AC 2007-581: PREPARING FOR NEXT GENERATION SYSTEMS

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Preparing for next-generation systems

Abstract

The paper presents outcomes from a top-down analysis of changes in the business environment and what needs to be done to extend and enhance competitiveness through professional workforce development. The work was done by an industry consortium with academic partners. The companies are system integrators at the top of the supply chain. However, their business structure has changed substantially in the past decade. A substantial amount of work that was once done in-house is now outsourced so they have to deal with a huge range of suppliers and commodity components to assemble 'systems of systems'. Training programs for technology executives have been used to elucidate the features of complex systems that would benefit from cooperative training and where no provision currently exists. The outcomes include improved characterization of requirements and identification of further educational development that can be undertaken both inside companies and in university graduate programs.

Introduction

Companies engaged in the design, production and field-support of complex systems are experiencing a broad and fundamental change in how they do business. Over the past 20 years, the systems they produce have grown rapidly in scale and complexity. The change has been driven by powerful computing and communications networks that deliver vastly more functionality at lower cost and higher reliability. As examples, consider: flying drone aircraft on the other side of the world, an automated assembly line or load management in a communications or distribution network. The resulting systems have capabilities many orders of magnitude greater than even two decades ago. To deliver and sustain such systems, the large monolithic, vertically integrated organizations of the 1970s have largely been restructured and re-engineered into highly focused, tightly interlinked units in a global supply network.

There are worrying implications about how to organize this sprawling combination of organizations often located in many countries. There are few precedents to show how to manage the combination of complexity, rate of change and diversity of functional components. Solutions are invariably an *ad hoc* combination of technical and business methods. As a result, the expertise may largely be classed as 'tribal knowledge'. It is a pragmatic approach that works tolerably as long as there are no rapid changes. However, many systems companies now face a major demographic risk as a large proportion of their senior engineers retire in the next few years. Concern has been widely expressed throughout the high-tech sector [1,2]. A training solution to prepare the next generation of technical managers has been implemented [3,4] by an industry-based consortium that is deeply involved in designing, producing and sustaining complex systems.

In executing this training program, it has become evident that the challenge is much broader than simply preparing the next generation of technology leaders. The purpose of this paper is to take the analysis to the next stage and examine the real-world features of the systems that will form the basis of future high-technology products. The factors that have driven so much change in systems technology show no likelihood of waning. We can therefore expect the next generation of systems to be more complex still. The question therefore arises whether we can keep developing *ad hoc* solutions or is there a more systematic approach that can be taken? In the latter case, there are implications throughout all industry-based training and into the preparatory academic programs. Finding a solution for the shortage of chief engineers and technology executives only served to demonstrate that it was a short-term fix and that we also had a long-term issue to manage. However, the outcomes from the executive training program were an ideal starting point for a top-down view that would identify the key characteristics of the systems we seek to develop and exploit. The purpose of this paper is to present some early outcomes of requirements for competency in creating advanced systems.

Next-generation systems

The term 'ubiquitous computing' has become a cliché, but in the case of complex systems, it has radically changed the way products function, how they are made, how the participating companies are structured to do business and business interactions at every stage of the extensive system life cycle. Over the past 20 years, many large monolithic organizations have split into smaller units. If the groups stayed within the larger company, they are now more independent and accountable for their own business success. There has also been a parallel move through mergers and horizontal integration to create larger units with a single market focus. Companies can thus provide the steadily-rising critical mass of capital (human and materiel) needed to create the next generation of systems-based products. By focusing on core competencies, companies can provide the expertise to produce a competitive response to global market requirements.

The strategic challenge is to be agile as well as large and capable. We must create new systems faster and more efficiently than any of our overseas competitors who are also fully aware of the opportunities and potential solutions [5]. All solutions depend on fully understanding their boundary conditions, so the first step has been to understand the determining features of today's systems. We have used seven characteristics that relate to change and technology evolution:

- The cost of communication and computing functions has decreased dramatically [6] and the trend appears set to continue for at least the next 10 - 15 years. As a result, today's business solutions are only the starting point for the next generation.
- Extensive but low cost communication networks can be exploited within complex systems and also to manage their design, production and support on a truly global scale.
- Manufacturing has become capital and technology-intensive. That forces companies to continue to focus on core competencies so they can drive innovation and development and reap the rewards that accompany ownership of intellectual property.

