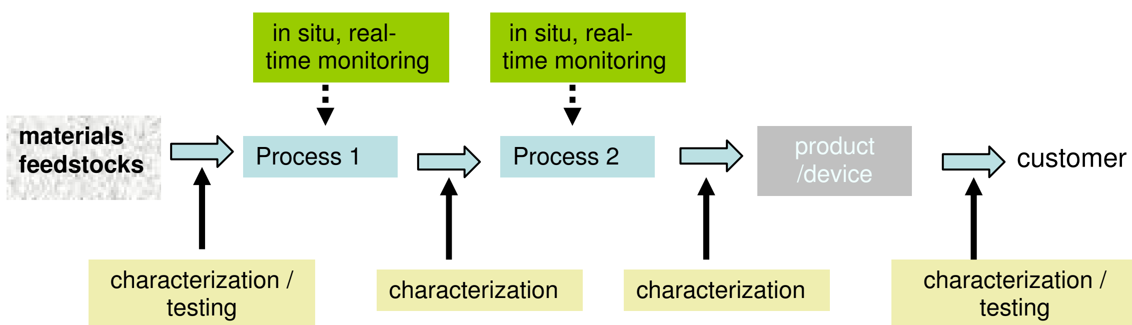

Figure 1. General outline of laboratory process flow used as case study in laboratory course.

Nanotechnology Laboratory Projects

The nanomanufacturing processes that will serve as case studies will fall into two broad areas:

1. Nanomaterials with biomedical applications in diagnostics and/or therapeutics.
2. Nanomaterials, structures, and devices with applications to energy conversion.

These applications are representative of two important areas in nanotechnology with different criteria for quality. For each of these areas, we will select a specific nanotechnology product, although it should be appreciated that the framework of the course can accommodate many different types of specific nanotechnologies. As an example of very basic experiments, the National Science Foundation-supported Interdisciplinary Education Group of Materials Research

Science and Engineering Center on Nanostructured Interfaces—University of Wisconsin, Madison, provides a wide range of experiments in kit form that can serve as the basis of numerous case studies for laboratory nanotechnology processes and products.[18] These include synthesis of aqueous ferrofluids, synthesis of nickel nanowires, titanium dioxide dye-sensitized solar cells, nano fuel cells, microcontact printing with thiols, organic LEDs, quantum dot nanoparticles, synthesis of nanocrystalline Y_2O_3:Eu phosphors, inverse opal photonic crystals, and Zeolite ZSMS catalysts for xylene isomerization to name a few. The purpose of the developed laboratory course is not to investigate specific nanostructures and nano-based processes per se, but instead to observe, characterize, and control the effects on a process that replicates or closely simulates nanomanufacturing. This innovative approach to nanomanufacturing education and training will allow for adaptation of this methodology by other universities and community colleges with their specific applications.

Nanotechnology Product with Biomedical Applications

Many biomedical applications of nanotechnologies use functionalized nanoparticles that enhance images of specific tissue types.[19] They can be selectively heated through tissue optically or magnetically.[20] There are five commonly used methods for making nanoparticles: sol-gel synthesis, inert gas condensation, mechanical alloying or high-energy ball milling, plasma synthesis, and electrodeposition. Aqueous sol-gel synthesis is suited to this teaching exercise since the manufacturing process can be easily sampled for testing/characterization along a temporal reaction coordinate, tracing particle growth to a desired end point. Simple tests, such as turbidity, can be correlated to actual particle size producing production datasets suitable for statistical analyses. The statistics can be derived from either multiple batch runs from several reactors or successive runs on a single batch reactor and used for exercises such as process definition or setting of manufacturing specifications via Six Sigma procedures.

The efficacy of clinical thermolysis can be crudely simulated by dispersing nanoparticles in an agarose matrix and observing the temperature and melting time under appropriate illumination or time-varying magnetic fields. The procedures for this laboratory will be carried out during a three-week period.

NanoStructured Device for Energy Conversion

Nano solar cells present an excellent case study for manufacture of a nanostructured energy conversion device.[21,22,23,24] Figure 2 shows several views of a titanium dioxide, dye-sensitized solar cell. A simplified method for fabricating such cells will be utilized during the laboratory sessions.[23] The tin oxide coating will be measured with a four-point probe and characterized by reflectance measurements, AFM, and/or SEM. The dye coating will be monitored by uniformity of color change.

