NACFAM
National Coalition for Advanced Manufacturing

Potentially Disruptive Advanced Manufacturing Technologies

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About NACFAM

NACFAM is an industry-led, non-profit 501(c)(3) education, research, and services organization committed to enhancing the productivity and competitiveness of US-based manufacturing. NACFAM's goal is the accelerated development and deployment of advanced technologies and related workforce skills and knowledge within all tiers of the U.S. industrial base.

Founded in 1989, NACFAM has built a unique, public-private community of over 1500 corporations, 20 national trade associations, and 350 non-profit organizations that offer productivity enhancing services to manufacturers: Federal labs and university research centers in the field of R&D; community and technical colleges in the field of workforce education and training; and manufacturing extension services in the field of supply chain optimization.

About the Center for Technology and Innovation Management (CTIM)

CTIM is a university–wide center at Northwestern University. Established with the ongoing support and encouragement of the Management of Accelerated Technology Insertion (MATI) industry consortium, CTIM carries out a range of projects under grants from government and industry related to technology assessment, integration and management and innovation. CTIM also works closely with other initiatives at Northwestern including the nationally recognized Nanotechnology Institute, the evolving Ford Design Center, and biotechnology, bioengineering and advanced materials programs. With MATI, CTIM is a lead organization in refining corporate roadmapping tools, including the evolution of a multi-scenario roadmapping approach.

Potentially Disruptive Advanced Manufacturing Technologies

Summary

What technologies will dramatically impact the U.S. aerospace and automotive sectors in the coming decade? How will those impacts change the way companies in those sectors are organized? What impact will they have on their supply base? Who will win and who will lose? What is driving change and what is hindering it? And, what does this mean for our nation as a whole?

In an effort to answer these questions, as well as others, the National Coalition for Advanced Manufacturing (NACFAM) and the Center for Technology and Innovation Management (CTIM) at Northwestern University undertook a study aimed at providing a fresh perspective, unconstrained by conventional wisdom, of the changing technological landscape in the U.S. aerospace and automotive sectors. However, this report should be viewed as indicative only given budget and time constraints.

Disruptive Technologies

The literature reviews, focus groups and interviews conducted during the course of this study point to key broader trends as well as technologies that individually, or more likely in combination, may have a disruptive impact on US manufacturing. However, the phrase "disruptive technologies" is a widely used but poorly defined concept. Clay Christiansen in his popular book, "*Innovator's Dilemma*" implicitly defines disruption in terms of impact (cheaper, faster alternatives emerge to replace current products or approaches), surprise for current major players, and level of acceptance in the market. Andrew Grove of Intel advocates consideration of the related concept of "strategic inflection points" referring to developments that force significant alteration in strategy. There can also be disruptions which become clear only in hindsight and that affect companies (including suppliers) in different ways depending on their industry, size, structure, culture and planning/management processes. "Disruption" in this report is used to mean developments that have reached sufficient critical mass or a "tipping point" causing a significant proportion of manufacturers to fundamentally alter their planning, operations, structure or processes.

The time frames under which these technologies were grouped for the purpose of this study are indicative only. However, in general, near term technologies are already developed (although serious technical issues may remain including how the technologies will be integrated with existing systems and frameworks) but they have not been fully deployed due to economic, regulatory, logistical, and other problems. Mid-term technologies are awaiting further development or refinement as well as deployment and acceptance before the anticipated disruptive impact will occur. Long term technologies are generally still in early development stages with significant technological (possibly even in underlying science) as well as, in several cases, infrastructural barriers still needing to be overcome.

Cross-cutting issues /knowledge management

As much as the technologies listed below may affect manufacturing, the study showed key disruptions may come from cross-technology/cross-cutting issues and developments. These include the emergence of entirely new fields, convergence of new technologies with legacy systems, and threatened continuous disruption. Timely, new and effective approaches and tools (including software and the application of simulation and visioning tools to technology management) will be critical and are evolving.

Near Term Technologies (less than 5 years)

- *Advanced Electrical Systems* – Such as x-by-wire and 42 volt capability
    - Full introduction of x-by-wire could render many mechanical systems obsolete, spawning new suppliers, effectively eliminating many old ones, and causing upheaval in the automotive support infrastructure (dealers, mechanics, oil changing companies etc.)

Mid-term Technologies (5-10 years)

- *Reconfigurable Software Tools and Systems* – Single tools or machines that can perform multiple functions *including functions not anticipated in the original design and without requiring new tool production.*
    - A key contributor to enhanced flexibility/responsiveness to change and competitiveness of manufacturing. Will further narrow supply bases by allowing fewer suppliers to produce a wider variety of parts. Also will change plant layout.
- *Solid Free Form Fabrication* – The rapid creation of solid objects through the deposition of raw material in a controlled, systematic fashion. In addition to enhancements in the functionality of prototypes produced in this way including the potential of die creation, now evolving is the integration with manufacturing where specification of manufacturing steps is produced along with the product allowing immediate review and design refinement (including in multiple remote locations).
    - When linked with advanced design tools and intelligent machines it will allow a product to be designed, a prototype generated, manufacturing process detailed and reviewed and then put directly into production, dramatically altering the role of manufacturing design engineering
- *Advanced Sensors* – devices that respond to external stimuli and feed that data into larger monitoring, diagnostic and actuation systems.
    - When fed into "smart systems", sensors enable "Total Information Awareness" of a system, including the manufacturing process.
- *Micro-fabrication* – The creation of materials and parts through the manipulation of matter at the molecular level.
    - This would dramatically disrupt the entire industrial supply chain. Products could be made using generic raw materials such as silica (sand) obviating the need for mining and processing of raw materials. Products could be designed and made at

the point of use or sale, eliminating the geographical dispersion of the supply base and making distributed manufacturing a reality.

- *Modeling, Simulation and Visualization* – Using high-speed computers, the ability to build virtual representations of parts, processes and systems, simulate their interaction with one another, and observe that process in a way that is useful.
  - This allows the visualization of things before they are actually created. Innovative capacity is greatly improved as the time required to experiment with new materials and simulate new processes is dramatically reduced. Impact of this technology area will grow both as raw computing power increases and as the number of collaborative users and uses increases.