- Products and systems created by advanced manufacturing techniques are faster, better and cheaper than their predecessors so the status quo is not a long-term business option.
- Advanced technology is now available to anyone in the world who can afford to buy it. Products are sourced and delivered on a global scale and the most competitive players win.
- As technology continues to change rapidly, the components and electronics have become (extremely powerful) commodity items. System implementation has shifted to managing the integration function; the 'glue' that holds the system together.
- Complex products and systems are long-term functional platforms but still have to be produced to meet point requirements for functionality, performance and cost.

Each of these topics (and especially the last) is a major challenge on its own and together, they represent the contextual framework for this paper. Interestingly, they are not industry-specific. The same conditions apply to any complex assembly of equipment or processes. In our case, the consortium has interests in aircraft, space vehicles, missiles, gas turbines, automobiles, communications, semiconductors, high-tech buildings and enterprise-level services, yet the technical executives in the member companies all identify the same combination of future constraints within which they have to succeed. The common feature in the new business paradigm outlined above is that the format of the supply chain is determined by the system integrators. The delivery consortium has five major companies in that category so our solution is a serious top-down attempt to tackle root-cause features and allow the benefits to flow to the wider economy.

Process to collect information

Highly networked systems pose a significant educational challenge. The basic concepts of systems design are taught in most engineering programs. However, the operational know-how to create and sustain the large complex systems that are our concern only exists in the business world. The scale and concentration of resources are far beyond the capabilities of any university. The laboratory to study next-generation system characteristics therefore has to be within the industry sector. One drawback is that business competitiveness can be an issue. Each company has its own procedures and solutions that are confidential or secure. Although that is a limitation to be openly acknowledged and managed, there are still many other topics that can be effectively attacked through cooperative action. The companies in the consortium have complementary interests so they appreciate the opportunity to see outcomes beyond their own market. At the same time, the academic participants can work with real cases. A side-problem is that there are no books and very few research publications that do justice to the scale of the task to specify, design, deliver and support complex systems. Given the rate of development, any treatments are quickly obsolete so training solutions should be designed to evolve with the state-of-the-art.

In order to examine a topic of the complexity and diversity of the systems we envisage for the next generation, we need an organization that can deliver:

- Administrative clearance to give access to the raw information within the participating companies.
- Several hundred experts who can comment on every facet of the subject, its problems and likely modes of evolution.
- Program managers who can break the sprawling issues of system design and implementation into manageable blocks and then manage the studies and compilation of the outcomes.

Fortunately, the consortium already has all these functions embedded within its existing structure to deliver training programs. The main features are:

Administration	**Function**	**Deliverables**
Policy Board	Strategy and commitment	Company commitment and access to technology leaders
Technical Advisory Board	How to execute program	Start and stop activities
Office of Director	Manage courses	Delivery of courses
Learning & Competency Teams	Oversee content and delivery	Define standards for Certificates as follows:
	Expert participants	Chief Engineer
	Expert participants	Instrumentation
	Expert participants	Software Engineering
	Expert participants	Project Management

An important feature of the management process is to ensure that the continuous improvement process to validate quality is systematically and extensively applied. The framework is shown in Figure 1.

