Applying Systems Engineering Methodologies to the Micro and Nanoscale Realm

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ABSTRACT

Micro scale and nano scale technology developments have the potential to revolutionize smart and small systems. The application of systems engineering methodologies that integrate standalone, small-scale technologies and interface them with macro technologies to build useful systems is critical to realizing the potential of these technologies. This paper covers the expanding knowledge base on systems engineering principles for micro and nano technology integration starting with a discussion of the drivers for applying a systems approach. Technology development on the micro and nano scale has transition from laboratory curiosity to the realization of products in the health, automotive, aerospace, communication, and numerous other arenas. This paper focuses on the maturity (or lack thereof) of the field of nanosystems which is emerging in a third generation having transitioned from completing active structures to creating systems. The emphasis of applying a systems approach focuses on successful technology development based on the lack of maturity of current nano scale systems. Therefore the discussion includes details relating to enabling roles such as product systems engineering and technology development. Classical roles such as acquisition systems engineering are not covered. The results are also targeted towards small-scale technology developers who need to take into account systems engineering processes such as requirements definition, verification, and validation interface management and risk management in the concept phase of technology development to maximize the likelihood of success, cost effective micro and nano technology to increase the capability of emerging deployed systems and long-term growth and profits.

Keywords: systems engineering, nanotechnologies, life cycle, third generation nanosystems, product systems engineering

1. NEED FOR SYSTEMS ENGINEERING FORMALISM

Applying systems engineering principles to the realm of micro and nano scale technology (MNT) development has been recognized as key to solving the challenge of increasing the success of MNTs transition from the laboratory to operational systems. In 2008 Yves LaCerte of Rockwell Collins addressed the International Council on Systems Engineering (INCOSE) regarding systems engineering for complex systems. In his presentation, he highlighted the key role that systems engineering will play in developing micro and nano systems by stating:

"Systems engineering will become a key enabler for the successful commercialization of multi-functional, micro and nano technologies. Systems engineering delivers methodologies, processes, and tools to enable the efficient integration and exploitation of these disruptive technologies."

K. Eric Drexler responding to Richard E. Smalley in a now famous debate in Chemical and Engineering News[1] wrote:

"… to visualize how a nanofactory system works, it helps to consider a conventional factory system. The technical questions you raise reach beyond chemistry to ***systems engineering****. Problems of control, transport, error rates, and component failure have answers involving computers, conveyors, noise margins, and failure-tolerant redundancy."* The traditional text book approach for systems engineering is a top-down hierarchical approach of reductionism and discovery which is used to understand the system. In his Appendix to the Rogers Commission Report on the Space Shuttle Challenger Accident, Richard Feynman pointed out that NASA's over reliance on the top down systems engineering approach to design the Space Shuttle's main engine resulted in the inability of NASA to assess accurately the reliability of the engine. He also writes that another disadvantage of the top-down method is that, if an understanding of a fault is obtained, a simple fix may be impossible to implement without a redesign of the entire system. Fortunately,

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systems engineering is agile enough to adapt to bottoms up or “coming into the middle” approach. Such is the case for space systems, where an instrument is designed first, and the spacecraft and mission are designed around it, or when a spacecraft is specified, and the other parts of the system have to modify their approach.[2]

In the case of nano technology, development which is often guided by bottom-up self-organization of molecules and super molecules, the less traditional bottom up approach is more useful in synthesizing nano scale technologies to determine technical feasibility and to drive out system enabling capability. In the realm of chemical engineering and nanotechnology, this bottom up approach is often described as design synthesis. On the other hand, too much bottom-up engineering can lead to missed requirements and integration problems as noted by Graham Stoney.[3] While requirements flow down the system hierarchy, the balancing force is feasibility which flows back up to ensure that higher level design decisions don't result in downstream requirements which are excessively difficult or impossible to meet. He states that “good engineering has a balance between top-down and bottom-up design, but there should generally be a bias towards top-down because the ultimate goal is to meet the system requirements which flow in at the top level.”

To be fully successful, development efforts for MNT based systems must be system-centric, particularly in the concept development and feasibility phases where critical decisions must be made about interfaces in the multi scale system. In considering system integration on multiple scales, the systems engineer must address issues such as, correlation between different scales, coupling between time and space dependencies, and identification of dominate mechanisms.

2. CHARACTERISTICS OF SYSTEMS ENABLED BY MICRO AND NANO TECHNOLOGIES

Future product generations will be integrated systems enabled by micro and nano scale technologies. They will be systems of increasing complexity which use the convergence of a whole range of technologies for the improvement of the characteristics of the overall system. Features of future systems are:

- Increasingly complex, involving quantum mechanics, quantum chemistry, solid state physics, materials science, and chemistry principles, especially when considering micro and nano scaling;
- Highly integrated systems of increasing complexity which use a range of technologies for the improvement of the overall system;
- Networked, energy-autonomous, miniaturized, and reliable for space, defense, medical, civil, and commercial applications;
- Operating within larger systems in which they are embedded;
- Interfacing with each other, with the larger system, the environment, and humans; and
- Ease of use and integration of mechanical, optical, biological functions.[4]

It is useful to consider Ottino’s criteria[5] to identify complex systems to understand how to approach the application of systems engineering principles to developing micro and nano scale technologies and systems with embedded micro and nano technologies:

a) What they do - they display emergence and
b) How they may or may not be analyzed - classical systems engineering approaches of decomposing/analyzing subparts do not necessarily yield clues of their behavior as a whole.