Long-term Technologies (10 plus years)

- *Smart Systems* – Computer-integrated, electro-mechanical systems and processes that have the capacity to *learn*.
  - Further refinements in reconfigurable tools will allow machines to work directly from product designs, correct problems "on the fly", detect and perform maintenance adjustments and adapt themselves to changing conditions. Software is an increasingly important component of these systems and in finished products as well.
- *Designer Materials* – For example, an airfoil that responds to airflow by changing shape or a synthetic material that mimics that which occurs in nature.
  - New materials engineered for a specific purpose have the potential to dramatically improve the quality and performance characteristics of nearly every man-made product.
- *Advanced Power Systems* – ultrathin/micro batteries, flexible transistors, efficient and affordable solar cells.
  - They will be key enablers of advanced sensors and smart systems (mentioned above).
- *Fuel Cells* - and a class of potential alternatives or dramatic enhancements (e.g. using hydrogen) to the internal combustion engine that are much more efficient and may emit only water and heat.
  - The potential disruption to the entire automotive industry cannot be overstated. If the rate of transition is slow, industry may be able to adjust, retraining workers and shifting jobs. If not, entire classes of suppliers and the components they produce will simply become obsolete.
- *Upgradeability* – Value Added Recycling – The isolation of a consumable element within a platform that can be replaced and/or upgraded while retaining the basic platform.
  - This disrupts the historical "cradle to grave" process of manufacturing. Platforms might remain the same for decades. Manufacturing core-competencies will need to shift to services as consumers look to value added upgrades, software enhancements, and aesthetic design changes (not structural) as needs and tastes change.

Other findings:

- While important, the scientific and technical obstacles in developing these technologies were of less concern than numerous contextual or technically exogenous factors. For example, shortage of capital for longer term process technology R&D, macroeconomic climate, geopolitical stability, favorable government regulation, shifting consumer needs and demands (including consumer resistance), and availability of skilled labor.
- Government plays a significant role in enabling these technologies to reach commercial application through research & development expenditures, the educational system, technical standards and "enabling" regulation.
- Disruption will come about not as a result of a single technology but rather the parallel development and application of multiple, interdependent technologies such as those listed above.
- Disruption will also be the result of cumulative change in these areas rather than from a "sudden" development. The result? Disruption will appear to be gradual while it is occurring, clearly perceptible only in hindsight.
- Technology management systems that allow companies and industries to successfully recognize, act upon, anticipate and manage change will provide the greatest long-term benefit.

Introduction

It is axiomatic that the rate of technological change is accelerating. Responding to that change is a challenge for employees, companies, industries and entire economic sectors. Nowhere is this truer than in today's advanced manufacturing economy. Driven by intense global competition, narrowing margins and changing industry structures manufacturers are forced to stay on the cutting edge of technology, and the attendant worker skills and knowledge to use it, in order to remain economically viable. They do not do it alone, however. Manufacturing depends for its survival on a robust public infrastructure as well. And that infrastructure plays a critical role in either enabling or hindering the development and use of the technologies they need.

Anticipating changes in technology, as well as its impact, is thus not only extremely important to its end users but also to those entities in the public infrastructure that play a role in supporting them. Government laboratories conduct research in numerous technology and standards-setting areas that have direct application in a manufacturing setting; public educational institutions provide workers with the skills and knowledge needed to develop, apply and utilize technological advancements; and, various regulatory agencies play key roles in enabling, or at times hindering, the process of technology development and use. Government entities are, therefore, market actors and have a vested interest in anticipating technological developments that have the potential to dramatically alter the long-term health of our economy.

Peering into the Future

The future state of particular industries or technologies has frequently been presented through the use of "industry roadmaps" (distinct from individual corporate product and technology roadmaps.) These roadmaps can be very useful tools in developing a common vision, identifying areas of needed research, and setting research goals and milestones. However, because roadmaps are developed by groups of people they are by their very nature consensus documents. Generally speaking, they are also public documents.

This means that, while industry roadmaps are a useful tool for identifying future research needs, they have three potential weaknesses. First, the consensus view may not take into account an opinion that may turn out to be prophetic. Second, because roadmaps are developed in open forums, participants are less likely to share their most sensitive and potentially groundbreaking work with their competitive peers. Finally, they are often too narrowly focused on a specific sector and miss, or gloss over, important and changing interdependencies with other sectors.

This study sought to overcome these drawbacks by focusing on questions not typically answered by traditional roadmapping exercises including:

- What will be the game-changers, the disrupters, the technologies that will come "under the radar"?
- What are critical underlying requirements (which may need to come from other industries), key enablers, and potential inhibitors to successful development and implementation of these technologies?
- How will these technologies interrelate with each other and with existing technologies and systems? In other words, what aren't the roadmaps telling us?

Project Methodology

To answer these questions NACFAM and CTIM used a research methodology that increased the likelihood of answering these questions by focusing on extracting the views and visions of the future manufacturing landscape directly from those who have significant expertise – and direct stakes- in developing, analyzing, acquiring and using manufacturing technology. This included personal, off-the-record, anonymous interviews with directors of manufacturing R&D, advanced manufacturing technologists, and chief technical officers in some of our nation's most innovative companies as well as research academics, venture capitalists and futurists. The results of that work have been summarized here.

The Project consisted of three phases of work. Phase I consisted of data collection, analysis and development of a preliminary set of potentially disruptive technologies; In Phase II, the list of technologies was presented to members of industry for feedback and discussion. This took place both through one-on-one interviews as well as in one live and two "virtual" focus groups; Phase III consisted of synthesizing the data gleaned from all sources in order to discover common patterns as well as uncommon insights.

Phase I: Data Collection and Analysis

In order to develop a preliminary set of technologies, some 40 industry roadmaps (selected based on potential relevance to the project) were reviewed and analyzed using custom designed template (Appendix 3 - figure 4). The purpose was to look for indications of needs, constraints, and technical specifications of potential high-impact technology changes and critical technology evolution steps. Analysis was conducted both of individual roadmaps as well as across them for the purpose of surfacing common technical and contextual considerations. Appendix 3 includes examples of completed roadmap analysis summaries.

Based on preliminary interviews with industry representatives, a framework technology development model was also developed to categorize specific technologies and disruptive systemic developments. (See Appendix No. 1– Figures 1 and 2) The model was designed to capture at a glance the myriad technical and contextual forces that either inhibit or enable the commercialization of a given technology. Examples of contextual factors include: Globalization, shifts in demographics, regulatory approval processes, R&D funding, availability of capital, geopolitical stability etc.

The technology roadmap and literature analysis as well as the preliminary model was then thoroughly reviewed and critiqued in a roundtable/focus group conducted on November 11, 2002 attended by senior managers with technology development and deployment responsibilities, academic experts and futurists. The roundtable/focus group was deliberately arranged to immediately precede a meeting of the Management of Accelerated Technology Insertion (MATI) industry consortium devoted to the highly relevant topic of managing science-based technologies (Appendix 2). Discussion continued informally with not only attendees at the roundtable/focus group who stayed for the MATI meeting but also extended to include other MATI meeting participants.

Based on their comments (they were very familiar with industry roadmaps) and our own assessment, it is clear that the concerns expressed about industry roadmaps in the project proposal are well founded. However, the group also pointed out that several industry roadmaps merited a deeper analysis including the sub-sector roadmaps developed by the chemical and electronics industries. The SEMATECH roadmaps were also lauded but it was noted they are well documented and needed less attention for the study.