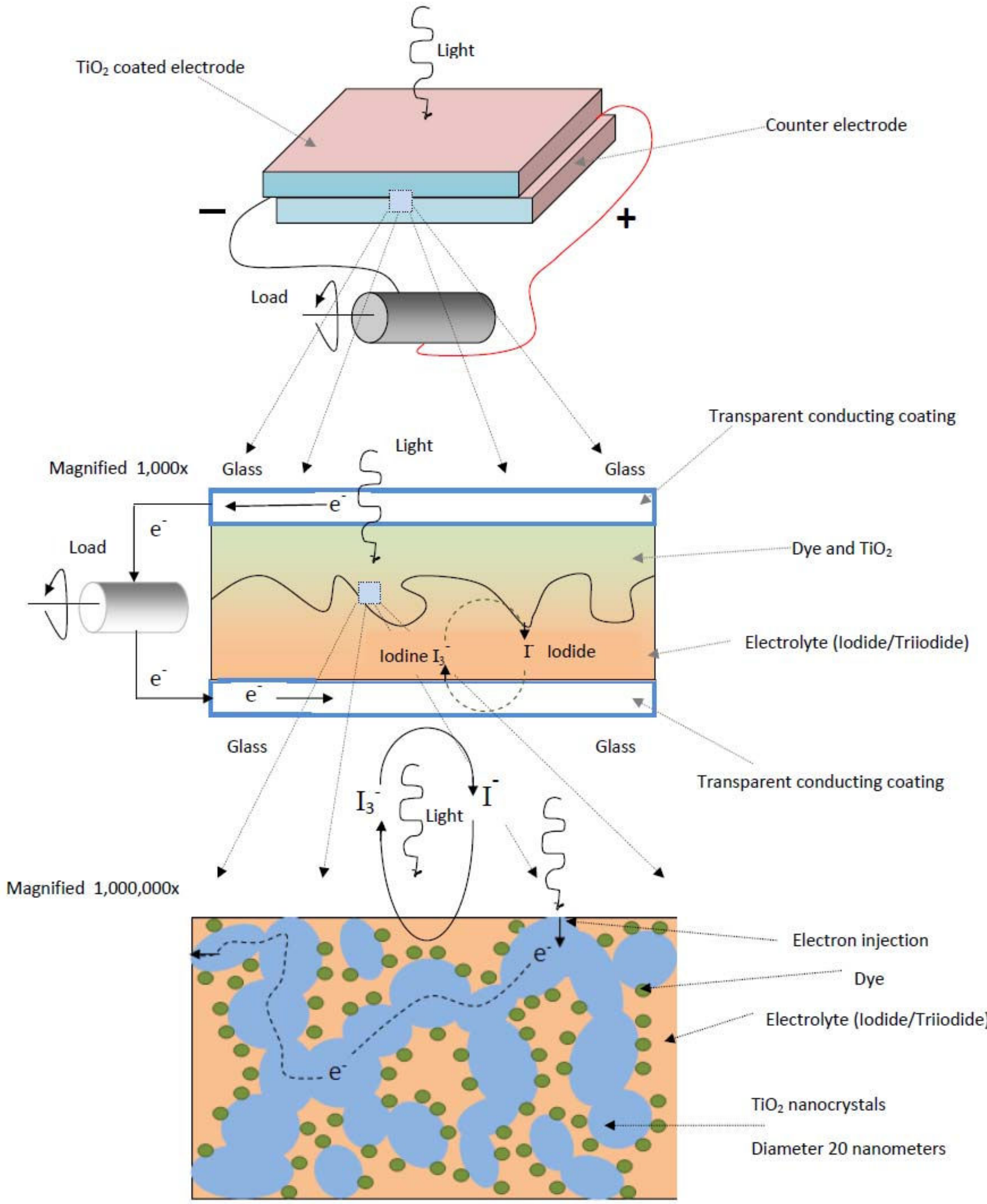

Figure 2. Nanostructured dye-sensitized TiO_2 solar cell.
Adapted from Greg P. Smestad. Education and solar conversion.[23]

The production and characterization of such a nanostructured solar cell provides various points for process characterization that can be correlated with value-added features of a final product (e.g., efficiency). Furthermore, all of these measurements are amenable to Six Sigma statistical analysis. Students will thus appreciate the impact of processing parameters and their variability on product performance and quality, and the utility of Six Sigma methods in controlling processes and optimizing value-added features. The nanosolar cell and its production use important nanostructural elements and nanocharacterization techniques that will be studied in depth in the laboratory over a four-week period. Nanocharacterization techniques will be coupled with manufacturing control to improve performance and quality.[25] Nanosolar cell products can be characterized by electrical measurements (open-circuit voltage, short-circuit current, series resistance, diode factor, shunt resistance), light-to-electrical conversion efficiency, spectral response, temperature stability, and uniformity of appearance. Characterization of the material's physical properties, such as the particle size, size distribution, molecular weight, density, surface area, porosity, hydrophilicity, surface charge density, purity, sterility, surface chemistry, and stability will be included in the laboratory procedures. These value-added attributes represent excellent metrics for Lean Six Sigma manufacturing.