Micro and nano scale technologies (MNT) are complex systems in and of themselves. In addition, adapting these technologies to the human and environmental landscape requires that they are embedded within larger systems. This further increases system complexity because the scale order between the macro and nano realm is very high (over 10^9). Integrating systems across macro scale to nano scale regime poses integration issues related to physical properties (e.g., physical, electronic, chemical) which do not scale as they would between differently-sized macro scale objects. For example, Van der Waals, surface tension, and frictional forces increase, and there are changes in fluid flow properties and melting point. The realization of systems based on micro and nano scale technologies is dependent on understanding their complexity, reproducibility, and ability to interface with the systems within which they operate. These challenges were well summarized by Alhoff, Lin, and Moore, “It is sometimes very easy to get caught up in what is scientifically possible and ignore the engineering problems that come with it.”[6]

3. MIGRATING FROM THE MACHINE AGE TO THE SYSTEMS AGE AND BEYOND

The concepts of Russell Ackhoff put forward in 1981[7] define the difference between the Machine Age and the Systems Age. Table 1 compares these two approaches. In general, these differences correlate well with the macro traditional systems engineering approaches versus the nano science based synthesis approach. Science and engineering has many foundational principles based on the concept of reductionism. Reductionism is defined as the analysis of complex things, data, etc, into less complex constituents or as any theory or method that holds that a complex idea, system, etc, can be completely understood in terms of its simpler parts or components.[8] This was based on Descartes in 1637 whose principles are stated as:

- Accept only that which is clear and distinct as true.
- Divide each difficulty into as many parts as possible.
- Start with the simplest elements and move by an orderly procedure to the more complex.
- Make complete enumerations and reviews to make certain that nothing was omitted.

This reductionist path has served the systems engineering community well.

In 1981 Russell Ackhoff promoted the concept that although the reductionist approach has served the "Machine Age system thinking" that there is a need to move into system age thinking. In applying systems engineering processes to the micro and nano realm we will take a Systems Age focuses on functionality or capability. In an idealized systems engineering process a set of defined requirements derived from customer agreements form the base inputs. This requirements driven approach has led to the use of deconstruction (decomposition, reductionist) techniques. In the function or capability approach the emphasis is on the synthesis or a constructionist approach. This synthesis approach is required considering both the complexity and uncertainty of these systems.

Table 1: Comparison of Machine Age Thinking and System Age Thinking

Machine Age Thinking	System Age Thinking	Machine Age Analysis	Systems Age Analysis
Procedure	Procedure	Analysis focuses on structure; it reveals how things work	Synthesis focuses on function; it reveals why things operate as they do
Decompose that which is to be explained	Identify a system containing the thing to be explained is part	Analysis yields knowledge	Synthesis yields understanding
Explain the behavior or properties of the constituent parts separately	Explain the behavior of the properties containing the whole	Analysis enables description	Synthesis enables explanation
Aggregate these explanations into an explanation of the whole (synthesis)	Then explain the behavior of the thing in terms of its roles and functions within the whole	Analysis looks into things	Synthesis looks out of things

4. ENGINEERING PERSPECTIVE: FOUR GENERATIONS OF NANOTECHNOLOGY APPLICATIONS

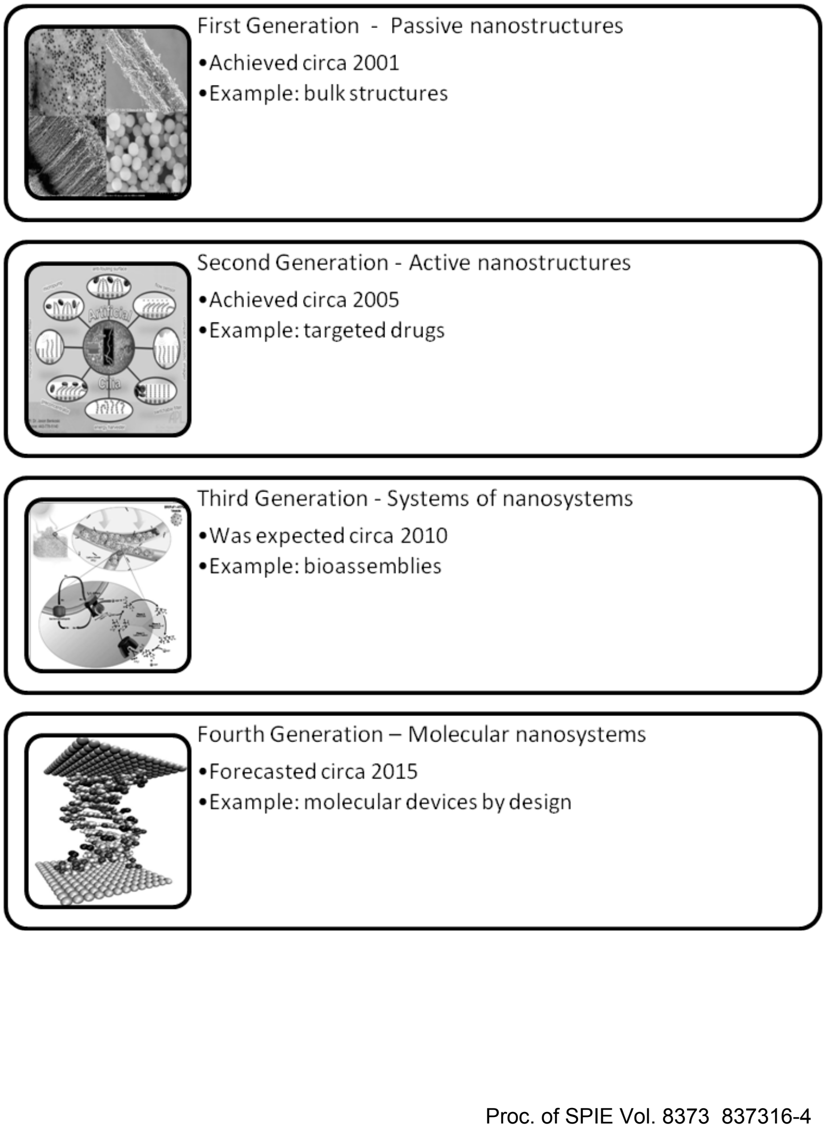
Micro and nano scale technologies (MNT) have been discussed in the context of systems engineering of multi scale systems. MNT covers the scales of 10^{-6} to 10^{-9} meters for those who want a linear reference point. There are several key assumptions that one will note in the material that have been gathered for this paper. The first is that we are dealing with multi-scale systems, with innate complexity. Our second assumption is that nanotechnologies demonstrated by the bottom up manufacturing techniques have less in common with macro and nano scale (top down) systems. This unique region is explored in terms of translating classical systems engineering into the nano realm. This is the final precept or assumption that the nano world of technologies is not mature and therefore we are emphasizing exploring systems engineering technologies in the research and development phases. The emerging field of nano technologies is just entering the third generation. It is interesting to note the lack of articles describing this third generation. The fourth generation is actually covered very well by futurists such as Kurzweil and Drexler. The first forays into the third generation of nanotechnology are being seen with "lab on a chip" technologies, such as bioassay, driven by the bio medical engineering world.