The roundtable/focus group and MATI meeting participants felt industry roadmaps tend to fall into 4 categories:

- Destination roadmaps where wants and needs are presented but without a path or process to meet the needs. Costs and other requirements are rarely detailed.
- Static roadmaps in which needs and wants may be more defined but the future is assumed to be much like the present. Competitive technologies and disruptions are not considered (actually few industry roadmaps specify disruptive technologies in their own industries).

- "Gimme" roadmaps which simply present desires or visions with little discussion of trade-offs or basis for technology planning.
- Advocacy or marketing roadmaps. These are probably the most common and are created primarily to elicit research funding. The technologies described are drawn primarily from current research agendas and build on existing capabilities rather than addressing user requirements or constraints.

In response to the preliminary model, the groups suggested that optimal targets for government and industry support would be technologies that could have significant impact but which face development constraints that can only be overcome with help. As depicted in figure 3 (Appendix 1), the groups further recommended that a target *portfolio* be developed with a mix of somewhat lower constraints and lower impact but greater likelihood of success and technologies that offer greater impact but also have greater constraints (and more uncertainty).

The need to consider context in forecasting was repeated many times along with the observation that it may be counterproductive to consider only individual technologies rather than the underlying and enabling *system* in which the technologies must be implemented. In fact, several managers expect true disruption will come more from changes in planning (enhanced by advances in planning technology and improved techniques) and systems than from any other product or process.

Focus Group Findings and Recommendations:

- Industry roadmaps, while useful for certain purposes, have significant inherent limitations for forecasting or identifying disruptive technologies. One senior manager noted that participants in industry roadmapping are very careful to conceal any technology potential that could give them a competitive advantage. In fact, key reasons for participation in industry roadmapping are to benchmark and get ideas for independent research.

- Given that the goal of the study is to identify game-changing, disruptive technologies, effort should be focused on tapping the tacit knowledge of individuals in a manner that allows discretion, even anonymity. Participants will still be reluctant to share anything that gets too close to revealing the core intellectual property of their organization. However, recent retirees are a good source of information in this regard.

- The manufacturing universe is too large to study as a whole. Narrow the projects focus to one or two sectors. Suggested candidate sectors included: medical equipment products, pharmaceutical/biologics, food processing, industrial controls, automotive and aerospace. Selection criteria included:

    - Significant changes occurring in socio-political context, technologies, industry structure and infrastructure offering significant impact specifically on manufacturing
    - Significant constraints, obstacles, and deployment and implementation issues
    - A significant value/supply chain and a range of small as well as large companies offering high and broad economic impact

- A potential model in terms of issues and activities that may be useful in other industries

Against these criteria, the automotive and aerospace sectors were chosen.

The literature review, roadmap analysis, one-on-one interviews and the focus group review and validation resulted in a preliminary list of disruptive technology areas that offer the potential to significantly impact the aerospace and automotive industries. Those technology areas are:

- Advanced Electrical Systems
- Reconfigurable Tools and Systems
- Solid Free Form Fabrication
- Advanced Sensors
- Smart Systems
- Designer Materials
- Advanced Power Systems
- Fuel Cells
- Micro-fabrication
- Modeling and Simulation
- Recyclability and Upgradeability
- Visualization, planning and knowledge management

While the list in and of itself is an important start, the first phase of research activity made clear that the degree to which these technologies will be "disruptive" will be determined by the multiple contextual factors in our Project Model. The focus of the interviews and focus group discussion in phase II sought to illuminate those factors.

Phase II: Emerging Technology Focus Groups and Interviews

The focus of our effort at this stage was on contacting and recruiting focus group participants and interviewees. Corporate candidate criteria included those who had direct responsibility within the automotive and aerospace industries for directing internal R&D efforts and therefore had a strategic view of technologies of interest to their organization; those who also looked externally and were responsible for technology acquisition as well as collaborative technology development; those who were responsible for implementing change and putting technology to work in a manufacturing setting; and, senior decision makers who could provide an overarching perspective and look across corporate domains. Significant input also came from recently retired corporate executives in the above areas. Their feedback was particularly insightful since they were not too far removed from the inner workings of their former organizations and they were not averse to sharing what they knew.

Study participants were also recruited from academia, the venture capital community, non-profit associations and futurists. All were able to draw from their expertise in a specific technical area, the management of technology development, knowledge of government roles and responsibilities, experience in capital and company formation as well as extensive experience in studying the future technology landscape.

Corporate views were the sole domain of the 19 interviews we conducted. However, not all were still employed at the time of the interviews. We discovered early on in the study that corporate participants demanded anonymous attribution, if not anonymity entirely, in return for agreeing to participate. As mentioned above, recent retirees were not so constrained.

In addition to the 19 interviews, and still in keeping with the need for anonymity in acknowledgement and attribution, we also chose to gather individuals virtually in an online environment. Several models and providers were considered and E-FocusGroups of Rohnert Park, California was chosen. The President of E-FocusGroups, Dr. David van Nuys, is a recognized leader and pioneer in online qualitative market research and group facilitation. His long list of blue chip clients included many of the companies we sought input from and his decades long experience with California-based technology companies demonstrated his ability to effectively deal with some of the complex technical issues we thought might arise.

The focus group format was that of a "threaded discussion," much like a moderated bulletin board. Each discussion was held over the course of three days, the Automotive from March 18-20 and the Aerospace from March 25-27. Participants we asked to respond to a series of questions designed to validate the preliminary technology list developed in Phase I and add to it if necessary; assess the probability and impact of eventual commercial application; comment on factors furthering or hindering that development, including government roles; and, offer baseline, worst and best case contextual scenarios worth considering.

The asynchronous nature of the online tool allowed participants to respond to these questions in a thoughtful manner while simultaneously encouraging iterative dialogue and debate. The full transcripts of each focus group can be found in Appendix 4.

Phase III: Synthesis and Findings

The results of the roadmap analysis, model development, preliminary technology list, interviews and focus groups were analyzed in an effort to discover "out of the box" and "game-changing" technologies, the overarching purpose of the study. However, while the research process outlined above sought to maximize the likelihood of such insight by focusing solely on the tacit knowledge of capable individuals, no such "lightning strike" occurred or "golden nugget" found. Instead, what was discovered were thought provoking opinions, and creative pure speculation, about alternative futures that could result from the multiple contextual factors acting upon a given technology or set of technologies.