Six Sigma Quality Assurance and Statistical Process Control

Process analysis and optimization will be implemented through a Six Sigma "tool box" of methodologies that are applied in five stages: Define, Measure, Analyze, Improve, and Control (DMAIC). The Define stage will comprise Voice-of-the-Customer and Quality Function Deployment analysis wherein process variables that impact customer-valued features of the final product are prioritized. For example, for a solar cell it is likely most users will value cost, efficiency, reliability, low toxicity, and aesthetic features. These characteristics will be correlated to process parameters that are optimized in the Six Sigma process to maximize added value for the customer. Other activities in the Define stage include Value Stream Mapping, High Level Process Map, Non-value added and stakeholder analysis, and a multigenerational plan. The Measure stage includes a data collection plan, measurement systems analysis such as determining gage repeatability and reproducibility (GR&R), control charts, statistical sampling of the process, calculations of process capability and process cycle efficiency, and process sizing. The Analysis stage comprises constraint identification, hypothesis testing, regression analysis, time trap analysis, failure mode and effects analysis, and Analytical Batch Sizing. The Improve stage includes benchmarking, line balancing, process flow improvement, set-up time reduction, piloting and simulation, and Poke-Yoke (mistake-proofing). The Control stage uses control charts, visual process control, and formulating a Plan-Do-Check-Act cycle. The described statistical analysis methods will be implemented with easy-to-use commercial software packages such as MiniTAB.

Lean Manufacturing Aspects

Laboratory activities will be organized and run on Lean Manufacturing principles, by which students can understand and appreciate Lean methods for nanomanufacturing. Production of nanoproducts will be organized into cells. Sample flow, work-in-process (WIP) analysis, and value-stream maps will be constructed following Lean principles. The laboratory will use the following visual indicators:

- areas with clearly marked bins for samples that need processing and characterization
- level loading where samples are characterized as they become available (rather than treated in batches)

- mistake proofing, such as limiting the tools available at a work station to only those needed for the task at hand
- rapid set-up and change of work station equipment

The details of the appropriate level of incorporation of Lean manufacturing principles will be worked out by the AET industrial advisory committee and implemented in the developed course.

Assessment and Evaluation

Evaluation of the developed material and data collection will begin during the first class session of the new course. Students will be administered a pre-test, which assesses the entering knowledge requirements for the course. For example, their knowledge of appropriate physics and chemistry will be evaluated. Based on the results of the test, students will be divided by groups according to the think-share-report-learn (TSRL) process, which will involve student peer coaching to help each other during the laboratory procedures.[25]

An independent evaluator from the *Evaluation & Research Network at Drexel University* will manage the implementation of an integrated collection of formative and summative assessment strategies for the laboratory-based course in Lean Six Sigma namomanufacturing.

The formative evaluation will provide evidence of the strengths and weaknesses of the project, informing the instructor of what works and what does not in order to implement necessary changes. Document analysis will interpret the quality and usefulness of materials produced in project delivery, while surveys will reveal attitudes and levels of understanding among participants—students and the AET faculty. Knowledge outcomes and skill development in the form of instructional materials and strategies, as well as applied knowledge products will be evidenced in the form of content generated in the course. Data and statistical analysis generated by students in analyzing the nanomanufacturing processes will be used by instructors in assessing the progress of the students in learning the course content. Thus, through each phase of the course, a statistical database is developed and augmented about processes and products. The preliminary and intermediate analyses made by the students also will provide numerous metrics to the instructors, which can be used to monitor the competency and understanding of the students' use and application of Lean Six Sigma techniques.

A summative evaluation will assess the quality and impact of an implemented project based on the students' final presentations, including corrections of the collected results and conclusions. Standard course evaluation forms will ask students to compare their level of competence in areas identified in the course objectives at the end of the course to their level before taking the course. This provides immediate feedback on the success of the course in meeting its objectives. Industrial evaluators will be involved in both formative and summative evaluations. The Industrial Advisory Committee will make necessary recommendations regarding course procedures and reports.

Summary

The quarter-based three-credit course "Introduction to Nanotechnology" was offered to AET students of Drexel University since 2004. After completion of this course, students demonstrate an understanding of scientific notation, concepts of chemistry, biology and physics and their relevance to nanotechnology, and key nanotechnology concepts such as bottom-up, self assembly, molecular recognition and size relationships between nanometers and other metric measures. Students are able to explain the operation of the instrumental tools used to measure and make nanostructures, as well as the relationship of nanotechnology with other state-of-the-art technologies.