As noted in the introduction, commercial nanotechnology is not as mature as micro technology. Here the four generations of nanotechnology products as described by Roco[9] are discussed in more detail. The capabilities of nanotechnology for systematic control and manufacture at the nano scale are envisioned to evolve in four overlapping generations of new nanotechnology products with different areas of research and development focus. Each generation of products is marked by the creation of commercial prototypes with systematic control of the respective phenomena and manufacturing processing.

(a) **First Generation of products (2001-): passive nanostructures,** illustrated by nanostructure coatings, dispersion of nanoparticles, and bulk materials - nanostructure metals, polymers, and ceramics. The primary research focus is on nanostructured materials and tools for measurement and control of nanoscale processes. Examples are research on nanobiomaterials, nanomechanics, nanoparticle synthesis and processing, nanolayers and nanocoatings, various catalysts, nanomanufacturing of advanced materials, and interdisciplinary simulation and experimental tools.
(b) **Second Generation of products (2005 -): active nanostructures,** illustrated by transistors, amplifiers, targeted drugs and chemicals, actuators, and adaptive structures. An increased research focus will be on novel devices and device system architectures.
(c) **Third Generation (2010 -): 3-D nanosystems and systems of nanosystems** with various syntheses and assembling techniques, such as bioassembling; networking at the nanoscale and multi scale architectures.
(d) **Fourth Generation (2015 -): heterogeneous molecular nanosystems,** where each molecule in the nanosystem has a specific structure and plays a different role. Molecules will be used as devices and from their engineered structures and architectures will emerge fundamentally new functions[10].

This timeline is represented in Figure 1.

Figure 1: The Evolution of the field of Nanosciences through Four Generations



4.1 From the third to the fourth generation

The promise of nano and micro technologies for the future will be enabled by investigations into applying system engineering techniques. Figure 2 demonstrates the convergence of our fabrication techniques from bottom up to top down on a linear scale (Y axis) versus our time frame (X axis) of entering the third generation. The true textbook of nano systems (synthesis) engineering will need to reflect this activity as it relates to the third generation which is in development phase and the fourth generation which has yet to come to fruition.