For the purpose of stimulating discussion about alternate manufacturing futures, the preliminary set of technologies held up well to scrutiny during the interviews and focus groups. Where disagreement did occur, it generally had to do with either the timing of commercialization or the prioritization of a given technology relative to others. Otherwise, with a few notable exceptions, it was well-validated as a comprehensive list of specific technologies and technology areas of interest to the aerospace and automotive industries alike. The following is a detailed description of these technologies, including some of the challenges faced in making them a reality.

Changing the Game

The following technologies offer the potential to significantly impact manufacturing, particularly in the target sectors. Although the list is a refined version of the one presented in the interim report, based on further research, including input from interviews and focus groups, it remains a preliminary list intended to stimulate productive discussion. Though a number are presented as distinct technologies or sets of technologies, the point will be asserted that the most critical developments are likely to be in the evolution of new systems in which these and other new technologies may be integrated. Indeed as the technologies are described their interconnections will be clear. A section has been added that discusses specifically the potential impact of key cross-cutting issues and developments.

The primary generic drivers of improved technology in aerospace and automotive have clearly been fuel prices, overall costs (including labor costs) and greater regulatory pressure, particularly from Europe. These have led to concerns for overall efficiency in both end products and manufacturing processes. With the increasing pace of technology change and increased competitive intensity, speed to market (and, potentially, multiple markets or even mass customization) is essential. But there are more complex factors, as well as global and scenario variations that deserve attention. For example, technology development in aerospace has slowed recently because gas prices and regulatory stringency have not risen to the degree expected. The poor economy generally has also limited investment.

An important issue raised in the interviews and focus groups, and discussed further as a cross-cutting issue, is the need to reconcile new technologies with current legacy issues and systems. Indeed, several respondents suggested putting technologies into the mid or even longer term impact category even though they are already in use because they need more time to be fully refined, widely recognized and accepted, and *integrated with current processes*.

Legacy issues can be structural, physical, and cultural. For example, many of the technologies will demand dramatic changes in supply chains requiring wholesale retraining of suppliers, both labor force and management, and even customers. Physical legacies exist in both of the selected industries in the form of massive investment in equipment, factories, and use infrastructure (e.g. highways, traffic management systems, parking garages, airports, air traffic control). And cultural legacies in the areas of longstanding policies, procedures, communication channels and cultures play no small role. Resistance to change can be expected at all levels.

The interplay between complexity and standards is also a common theme. As reflected in the industry roadmaps reviewed and reiterated in the interviews and focus groups, as cars and aerospace vehicles become more and more complex, the refinement of current standards and timely development and deployment of new standards (including basic safety standards, and *anticipatory* standards that can guide development rather than respond to markets) will be more difficult – and more critical to support key technology innovation and commercialization.

We have very loosely divided the technologies into near-term (less than 5 years), mid-term (5-10 years) and long-term (more than 10 years) based on estimates as to when they could be sufficiently deployed to have a significant impact. The timing issue was primarily addressed in the focus group and interview comments, but is still tentative. Often impact will begin early, particularly in major OEMs, but take longer to realize its potential and be fully accepted across value chains. Changes are expected. The conversion to 42v, for example, has recently been delayed (which in turn is likely to delay other changes in the electrical/electronic system including x-by-wire) and several of the technologies in the mid-term range could be deployed more quickly. Most of the technologies build on established science and practice but their evolution is uncertain. In general, near term technologies have already been developed (although serious technical issues may remain including how the technologies will be integrated with existing systems and frameworks) but they have not been fully deployed due to economic, regulatory, logistical, etc. problems. Mid-term technologies are awaiting further development or refinement, as well as deployment and acceptance, before the anticipated disruptive impact will occur. Long term technologies are generally still early in development with significant technological (possibly even in underlying science) as well as, in several cases, infrastructural barriers to be overcome

Finally, to the extent possible and meaningful, the descriptions will follow the model framework which guided the evolution of the list including suggested drivers, enabling and inhibiting factors and broader contextual considerations.

Coming Soon (Less Than 5 Years)

<u>Advanced Electrical/electronic systems</u>

x-by-wire: Over the past 25 years, an increasing number of mechanical processes have been changing to electronic processes. This migration has the potential to be significantly accelerated through a number of enabling technology developments including the introduction of low cost microprocessors and sensors. X-by-wire, a key example of the transition to electronic processes, refers to the replacement of a (potentially) wide range of traditional mechanical or hydraulic systems with electric or electronic connectors using electronic controls. It could fundamentally alter automotive and aerospace system design, enabling new product configurations as functionality would no longer require a direct mechanical linkage.

Frost Sullivan, a New York based market research and consulting group, notes a range of potential benefits from x-by-wire including increased modularity (although the interconnection of modules would need to be well coordinated and planned), improved driver interface, added flexibility such as in the placement of hardware components, and reduction in lead-times as soft tuning could be done with a laptop rather than through manual adjustment of mechanical parts. X-by-wire is expected to increase safety through improved accident avoidance and improved vehicle responsiveness as well as enhanced crash worthiness if drive-by-wire eliminates the traditional steering column. Reduced emissions, improved fuel efficiency, noise and vibration reduction and lighter weight vehicles will also be beneficial outgrowths of this migration.

Full introduction of x-by-wire in braking, climate control, steering, suspension, and throttle systems would also make current pumps, hoses, seals, fluids and other components obsolete. This would clearly have major adverse impact on current suppliers. Indeed new suppliers, or existing suppliers currently serving other industries such as electronic contract manufacturers, with expertise in electronics and software could replace current suppliers.

However, there are several technical hurdles that still need to be overcome. Improved heat management technologies and systems to minimize electromagnetic interference would be needed throughout the vehicle since controllers and motors would be located near the function they control. X-by-wire systems will need to be reduced in size from current models to facilitate locating them without redesigning vehicle bodies. Supporting components such as actuators and gears also need refinement. Implementation will require new tools and testing technology that is not yet developed. Testing of these highly interrelated systems will be considerably more complex than with current systems and will also require new infrastructure and skills in workers. This is particularly important if x-by-wire systems move to what many see as their full potential – closed loop systems where the vehicle can act independently of the driver/pilot, something much further along in Aerospace. Many argue that the complexity and safety risks will drive standardization of hardware and software architectures (which could increase economies of scale for suppliers).

There are other factors which could delay x-by-wire including: supplier resistance, consumer resistance and delays in needed enhanced electrical power including the expected move from 12 volts to 42 volt systems. Suppliers may be slow to recognize the paradigm shift and unwilling or unable to make the necessary changes and investments. The rate of change, however, will be driven by consumer demand and acceptance. If consumers show a willingness to pay for the additional features and functionality x-by-wire brings, the rate of supplier upheaval will accelerate. In varying degrees, OEM's are poised for this paradigm shift and will respond to market demands quickly relative to suppliers. If, however, consumer enthusiasm is measured, gradual retooling and reconfiguration of the supply base will be possible (much the same can be said of fuel cells, mentioned below).