Based on our experience, students' course evaluations, and recommendations of the members of AET Industrial Committee, it was proposed the development of the new hands-on laboratory- and project-based course organized on Lean Six Sigma principles. The development of this course represents an innovative new approach for integrating Lean Six Sigma methods and principles with hands-on laboratory- and project-based learning in nanotechnology. The course is under development and will be offered during the next academic year. The emphasis will be placed on two important areas of nanotechnology with different criteria for quality: nanomaterials with biomedical applications, such as quantum dotes used as reporters for clinical diagnostics, and nanomaterials, structures, and devices with applications to energy conversion, such as photovoltaic solar cells. For each of these areas, we will select a specific nanotechnology product that would be developed and studied during laboratory sessions.

References

1. http://www.aaas.org/publications/annual_report/2006/aaas_anualreport06.pdf. Accessed March 25 2008.
2. Workforce 2000: An Annual Report on Greater Philadelphia's Labor Market.
3. Workforce 2002: Measuring what matters. The Reinvestment Fund. October 2002.
4. Pennsylvania Economy League's Report, *Building a World-Class Technical Workforce.* Report #686.
5. The Greater Expectations. National Panel Report. http://www.greaterexpectations.org. Accessed February 8, 2008.
6. V. Genis, W. Rosen, R. Chiou, W. Danley. Capstone Courses for Engineering Technology Students. Proceedings of the ASEE Annual Conference, pp. 1-11, 2008.
7. R.M Felder and R. Brent. The Intellectual development of Science and Engineering students. Part 2: Teaching to Promote Growth. Journal of Engineering Education, Vol. 93, No. 4, 279, 2004.
8. D. Tolfree. Commercializing Nanotechnology. Concepts–products–markets. Int. J. Nanomanufacturing, Vol. 1, No. 1, pp. 117-133, 2006.
9. S. Fonash *et al.* Nanotechnology Education: The Pennsylvania Approach. MRS Symposia, Vol. 931, Section E, 2006.
10. A. K. Lyton-Jean, H. S. Han, and C. A. Mirkin. Microarray Detection of Duplex and Triplex DNA Binders with DNA-Midified Gold Nanoparticles. Analytical Chem., Vol. 79, pp. 6037-6041, 2007.
11. J. S. Lee, S. I. Stoeva, C. A. Mirkin. DNA-Induced Size-Selective Separation of Mixtures of Gold Nanoparticles. J. Am. Chem. Soc., Vol. 128, pp. 8899-8903, 2006.
12. J.R. von Ehr, "Zyvex Corporation: Providing Nanotechnology Solutions-Today" in D. Tolfree and M.J. Jackson. Commercializing Nanotechnology. (CRC Press, New York, 2008) p. 167.
13. F.W. Breyfogle. Implementing Six Sigma. Ch. 1 (Wiley, New York, 2003) pp. 3-51.
14. P.S. Pande, R.P. Neuman, and R.R. Cavanagh. The Six Sigma Way Team Fieldbook. Ch. 1 (McGraw-Hill, New York, 2002) pp.23-31.
15. P. Dennis. Lean Production Simplified. Ch. 1 (Productivity Press, New York,

2002) pp.13-25.
16. I. Odeh. Application of Lean Principles to Testing Laboratories—Only Value Added Work Allowed. American Biotechnology Laboratory, Vol. 26, No. 1, p. 20, 2008.
17. http://www.mrsec.wisc.edu/Research/IRG3.php. Accessed April 7, 2008.
18. H. Chen, R. C. MacDonald, S. Li, N. L. Krett, S. T. Rosen, and T. V. O'Halloran. Nanoparticle- Arsenic Combination Makes for More Potent Anticancer Agent. J. Am. Chem. Soc., Vol. 128, No. 41, pp. 13348-13349, 2006.
19. Korneva, G., Ye, H., Gogotsi, Y., Halverson, D., Friedman, G., Bradley, J.-C. & Kornev, K. G. Carbon nanotubes loaded with magnetic particles. Nano Letters, Vol. 5, pp. 879-884, 2005.
20. http://www.sciencedaily.com/releases/2008/04/080410140451.htm. Accessed March 8, 2008.
21. http://www.sciencedaily.com/articles/s/solar_cell.htm. Accessed March 8, 2008.
22. G.P. Smestad, M. Grätzel. Demonstrating Electron Transfer and Nanotechnology: A Natural Dye-Sensitized Nanocrystalline Energy Converter. J. Chem. Educ., Vol. 75, p. 752-757, 1998.
23. G.P. Smestad. Education and Solar Conversion: Demonstrating Electron Transfer. Solar Energy Materials, Vol. 55, pp. 157-178, 1998.
24. S.J. Oldenberg, R.D. Averitt, S.L. Westcott and N.J. Halas. Nanoengineering of Optical Resonances. Chemical Physics Letters, Vol. 288, pp. 243-247, 1998.
25. J. F. Westat. The 2002 User Friendly Handbook for Project Evaluation (NSF 02-057). (The National Science Foundation, Arlington, VA, January 2000).