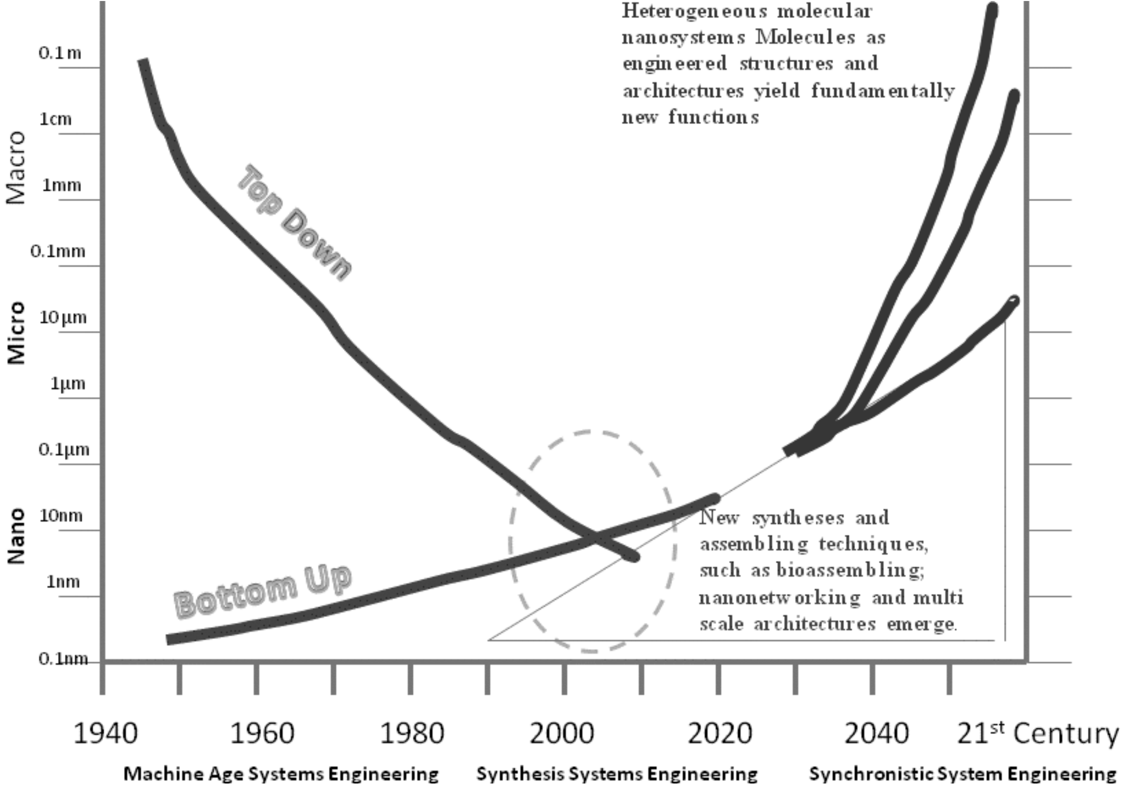


Figure 2: Convergence of bottom up/top down nano fabrication techniques and the third generation **nanotechnologies**

4.2 Technology development in the third generation

Technology development programs are critical to increasing the capability of emerging and deployed systems and, in the case of private companies, to long-term growth and profits. The success of research and development programs has inherent uncertainty; therefore, potential return of these projects is riskier than for well established programs. The program implementation plan must include a process to track and assess the risk of the new technology development throughout the life cycle. The risk of incorporating a new technology in a program is tracked by the program's systems engineering process to ensure that the realized benefits of the technology will not have an adverse impact on the program's budget and schedule. Risk management is particularly important for micro and nano technologies (MNTs), which are complex systems in of themselves. And the requirement for developing interfaces to adapt MNTs for human use adds further complexity in the development of MNTs and complicates assessing programmatic risk.

5. SUCCESSFUL TECHNOLOGY DEVELOPMENT

5.1 Organizational culture

To achieve robust technology development programs leading to the successful development of smart systems, it is paramount for the technology development (TD) manager to create a culture that fosters innovation, rapid development, and accelerated insertion into applications. This organizational culture is needed to keep pace with technology innovation. The success of a new technology development is the responsibility of the technology development manager.

The TD manager not only sets the research vision for an organization, but must also ensure that technology projects are completed accurately, within budget and on time.

It is a difficult challenge for advanced technologies to bridge the gap between the research laboratory and operational systems. The uniqueness, complexity, and uncertainty inherent in micro and nano technology (MNT) development increase the risk that these new technologies will not reach a maturity level that is required to be embedded in existing or new applications or to be successful stand-alone commercial products.

According to an analysis performed by the National Research Council[11], common characteristics of successful technology transition efforts include the following:

- The establishment of “Skunk Works-like” environment —these groups are committed, multidisciplinary teams led by champions who inspire and motivate their teams toward specific goals;
- Team determination to make the technology succeed—which may include making the technology profitable and demonstrating to customers that they need the technology;
- The use of expanded mechanisms of open and free communication—especially involving the ability to communicate an awareness of problems that will affect process goals; and
- The willingness of the champion to take personal risk—such leadership results in the willingness of the organization to take risks at the enterprise level.

Additionally, success stories from commercial, sports, and defense industries suggest that the characteristics of such a culture include the following:

- Acceptance of risk, anticipation of failure, and plans for alternatives;
- A flexible environment with the ability to accommodate change during the development process;
- Open communication in all directions without regard to hierarchy;
- A widespread sense of responsibility and commitment to success that exceed defined functional roles;
- Valuing innovation over short-term economic efficiency; and
- A passionate focus on the end-user's needs.

It is clear that innovation requires an organizational culture that accepts, defines, and manages risk. Successful technology development requires defining and managing risk throughout all phases of the development program by including rigorous systems engineering processes and having systems engineers, i.e., “product” systems engineers, embedded on technology development teams. The “product systems engineer” is crossed trained between MNT and systems engineering on the technology development team, directly supporting the TD manager, will greatly increase the success of technology transition from research into products and operations. This is especially critical for MNT developments due to their uniqueness and complexity, the immaturity of the processes and tools used in their development, and the rapid pace of their development.

5.2 Implementation of Technology Development Programs

A description of the life cycle stages in development programs is shown in Table 2. The advancement of the development program is controlled by decision gates where progress is reviewed against established, stakeholder coordinated metrics, and technical and schedule risks are assessed. Here we will delve further into systems engineering life cycle stages[12] as they apply to new technology development.