From a technical standpoint, even if 42v is adopted, additional highly dependable back up power will be needed to ensure the critical electronic functions are always fully functional.

42 volt systems: Today's electrical systems are effectively at their limit in what they can handle. Conversion to 42 volts could enable added functionality, including x-by-wire, but also such features as integrated starter/accelerator/generator and idle stop where a car's engine shuts down at traffic lights saving gas and reducing emissions. Desired future capabilities such as adaptive cruise controls also require 42v. Without 42v, advanced power train technology would need to be developed – *at a far higher overall cost*.

Although 42v is widely accepted as the future standard (details of steady state, reverse voltages, etc. are being finalized in standards working groups), implementation has been delayed by at least 2 years. Delaying factors include contextual developments such as the slowdown in the economy as well as technical barriers such as the need for improved battery technology (42v batteries do not last as long as 12v versions), managing arcing, and cost incurred by 42v requirements for more costly power semiconductors. Arcing will also require new switches. Appropriate technologies exist but are presently too expensive.

42v will also require significant system changes as the full electrical system will need to be modified in each vehicle. Because such functions as lighting do not work well with 42v, a dual voltage system (12v and 42v) may be needed as a transition to full 42v implying two batteries, etc. Under intense pressure to reduce costs, but less hampered by regulatory pressure in the current political environment, a number of Aerospace manufacturers have switched their attention to improving 12v systems (to the extent possible) rather than continuing to advance 42v.

42v would require suppliers to adapt to provide new batteries, power semiconductors, dc/dc converters and other load control devices. Suppliers constructing transmission and engine related products would need to adapt their own systems to use 42v.

In the Not-so-Distant Future (5-10 Years)

Software reconfigurable tools and systems

To respond to increasingly frequent and unpredictable market changes (including introduction of new products and new parts for existing products, changing government regulations and new process technologies) responsive, rapidly reconfigurable/upgradeable/changeable manufacturing systems of tools are evolving. The potential of reconfigurable tools is reflected in a recent example in the aerospace industry.

In 1998, one company alone spent some $5 million and 27,000 work hours on tooling related to F-14 fighter stretch forming. Response to this specific need illustrates the challenge of the task. A prototype reconfigurable tool was developed to address certain design problems. The complexity is such that by 2002 tools were still evolving and in prototype stage. The latest version uses a local microprocessor to control all functions based on instructions from a host computer. Each of 2,688 pins has an individual motor. Among the technical challenges faced in its development was redesigning the pins with threaded support rods and enabling tool reconfiguration in stages to reduce the significant power requirements. With the current set up, reconfiguration can be done in less than 12 minutes.

The key disruption will come from the shift to software based reconfigurability allowing functionality to be changed in ways not anticipated in the original design of the system of tools and not requiring the manufacture of new tools.

The primary current constraints to reconfigurable tools and systems, according to the University of Michigan's Center for Reconfigurable Machining Systems (developed with industry), is the lack of scientific conceptual models for optimal, scalable system configurations. Reconfigurable tools, along with the use of new materials and free form fabrication (see below), will clearly alter demand on suppliers, reducing the overall need for tools but increasing the complexity and function of required tools. Finally, with the desired increase in functionality of tools and machining units, maintenance of the new tools and machines becomes critical.

Some machine tool builders offer internet-based links to support, diagnose and repair tools. A factory manager's dream, still far off, is *adaptive learning* machine tools.

Solid Free Form Fabrication

Virtual and rapid prototyping is now regularly applied. This allows prototypes to be shaped directly from a computer generated design file (which, in advanced programs may be created using 3 dimensional topographic imaging.) The techniques, which have grown considerably in sophistication, produce prototypes in hours instead of months and the design files can be sent via internet to suppliers, customers or remote manufacturing sites around the world. John Deere, among other companies, invite customers to "test drive" virtual designs making "on the spot" refinements possible. Applying state of the art computing, Argonne National labs has introduced a demonstration process that uses a sweeping material feed head to deposit materials onto an inert surface. This approach can develop far more complex parts than has been possible with molding processes.

But the game-changing potential of such fabrication will come as the process not only links design and manufacturing but simultaneously designs the product, produces the prototype and creates detailed models and guides for the manufacturing process. This could dramatically change the function of manufacturing design engineers. It would also enable testing and review of models, products and manufacturing processes in near real time by people in disparate locations.

Another key evolving change from earlier virtual prototyping is that now *functional* prototypes are becoming possible rather than only display models. It is envisioned that, particularly if costs come down, the fabrication process could feed rapid automated manufacturing lines where not only prototypes are produced but thousands of dies (dramatically reducing their now significant cost) or even finished products. This would have profound effects on suppliers (particularly die suppliers). Shop floor configurations would also change dramatically.

Solid free form fabrication could also be used with simulation technology to test new material compositions. Currently limiting this is the absence of structural software that understands the structural properties of materials and can apply that knowledge as parts are made.

Advanced sensors (including wireless sensors, micro sensors and sensor fusion; MEMS)

This technology feeds into evolving "smart systems" potentially making actuation more directly responsive to subtle changes. Researchers are developing wireless networking applications that use linked tiny sensors (Berkeley scientists are reducing the size of sensors to one cubic millimeter). Each sensor uses very little power because most of the time they can be off. Potentially such sensors could permeate vehicles as well as (for automotive) highways ("intelligent highways") to enable highly detailed knowledge flow of materials (as flaws evolve), systems and environmental conditions including sudden obstacles. Similar sensing could give detailed real time feedback during the manufacturing process. More sophisticated knowledge management programs will need to be developed to effectively use the information generated.

More broadly, sensor fusion – sharing of information between sensors and with other functions – is an important enabling input into active safety systems, automatic suspension as well as climate and heating controls. A trade off being debated related to cost is over the number of sensors versus the development of ability to interpret and extrapolate data.

Micro-electromechanical systems (MEMS) are also being studied for broader use. These are silicon semiconductor chips that integrate sensors, information/signal processing and control circuits. Actuators may be located on the chip or separately. More extensively used in aerospace, the widest application in automotive has been in airbag deployment. Among constraints to MEMS development is the traditional separation of electronic and mechanical system and component design teams, inadequate training of engineers to understand the technology, and difficulty in achieving cost effective volume manufacturing. Sophisticated solid freeform fabrication incorporating manufacturing process specification could help address these problems.

Modeling, simulation, visualization

Advanced modeling and simulation is mentioned as a need in many industry roadmaps. Along with visualization (grouped with modeling and simulation based on input from the focus groups and interviews which saw common issues and closely related potential), this technology set was also the most frequently raised and discussed in the focus groups. As a number of participants felt significant impact would be seen soon here, the set has been moved to "mid-term" rather than the "long-term" position assumed in the interim report. But many experts see the full potential coming only with significant advances in computing power. The benefits of modeling, simulation and visualization fall into three main categories:

A) They should enable the iterative virtual development and testing of product and process design as well as manufacturing processes. This, in turn, should dramatically reduce the number of unnecessary changes and enable rapid response to desired ones. True advances will require enhancements in computers and software. General Motors sees a key application of system simulation to be optimizing multiple vehicle attributes such as handling and suspension aerodynamics and crash worthiness. Simulation and modeling support configurable tooling and, potentially enable tool design, process specification and product design to be done concurrently –and all virtually.

In today's simulations, different aspects of vehicle performance are modeled separately. A common complaint is that everything is "in spec" but it doesn't work together. A potential game changer would be a computer representation of a vehicle as a complete system enabling evaluation of tolerances and design when the parts are joined together as well as optimization of weld positions and sequence.

With radical new product designs and configurations possible, the full manufacturing process could be simulated to test feasibility within budget and alternative approaches allowing changes to be made early in development rather than later when the cost of change can be orders of magnitude higher.

This level of simulation would enable design with new materials, new processes and new technologies and allow modularity and integration into planning of multiple and possibly new tiers of suppliers, which many automotive and aerospace manufacturers have begun to advocate. Currently the challenge is integration of modules and allowing x-by-wire and other technology advances that move across the vehicle.

B) Communication and coordination; Visualization tools have been used in major automotive and aerospace manufacturers for some time. But as companies such as GM increasingly assign responsibility for engineering to widely dispersed parts suppliers, collaborative 3D visualization with unambiguous sharing of parts information with suppliers (with links to parts numbers) on a real time global basis is required. This is beginning to be implemented using advances in software, virtual reality and product lifecycle management systems. A May, 2002 article in *Manufacturing Engineering* noted that visualization tools have the potential to impact the most common breakdowns in aerospace: at the handoffs between engineering and manufacturing, between manufacturing and suppliers, and between individual work stations on the factory floor. A European based automotive multinational has invested massively (reportedly 8-9 figures) in processes and systems to enable digital factory design to guide planned retrofitting of all plants within the next few years. This is expected to reduce the company's new vehicle production cycles by up to 30%.

C) In connection, interviewees from a major automotive OEM saw the need for enhanced computer-based dimension and locating schemes within virtual systems to pinpoint parts in highly complex setups. Already in 2000, a prime defense contractor was applying, on a preliminary basis, digital mock ups to specify and communicate to suppliers and in-house engineers specifications of parts experiencing problems and other parts being affected. This approach significantly reduced error rates. Lockheed Martin is converting legacy products to visualization with expected dramatic improvements in performance due to the improved ability to expose and analyze interfaces and interference.

Increased attention to this technology set has come as improvements in display and computer technology have dramatically improved image resolution and enabled new analytic processes. Companies such as GM and Motorola (as well as the former GD Searle) have used

CAVES (Computer Automated Visualization Environment) which allow users to see inside large-scale 3D representations of products and components. In the case of Motorola engineers, for example, engineers use a CAVE to see inside a cell phone as it breaks on impact with a hard surface facilitating improved construction.

This kind of impact simulation is particularly important in the automotive industry. However, simulations are not close to being accepted by customers and regulatory agencies as substitutes for the real thing. One major tier one automotive supplier reported that the need to crash test a car in order to measure the response of a recently developed component added a full year to the product development life cycle, even though it had proven to be safe in numerous simulations. While safety is critically important, the added approval time exposes the supplier to "rejection" risk up until the results of the crash are known (not to mention to the statistical vagaries of a "universal sample of one"). Until simulations are widely accepted as being as good as the "real thing", the time-to-market acceleration it makes possible will be somewhat muted.

Significant jumps in computing power are also another impediment to the full realization of modeling and simulation. However, 3D visualization is beginning to penetrate wider audiences, down to Tier 3, due to the development of basic virtual reality systems that can be used on relatively low end desk top computers at a fraction of the previously required up front investment.

Other enabling needs include the standards needed to facilitate simulation tool development and data transfer and manipulation. As the modeling and simulation industry roadmap points out, also needed are general toolsets that can be applied across diverse manufacturing processes. Currently most applications must be tailored to specific requirements.

Micro-fabrication

This process, which may still be far off, involves fabrication of materials and parts at the molecular level using principles being developed in nanotechnology. If technology breakthroughs are achieved, this could fundamentally alter the nature of manufacturing. Potentially, common materials such as sand (silica) could become a basic manufacturing material. Micro fabricated materials and parts could have a wide range of desirable features. A key barrier to effective application of nanotechnology continues to be scale up and manufacturability. In addition to the still challenging tasks of determining most appropriate building blocks (for optimal durability, chemical stability, ease of manipulation and versatility) and designing systems and subsystems, there is a lack of appropriate cost effective tools and skill for molecular assembly. Different approaches are being studied ranging from nanoprobes and nanorobots to chemical assembly processes. Some researchers have developed ways to imprint nanoscale features on silicon and metals using powerful lasers but alignment through the complex stamping and heating steps is difficult to control.

Long term Horizons (10 Years Plus)

Smart systems (including telematics)

Smart systems are in development both for products and for manufacturing processes. Machines will have better understanding of manufacturing processes and will be able to optimize production, working directly from product designs, sensing and correcting problems in process through embedded sensors. Prove-out test parts will not be required and preventative maintenance (with alerts from the system) will avoid costly downtime. Machine tool accuracy and productivity of tool development will increase dramatically.

In products, software is becoming a basic component. Cambridge Consultants expects car features will ultimately be entirely determined by software (To illustrate its value-add, a major European automotive OEM estimates the value of software in a car today at $2-3,000, a figure they project to double every 2-3 years). A researcher in Germany is developing software for x-by-wire braking which illustrates the challenge of software development and application. His software will track, integrate and interpret data from 3 sensors – one reports the flow of electricity to the brake, one follows the position of the actuator, and one measures clamping force. The software will alert a driver of the need for brake service.

The same researcher is also developing software to detect combustion misfires that could damage catalytic converters and increase emissions. The software requires data from sensors which track crankshaft speed variations and oxygen levels in the exhaust.

Cambridge Consultants argues that software will need to be separated from hardware – a departure from current procurement –with a new pricing business model for OEMs and suppliers (and likely involving different suppliers.) This is in part recognizing that design lifecycles are much shorter for software than for hardware.

Already noted in discussing advanced sensors, a range of responsive automotive and aerospace functions are envisaged. This is in part driven by the recognition that drivers/pilots could suffer from information overload as more and more data becomes available. The development of such systems is also partly a response to declining physical abilities as the automotive driving population ages. However, resistance is expected from drivers to cars taking over. An alternative might be an aircraft like cockpit display that could present complex information relatively simply. The implication is that alternative presentation media (voice. Etc.) being developed, when combined with smart sensors and systems, will alter the way human beings interact with machines.