Table 2. Description of Life Cycle Stages

Life Cycle Stages	**Purpose**	**Decision Gates**
Concept	Identify stakeholders’ needs Explore concepts Propose viable solutions	*Decision Options* *– Execute next stage* *– Continue this stage* *– Go to a preceding stage* *– Hold project activity* *– Terminate project*
Development	Refine system requirements Create solution description Build system Verify and validate system	
Production	Produce systems Inspect and test [verify]	
Utilization	Operate system to satisfy users’ needs	
Support	Provide sustained system capability	
Retirement	Store, archive, or dispose of the system	

The uniqueness and complexity of MNT development requires a defined process to review and evaluate (described in 5.3 below) these programs as they progress. The purpose of the process is to accept the uncertainty of the MNTs and manage risk to maximize the organization's return on research and development investments and to increase the likelihood of success for innovations. For the TD manager, bridging the gap between the "Concept" and "Production" stages carries inherent uncertainty and requires a carefully thought out program implementation plan. Risk is managed by setting "Decision Gates" where the options are to execute the next stage, continue in the current stage, return to a preceding stage, hold the project activity, or terminate the project. Decision gate criteria that are used in traditional systems engineering to determine whether the program can proceed to the next phase will likely guarantee that a new technology program will be cancelled because the uncertainties and risks are difficult to define, poorly understood, or may be too large.

5.3 Phases of technology development programs

Decision Gate 1. The process starts with "discovery". The idea can be the result of a competitive research initiative, a technology road mapping exercise, strategic planning that is part of a regular business plan, a brainstorming session, or input from a customer with a specific need. Ideas for new technology development are next screened at the first decision gate. The criteria for passing from the first phase are largely qualitative and determine if the discovery warrants additional investment of research funds. Criteria for success can include likelihood of success, return on investment, fit to the organization's overall strategic plan, and/or criticality of the customer's need.

Decision Gate 2. The second phase is "project scoping", which defined the scope of the project and creates a top level work plan and schedule. During this time, a literature search, a patent and intellectual property search, and resource gaps assessment are performed. Colleagues are engaged and potential outside partners are identified for teaming. The output product of this phase is the "preliminary technical assessment" of the program which is presented at Decision Gate 2. The second decision gate is also mostly qualitative and determines if the top level work plan is reasonable and is the projected resources are adequate to support the next phase of the program.

Decision Gate 3. Phase 3 is the "technical assessment" effort, which must demonstrate the viability of the discovery. During this time, the *ad hoc* research team is formed to perform technological analyses and experiments to demonstrate feasibility and to address required interfaces to existing systems. The team also defines the resources required to complete the project including the level of effort, maturity of modeling and analysis tools, adequacy of laboratory facilities and equipment, and required research disciplines. At this point, the success of the development can be increased by indentifying a dedicated product systems engineer at the beginning of this phase. For a technology that will be embedded in a larger system, the systems engineering team for the larger program also must be involved. At the end of this phase, the technical assessment is conducted at Decision Gate 3, the first rigorous screen for the program. This review is modeled after traditional systems engineering principles. The review assesses the level of development to measure design maturity, reviews technical risk, and determines whether to proceed to the next level of development. For MNT development, this review also evaluates emerging properties of the MNT and assesses the (positive and negative) impact on customer requirements. At this decision gate, the technical review addresses program risk and eases the transition to detailed investigation phase by:

- assessing the maturity of the design/development effort,
- assessing the maturity of modeling and simulation tools,
- clarifying design requirements for the end product,
- challenging the design and related processes,
- checking proposed design configuration against technical requirements, customer needs, and system requirements,
- evaluating the system configuration at different stages of the development,
- providing a forum for communication, coordination and integration across all disciplines,
- establishing a common configuration baseline from which to proceed to the next level of design, and
- recording design decision rationale in the decision database.

These formal technical reviews are typically preceded by a series of technical interchange meetings where issues and problems and concerns are surfaced and addressed. The formal technical review is not the place for problem solving, but to verify problem solving has been done; it is a process rather than an event.

Planning for technical reviews must be extensive and up-front-and-early. Important considerations for planning include:

- timely and effective attention and visibility into the activities preparing for the review,
- identification and allocation of resources necessary to accomplish the total review effort,
- tailoring consistent with program risk levels,
- timing consistent with availability of required data and resources,
- establishing event-driven entry and exit criteria,
- where appropriate, conduct of incremental reviews,
- review of all system functions and the impact of new technology, and
- confirmation that all system elements are integrated and balanced.

Reviews should consider the testability, producibility, needed training, and supportability for the system, subsystem, or configuration item being addressed. The depth of the review is a function of the complexity of the system, subsystem, or configuration item being reviewed and the related maturity of the technology. Where the system is pushing state-of-the-art technology, the review will require a greater depth and insight than if for a commercial off the-shelf product. Items which are complex or an application of new technology will require a more detailed scrutiny.[13]

Criteria for success are similar as for the first decision gate (likelihood of success, return on investment, fit to the organization's overall strategic plan, and/or criticality of the customer's need), however, the criteria will be more rigorous due to the increased maturity of the MNT innovation and because the next phase (detailed investigation) requires a large increase in the financial investment. The process will assess if the technology product continues to fit the overall strategic plan for the organization, has strategic leverage, has a high probability of technical success, and has a path to transition into applications. The technical screening will also assess whether the product has high potential for up scaling of production. To increase the assurance that there is a feasible path to transition into operations, systems engineering must be engaged at this key decision point and the stages leading up to the decision.

The detailed investigation is performed in the fourth phase of the technology development program to prove technological feasibility and to assess the scope of the technology and its value to the organization. The program technical lead, the TD manager, and the product systems engineer must work closely together to set milestones and project reviews within this phase to ensure that the technology development stays on course and that the program is being managed to cost and schedule. In this phase, it is critical to engage tailored systems engineering processes to increase the likelihood of successful development. Sound systems engineering processes will track the technology product capability against requirements for targeted applications, develop and implement risk management strategies during development, and capture capabilities that are driven out in this investigation phase. The TD manager also begins to prepare a technology transition plan (to operation/incorporation) to present at the decision gate at the end of this detailed investigation phase.

Decision Gate 4. Using modeling and simulation is critical early in this phase of development. Modeling and simulation provides virtual duplication of products and processes and represents those products or processes in readily available and operationally valid environments. Until an MNT product is available with full system specifications, the TD manager and product systems engineer will rely heavily on the results of modeling and simulation to control costs and manage risk in the MNT transition to the system that it enables As high fidelity prototypes become available near the end of the detailed investigation phase, test and evaluation must be conducted to ensure that all customer requirements are being met. However, in the case of MNT technology development, full system specifications may never be available for testing. In this case, successful new technology deployment will rely on a combination of highly developed simulations and non-traditional test and evaluation techniques such as those developed for the very-large-scale integration (VLSI) integrated circuits. The results of the detailed investigation phase are presented at the final decision gate, Decision Gate 4, which coincides with the Preliminary Design Review (PDR) if the product is being inserted into a larger system. This decision gate determines if the technology product is ready for transition into production. The management team must also determine if the technology is ready for up scaling. Questions to ask are:

- Is the technology well understood to the point where the application is known?
- Have performance requirements for the technology been established and include thresholds and goals?

If the systems engineering team is using the NASA definition of technology readiness levels (TRLs), the technology needs to be at TRL 6, i.e., a high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.

6. TECHNOLOGY DEVELOPMENT MANAGEMENT

The TD manager [14] oversees the transition and/or optimization of technology products or capabilities within existing or new systems. In this role, he/she must act as a technical liaison with the technology applications manager, project managers, program systems engineers, and the technology development team's product system engineer.

The TD manager is responsible for directing the technical activities during the phases of the technology development program. Activities include:

- definition of program objectives, milestones, product capability, and cost
- technical planning,
- requirements management,
- interface management,
- technical risk management,
- configuration management,
- technical data management,
- technical assessment,
- decision analysis,
- quality management, and
- lessons learned.

6.1 Technical planning

Technical planning is a process for the identification, definition, and planning of the technical effort necessary to meet project objectives for each phase of the technology development program. The technology development manager must determine deliverable work products from technical efforts, technical reporting requirements, entry and success criteria for technical reviews and/or decision gates, product and process measures to be used, critical technical events, data management approach, technical risks to be addressed in the planning effort, and tools and engineering methods to be employed. The manager is also the team lead who is responsible for obtaining stakeholder commitments to the technical plans, planning the approach to acquire and maintain technical expertise needed throughout the program, and issuing authorized technical work directives to implement the technical work. The overriding System Engineering Management Plan (SEMP) and other technical plans must be put in place to monitor and manage progress.

6.2 Requirements management

The management of the technical requirements includes providing bidirectional traceability and change management for established requirement baselines over the life cycle of the system products. The TD manager is responsible for preparing or updating a strategy for requirements management, selecting an appropriate requirements management tool, training technical team members in established requirement management procedures, conducting expectation and requirements traceability, managing expectation and requirement changes, and communicating expectation and requirement change information. The need for a change during a system's life cycle can come from many sources and affects the configuration in infinite ways. Customer needs can increase, be upgraded, are different, or are in flux, and technologies may be developed that allow the system to perform better and/or less expensively.[13] A change in requirements creates challenges for any new technology development. The challenges are even greater for MNTs because they are complex systems there are scaling issues, and they need to interface with macro. MNTs exhibit emerging behavior, so it is important for the product development systems engineer to track properties which can be enabling.

6.3 Interface management

The central activity of the system dictates the design requirements of the system. Design decisions regarding interfaces should be made consistent with what directly or indirectly contributes to the central activity of the system. In order to efficiently manage the system interfaces, the central activity of the system must first be identified and always remain the top priority as each component of the system is broken down and planned and what can be measured or assessed.

Interface management is the establishment and use of formal processes to establish interface definition, details, and compliance among the end products and enabling products. This includes preparing interface management procedures, identification of interfaces, maintaining interface documentation, disseminating interface information, and conducting interface control. MNT developments pose additional challenges to the management of interfaces due to their complexity. Also, interfaces may be multi-tiered and parameters at the interfaces are difficult to measure.

Embedded MNTs mean that heterogeneous macro/meso/micro/nano elements must all be integrated together, which requires careful tracking of interface requirements during the development. Micro and nanoscale interface design and control principles cannot be directly transcribed from fundamental systems engineering due to the dynamic nature of the interface at small size scales. Yet, fundamental systems engineering principles that dictate interface treatment can be built upon to devise a plan for the treatment of MNT system interfaces. There are four basic practices from macro interface control that can be adapted and applied to MNTs:

- define system boundaries;
- identify the internal and external interfaces;
- map out the functional and physical allocations at each interface; and
- manage the interfaces and incorporate necessary feedback mechanisms.