Designer, self-repairing, "smart" materials

The rate of materials evolution has accelerated from basic structural applications to functional materials with single transduction capabilities to smart materials. Unlike functional materials, smart materials can respond in different ways to more than one stimulus. A key differentiator is the potential sensing capability in materials that, in the latest research on nanotechnology, can be developed at the chemical or molecular level (but not yet able to be manufactured in quantity.)

Application of earlier (not as smart) technology includes materials that support self-monitoring. For example, responsive materials are being tested in airfoils (for airplanes) that respond to airflow by changing shape. Self-healing/self-repairing materials use shape memory alloys in composites which react or various chemical reactions including chemicals in microcapsules which are released, in response to stress. The challenge in the microcapsules is to design the right capsule wall characteristics and to include the optimal number of capsules (allowing multiple healing) – or a system that signals that a low number of capsules remain and enables replenishment. An alternative to capsules under consideration is a complex series of channels within materials. Clearly all of these approaches are in the early stages of development and require a combination of basic science research and engineering.

Broader designer materials are also being developed. Advanced composites with polymers, metal or ceramic reinforcement are already in use in space systems and aerospace but these are too expensive for automotive use (aerospace manufacturers are also under increasing cost constraints). Oak Ridge National Labs is actively working to reduce the cost of carbon fibers as an option. A nano-reinforced process in which steel powder is bonded to other materials shows potential. It can significantly enhance the strength and hardness of inexpensive materials without losing their malleability. Aluminum is a possible base material but testing is required.

Biomimetics also shows long term promise. For example, research is underway to apply studies of the high tensile strength and toughness characteristics of abalone shell. The protein in this shell has an unusual molecular structure that resembles a series of linked springs. When stressed, the “springs” uncoil one at a time protecting the inner layer. When the stress is removed, the coils regain their original shape. This material is very strong and less brittle than current man-made ceramic. Scientists and engineers are working together to try to reproduce this type of structure using even more ductile base materials. An immediate application could be the lining of a piston which now uses ceramic. Biomimetic healing processes (such as in living tissue) is also being studied for self-healing materials.

As with solid free form fabrication, these developments would challenge suppliers to work with smaller volumes of product but with more complex and advanced processes.

Advanced Power Systems

Micro, widely dispersed sensors and increasingly complex functions will require not only new battery technology (as noted for 42v) but new forms of batteries and other power sources. Examples of potentially relevant technologies in development are “2-dimensional” caseless batteries that can be screen printed onto a wide range of materials and surfaces effectively making the surface material the case. One version of this approach is being produced by a small firm in Israel. Another (earlier stage of research) uses a hybrid of inorganic (offering charge transfer capability and speed) and organic (offering flexibility and low cost) molecules that can be dissolved and printed onto paper and plastic as a flexible transistor. A third initiative is working to develop practical and affordable nano composite ultra thin sheets that can be spread or even painted onto a surface and act as solar cells. Current solar cells are too inefficient and too costly to be used in many applications.

Fuel cells

The potential of fuel cells has been touted for many years but the cost of manufacture and infrastructure developments are major obstacles. Fuel cells are attractive in that, compared to the internal combustion engine, they are more efficient, quieter and may have very low or no emissions. Advances in technologies, including several discussed above, will move fuel cells closer to practical reality, aided in part by favorable support in the current administration. (However, alternative technology in development could add emissions scrubbing to diesel, dramatically reducing pollutants. In fact, a number of study participants pointed to the benefits of "clean" diesel hybrids, both in terms of development and manufacturing costs, but also in that they rival fuel cells in terms of environmental impact on a lifecycle basis.). Much of the basic fuel cell technology has come from highly sophisticated aerospace technology but auto makers report that progress has been made in making it palatable for cars. However, substantial technology and market hurdles remain.

These include the need for developments in multiple disciplines including process engineering, chemistry and heat transfer (some components generate heat, others require it but moving the heat optimally is a challenge) to be optimized in a way that has not been done before. Fuel cells require multiple filters, humidifiers, expanders, compressors and energy recovery devices. Radiators may need to be much larger than current models to operate at a range of temperatures. Current materials (unless refined as discussed above) are likely to corrode with the fluids generally used in fuel cells. And, current fuel cell designs require zero defects, further increasing an already costly and time-consuming manufacturing process. Also, further research is needed to ensure fuel cells last as long as cars they power (or, are designed to be modular and easily upgradeable/replaceable).

There are multiple potential fuel cell approaches. All have tradeoffs including optimal operating temperatures. Although not the current favorite for broader applications, solid oxide fuel cells (SOFC) are being considered as a near term possibility for auxiliary power units for cars and trucks in place of alternators.

There is also debate over the best choice for fuel, although hydrogen is the likely favorite (over, for example methane which has toxicity problems). However, how the hydrogen is made, delivered (likely a massive overhaul of the gas station infrastructure – many see this as the greatest hurdle), and stored without real or perceived risk of burning or explosion during processing, transportation, storage in stations and in cars, is uncertain. Onboard storage could require advanced pressure vessels to contain the gas at high pressure. Both new materials in containers and new regulators are being assessed. Carbon nanotubes are under consideration for this purpose, having been shown to be able to absorb hydrogen. However, their use is still in very early stages.

A range of feed stocks including water (electrolysis), natural gas and petroleum are possible (one large North American OEM, for example, seems to favor the petroleum option as it uses current infrastructure.) Some predict different regions will opt for different feed stocks.

Weather and climate are also inhibiting factors to consider. As the fuel cells generate water, potential freezing even to a small degree is an issue as it could destroy delicate polymer membranes.

For many of these problems, technology solutions exist but so far at too high a cost. Finally, industry standards remain to be resolved. These range form general safety standards to such questions as standards for interlocks of dispensers as hydrogen fuel will not use nozzles like current gas pumps.

Although fuel cells have received the greatest attention and press, interviewees and focus groups noted that other applications of hydrogen fuel are also being studied including advanced internal combustion engines using hydrogen (either in place of fuel cells or as an interim process while fuel cells develop further.)

Upgradeability –Value Added Recycling

Recycling has traditionally meant reducing materials and products to their most basic state for reuse as a lower value commodity. A major cost saving game changer could be the isolation of consumable element within a component such as an engine for replacement and the design of systems enabling economic updating of remaining elements. This would be done by mainstream dealers or manufacturers rather than by the current aftermarket. The increasing role of electronics and software in automobiles, for example, is already making this feasible to an extent. The multiple computers within vehicles are flash programmed just before shipping to ensure the latest protocols are used. However, the use of even this capacity for routine upgrading after sale has been limited by regulation out of concern that testing and certification will be compromised.