6.4 Technical risk management

Technical risk management is paramount to successfully introducing a new technology into a program. It requires a continuous examination of the risks of technical deviations from the plans and identifying potential technical problems before they occur so that risk-handling activities can be planned and invoked as needed across the life of the product. This includes developing the strategy for technical risk management, identification of technical risks, conducting technical risk assessment, developing technical risk mitigation processes, monitoring the status of each technical risk, and implementing technical risk mitigation and contingency action plans when applicable thresholds have been triggered. To leverage bottom-up nanotechnology to exploit self-healing properties, adaptability, and scalability, product systems engineering may need to create entirely new concepts for handling uncertainty not only in the environment but in the state of the system itself as it evolves.

6.5 Configuration management

Configuration management is the process of documenting the configuration of the product at various points in time. This involves systematically controlling changes to the product configuration and preserving the integrity and traceability of the database throughout the full life cycle of the program. Activities include establishing configuration management strategies and policies, identifying baselines to be under configuration control, maintaining the status of configuration documentation, and conduct of configuration audits. The use of configuration management early in the technology development process is critical for MNT due to their complexity and emerging characteristics.

6.6 Technical data management

Technical data management is the process of identifying and controlling data requirements. This includes acquiring, accessing, and distributing data needed to develop, manage, operate, and support system products; managing the disposition of data as records; analyzing data use; obtaining technical data feedback for managing the contracted technical efforts; and assessment of the collection of appropriate technical data and information. Technical data management strategies and policies must be formally established to maintain stored technical data, provide technical data to authorized parties, and collect and store required technical data.

6.7 Technical assessment

Technical assessment involves monitoring the progress of the technical effort and providing statistical metrics to support system design, product capability and performance, and technical management efforts. This includes developing technical assessment strategies and policies, assessing technical work productivity, assessing product quality, and conducting technical reviews. Nanotechnologies may have emerging properties. It is critical for the product systems engineer to understand and track these properties against the requirements matrix to 1) ensure that requirements are met and 2) to capture enabling properties which may enhance the capability of the system.

6.8 Technical decision analysis

Technical decision analysis provides for the evaluation of technical decision issues, technical alternatives, and their uncertainties to support decision making. This is done throughout technical management, system design, and product realization to evaluate the impact of decisions on performance, cost, schedule, and technical risk. It includes establishing guidelines for determining which technical issues are subject to formal analysis processes, defining the criteria for evaluating alternative solutions, identifying alternative solutions to address decision issues, selecting evaluation methods, selecting recommended solutions, and reporting the results and findings with recommendations, impacts, and corrective actions.

6.9 Quality management

The uniqueness of MNTs requires a closer look at the reliability aspect of the quality management plan. Quality management is the planned and systematic activities necessary to provide adequate confidence that the product or service will meet the given requirements. The generic elements of a good quality management plan apply to the development and production of MNTs. The quality management plan must be carried out early in the formulation phase of the project and includes a broad range of activities change control; procurement; receiving, processing, fabricating, assembly, test, and inspection control; contamination control; handling, packaging, packing, and storage controls; quality records; quality audits; process improvement; reliability; and safety. In many organizations, quality management plans are governed by ISO standards such as the AS9100:2001.[15] Reliability is a critical element of quality management. Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time.[16]

7. SYSTEMS ENGINEERING APPROACHES FOR MICRO AND NANO TECHNOLOGY DEVELOPMENT

A study by the National Research Council [11] recommended “best practices” for technology development which are especially critical for MNT development. The first is developing a "viral" process for technology development, meaning that the process is infectious and self-propagating. This process entails quick, iterative development cycles and prototyping of materials and products and must be done in conjunction with the potential costumers. Viral development for MNTs is critically dependent on effective modeling of materials and processes which accelerate the iterative process by using predictive models to redesign the development processes.

The second best practice is increasing reliance on functional requirements rather than on specifications. One of the key limitations to the rapid insertion or development of new technology is the lack of information given to vendors about the relevant functional and technological needs. Instead, strict adherence to detailed but incomplete specifications is the norm. Specifications are essential for ensuring that a technology product will have an extremely low probability of failure. Previously, we saw that applying overly restrictive project management practices and/or systems engineering processes on new technology developments increases the chances that promising developments will be stopped in early phases. In this case, overdependence on specification will decelerate the rate of transition.

The third best practice is developing a mechanism for creating successful teams in a sustainable way. Successful teams consist of committed and multidisciplinary individuals who implement iterative prototyping and work to function rather than to specification. Overriding all of the program responsibilities of the TD is the need to develop staff that not only excel in their field of research but also have a passion for seeing their technology products inserted into application areas. For MNT developments, success depends on nurturing multidisciplinary teams (physicists, chemists, biologists, engineers). In the future, multidisciplinary employees, including the product systems engineer, will be highly valued employees in organizations working on MNT scale developments.

In addition these best practices, engagement of systems engineering expertise early in the process of new technology development is critical to the success of MNT development programs. Including a “product systems engineer” who is crossed trained between MNT and systems engineering on the technology development team, directly supporting the TD manager, will greatly increase the success of technology transition from research into products and operations. Table 3 lists the responsibilities of product systems engineering for each development activity. As MNTs mature from the early generations, the product systems engineer will play a critical role in deciding which systems engineering methodology to apply to the technology development process. While risks and benefits of reliance on an immature MNT technology must be evaluated case-by-case, general guidelines may benefit the TD manager, the MNT technologist, and system engineers for deciding when to apply the various risk mitigation techniques. These guidelines are provided in Table 4. The first consideration is to determine the most appropriate systems engineering methodology to apply to the development activity. As nanotechnology development matures from generation two into generation three, the application of the traditional Waterfall methodology is less likely to result in a successful technology development.

Table 3. Responsibilities of Product Systems Engineering

Development Activity	Product Systems Engineering Responsibility
Technical planning	- Develop or update planning strategies for common technical processes - Collect information for technical planning - Define technical work to be done - Schedule, organize and cost the technical work - Direct development of formal technical plans - Obtain stakeholder agreements with the technical plans - Develop technical work directives - Direct capture of work products and related information from technical planning activities
Requirements management	- Develop strategies for requirements management - Ensure that requirements are documented in proper format, baseline is validated, out-of-tolerance technical parameters are identified - Approve changes to out-of-tolerance technical parameters - Track between baselines - Develop and maintain compliance matrices - Review ECPs and provide recommendations - Implement procedures - Disseminate approved changes - Capture work products from requirements management activities
Interface management	- Develop procedures for interface management - Direct interface management during system design - Direct interface management during product integration - Direct interface control activities - Direct capture of work products from interface management activities
Technical risk management	- Develop strategies to conduct technical risk management - Identify risk - Coordinate stakeholders - Direct risk analysis - Select risks for mitigation - Develop risk mitigation/contingency action plans - Plan implementation - Capture work products from technical risk management activities
Configuration management	- Develop strategies to conduct configuration management - Identify items to be place under configuration control - Establish baseline - Contribute to configuration change control - Able to identify content of configuration control - Direct SE participation in configuration audits - Capture work products from configuration management activities
Technical data management	- Develop strategies to conduct technical data management - Direct data for storage - Develop lessons learned - Ensure measures to protect technical data - Develop procedures to access technical data
Technical assessment	- Develop strategies to conduct technical assessments - Identify process measures - Monitor progress against plans - Determine degree to which product satisfies requirements - Determine product performance variances - Select corrective actions - Identify type and when a technical review is needed - Direct review material preparation - Direct action item identification and resolution - Chair technical review boards (e.g. PDR, CDR, TRR) - Capture of work products from technical assessment activities
Decision analysis	- Develop for when to use formal decision making and who will make decisions - Establish criteria definition for types and range and rank criteria - Select evaluation method and solution - Identify and evaluate alternatives - Capture work products from decision analysis activities

Table 4. Guidelines for Evaluating Alternate Approaches for Incorporating an Immature MNT System Component

Consideration	**Guideline**
1. What is the preferred development methodology? (Waterfall vs. Agile)	If agile is preferred, make sure the technology development iterations are consistent with the system development iterations; otherwise, consider a waterfall or hybrid model with a dedicated technology development phase that precedes the system development.
2. What is the TRL of the MNT?	For TRL < 6, develop Technology Development Plan. TRL 1-3 may necessitate a technology development phase that precedes the main development effort. In some cases, additional mitigations may be needed, e.g., identify an alternate design to replace the immature MNT, and identify impacts on system and programmatic resources.
3. Can the interfaces between the MNT and the system components be defined and "frozen"?	If they can, and if the risk is low of timely MNT maturation, then it may be low risk to proceed concurrently with system development. If not, a precursor risk-reduction technology development phase may be warranted.
4. Can the performance of the MNT component be bounded?	If not, a precursor technology development phase may be warranted.

8. LOOKING TO THE FUTURE OF SYSTEMS ENGINEERING AND NANO AND MICRO TECHNOLOGIES

INCOSE has developed a vision for Systems Engineering in 2020. This study found that technology innovations are the primary drivers that influence the capabilities of system products, as well as the practice of systems engineering. Key drivers will be the continuing evolution of information technology, with associated applications to both system implementations (both large and small, including micro-systems) and to model-based techniques for systems engineering. This vision for the future is already seen in emerging conceptual and technological areas, such as complexity theory, nano-technology and genetic engineering which stretch the validity of present systems engineering processes.[17] Further the same study noted technology trends today that will affect future systems. These trends include:

- Increased miniaturization, including nanotechnologies
- Increased use of biotechnology
- Increased connectivity and interoperability
- Integrated process technology within the system.

In the conventional systems engineering approach, the project is recursively broken into subparts. The parts are then put together, with the task of the systems engineer to select and coordinate the subprojects appropriate.[18] The deconstructionism methodology does not, however, translate to the self assembly seen in bottom up nanofabrication techniques so a constructionist approach must be sought. This synthesizing approach is driven by the complexity of the systems. While the complexity of engineering projects has been increasing, it is important to recognize that complexity is not new. Engineers and managers are aware of the complexity of these projects and have developed systematic techniques to address them. There are several strategies that are commonly used including modularity, abstraction, hierarchy and layering. Modularity is a well recognized way to separate a large system into parts that can be individually designed and modified. However, modularity incorrectly assumes that a complex system behavior can be reduced to the sum of its parts. As systems become more complex the design of interfaces between parts becomes increasingly coupled and eventually the process breaks down.[19] The decomposition of elements to their respective subsystems is in the functional review steps. A system approach will be key to enabling this future.

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