GM's critically acclaimed skateboard concept would also facilitate this transition. The platform upon which the car rests would remain static but the functional aspects of the car the consumer interacts with would change as their needs change. Parts and entire assemblies could be traded in and traded up. Components could be offered to other buyers on the used market or recycled-manufactured for other purposes.

As we discussed potentially disruptive technologies, enablers, inhibitors, critical contextual factors and related needs with interviewees and focus group participants, a message that came up repeatedly was that the true game changers and most serious threats were not in the individual technologies or even technology sets at all. Rather, respondents described a fundamentally new reality requiring new methods, new organizational structures and value chains and continual re-definition of core competencies. We attempt to capture this message in the following interrelated themes.

<u>Blurred Technological Boundaries</u>

"Convergence" is a common buzzword used to describe the growing interrelationship between traditionally distinct industry sectors and disciplines. There have been isolated examples of this level of convergence for many years but now convergence is taking on a new dynamic with several phenomena.

For hundreds of years, science and technology were separate paths with scientific discoveries gradually seeping into commercial applications, but with neither scientists nor technology innovators overly concerned with the other. But now science and technology are becoming closely intertwined with the rapid emergence of application based on science. The National Science Foundation, in a recent massive publication reporting on a planning workshop, refers to "convergent technologies" as the "synergistic combination of four major provinces of science and technology, each of which is currently progressing at a rapid rate: a) nanoscience and nanotechnology b) biotechnology and biomedicine, including genetic engineering c) information technology including advanced computing and communication and d) cognitive science, including cognitive neuroscience." NSF sees this combination to be so interrelated that it has coined the term "NBIC" (**N**anotechnology, **B**iotechnology, **I**nformation Technology and **C**ognitive Science) and predicts (as do our respondents) massive socio-economic change resulting. For manufacturing companies, mass production with custom design will be routine. Transportation will be safe, cheap and fast due to ubiquitous real time information systems, extremely high efficiency vehicle designs and the use of synthetic materials and machines fabricated from the nanoscale for optimum performance with exactly desired properties and the ability to adapt to changing situations.

But the new technologies will also converge with legacy technologies and systems. Many of the technologies will require dramatic changes in supply chains and un-training and retraining suppliers, both labor force and management, and even customers. Physical legacies exist in both of the selected industries in the form of massive investment in equipment, factories, and use infrastructure (e.g. highways, traffic management systems, parking, airports). And cultural legacies in the areas of longstanding policies, procedures, communication channels and cultures play no small role. Resistance to change can be expected at all levels.

<u>Disruption as Normal; Continually Refreshed Core Competencies</u>

For many years automotive OEMs outsourced software. Now software development has become a critical core competency. The replacement of hydraulic mechanical controls with electronic processes obviates core competencies of suppliers. The move from analog to digital systems challenged the technical competency of executives who failed to recognize that analog skills and experience were generally not transferable to digital. The pace of core competency change is increasing exponentially.

The rapidity of fundamental science and technology changes is leading to what one interviewee described as a constant state of disruption. As NSF puts it, "The daunting challenge of managing rapid and complex technology-driven change is increasingly a disruptive force on today's markets, business, economics and society. Disruptions will cut deeper as innovations fostered by convergent technologies emerge faster. At the same time, opportunities will be present that offer unprecedented opportunities for those prepared to exploit them." The report goes on to say, "Many things will require change: educational curricula, workforce skills, business models, supply chains and the post-industrial infrastructure, to name a few."

Focus group participants and, particularly, interviewees stressed the urgent need for new management and analytic tools and processes to manage knowledge and coordinate the rapidly evolving and complex manufacturing and operating systems. Reflecting the need, in the automotive sector, what used to be an annual planning cycle is increasingly done in real time and now includes suppliers.

Knowledge management systems must, therefore, not only extract usable intelligence from endless data but also point to specific strategic implications and actions. It was suggested that corporate roadmapping be used to provide a strategic foundation. Roadmapping is a disciplined, structured and focused planning process used to clarify and communicate. It defines the critical sequence of steps needed to reach a defined objective; the key decisions that need to be made with related contexts and specification of stakeholders and decision makers; defines what resources are required and when; and, recommends actions to address obstacles and anticipated environmental and technology changes. The process also highlights gaps and misalignments on multiple operational levels. A variation on roadmapping has evolved to incorporate scenario planning and clarify strategic changes with potential discontinuities. Further refinements will certainly be needed for the new conditions.

An important unresolved issue is the reconciliation of varying rates of technology change in components. Traditionally, a new car would take 5 years to be designed. But control modules have a lifecycle closer to 3 years and the lifecycle of Microsystems can range from 2-7 years. Closed couple devices (CCD) generally change every 2 years. Software design may take 6 months or less. The challenge is even more severe in aerospace with much more complexity and longer life platforms. Here the development of sophisticated knowledge management systems that can feed initial architectural design and technology refreshment is critical with what essentially becomes a continuous process of re-manufacturing. A breakthrough here would enable new technologies to be incorporated much more effectively and efficiently and allow more productive planned supply chain relations and management. Lockheed Martin initiated discussion with Northwestern University to begin to address this need in connection with the joint strike fighter program and a consortium of firms facing similar conditions (United Technologies, GM, IBM, Siemens Westinghouse and others) is in formation within the GATIC framework discussed below.

Constant disruption and the science/technology convergence discussed will require new mindsets, and un-training and continual re-training of all levels of the workforce. The critical need for this is not yet recognized in manufacturing. The new Ford Supply Park being established in Chicago was intended to include a training center to provide ongoing training for suppliers, but although Ford will provide initial training to suppliers to support the innovative new relationships envisaged, neither the OEM nor suppliers was were willing to fund the Center.

Can’t do it alone: Strategic cross-sector collaboration

An NSF report indicates, “business and industry are already beginning to restructure themselves on a global scale as network-based organizations following fundamental new management principles.” Our respondents noted that continually changing core competency requirements are driving new alliances – with suppliers and even with former competitors. This, in turn, requires more in-house generalists who can span disciplines and technologies. Unfortunately this is not the background of most employees.

In addition to corporate to corporate networks, university-industry-government consortia are evolving. Participants in such consortia find value in pre-competitive discussion of technology management issues and approaches and pursue the development of new tools through task forces. Some claim this value exceeds what they could find from consulting firms, industry associations or universities alone.

There are even supra-national consortia being assembled to focus on the strategic implications of science-driven technologies (nanotechnology, biotechnology, advanced sensors, smart materials, etc.), including the central service/training and knowledge management support capacity that will be needed. .

In general, companies are struggling to determine with whom they should ally, under what conditions, in what form and what the implications are for their organizations’ planning and operations.