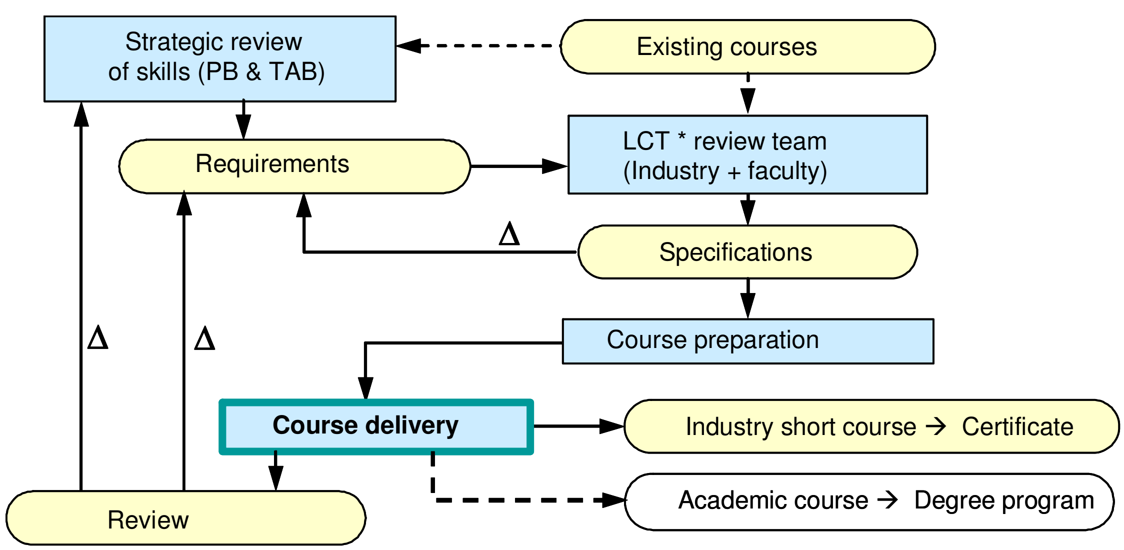

Figure 1. Continuous improvement process

The change management process has proved to be particularly important for courses directed towards senior engineers and managers. The participants interact strongly with each other and the facilitators. This means they examine and enhance course purpose and content very thoroughly in every delivery. The result is that we have unexpectedly created an engine that drives course change by 30% or more every time it is delivered. Although the change process shown in figure 1 was originally designed to provide top-down guidance on topics and content, its function has effectively been inverted. Change is now being driven from the bottom-up by the participants so the function of the working groups is much more responsive to provide cross-links, balance and strategic approvals. The other unexpected feature is that we have inadvertently created a loose and lightly coordinated team of several hundred experts who are incidentally telling us about the features and operational requirements of next generation systems.

Process for analysis

The consortium has 13 industry members and a technical workforce over 17,000 within the State. The companies range in size from five large system integrators at the top of the supply chain to small suppliers with only handful of employees. Together, they have a unique perspective on systems at all levels of maturity and the processes required to manage the supply chain. Conversely, every supplier competes globally to supply its key customers.

It would be a massive task to understand how these companies operate. However, through the certificate courses, we have a means to gain insight into the critical issues to be managed in the technical domain. It was clear many years ago that the conventional academic style of presentation that largely provides one-way information transfer was not appropriate either for the participants or the topics being studied. The format now used by many professional development courses developed by the consortium is to ‘chunk’ the content into 30 – 60 minute blocks. Each block has roughly the same format with five activities:

1. Define the topic and its operations
2. Individual or team analysis
3. Review, share experiences
4. Compile generic conclusions
5. Create individual plans to apply the lessons learned

With a simple structure of this form, it is clear that the role of the instructor is very different from a traditional course. The function is to facilitate discussion and to chart a path that makes best use of the combined experience of the group. The result is that each time the course is delivered, the stock of examples is enhanced. Repetition of cases provides a simple filter to show what is most common and the topic can then be give more emphasis in the next delivery. Obviously, this system works best with experienced personnel but since the Certificate programs are largely aimed at senior-level job categories, we have an asset to exploit.

The most highly developed examples are a set of Chief Engineer Case Studies. They are similar to Business School case studies but in this case, each participant selects, researches and writes his own case study. Examples are selected with advice and support from the technical leadership in the company. The evolution and decision-making associated with the case are examined and a report made to the others in the cohort. Most examples have centered on advanced trouble-shooting or design optimization. The topic is consistently given the highest feedback ratings by all participants.

The intensive class dialog and case studies have served to illustrate some defining features of complex systems. One of the most obvious is that systems are built using many skills and engineering disciplines. The structure is illustrated in figure 2.

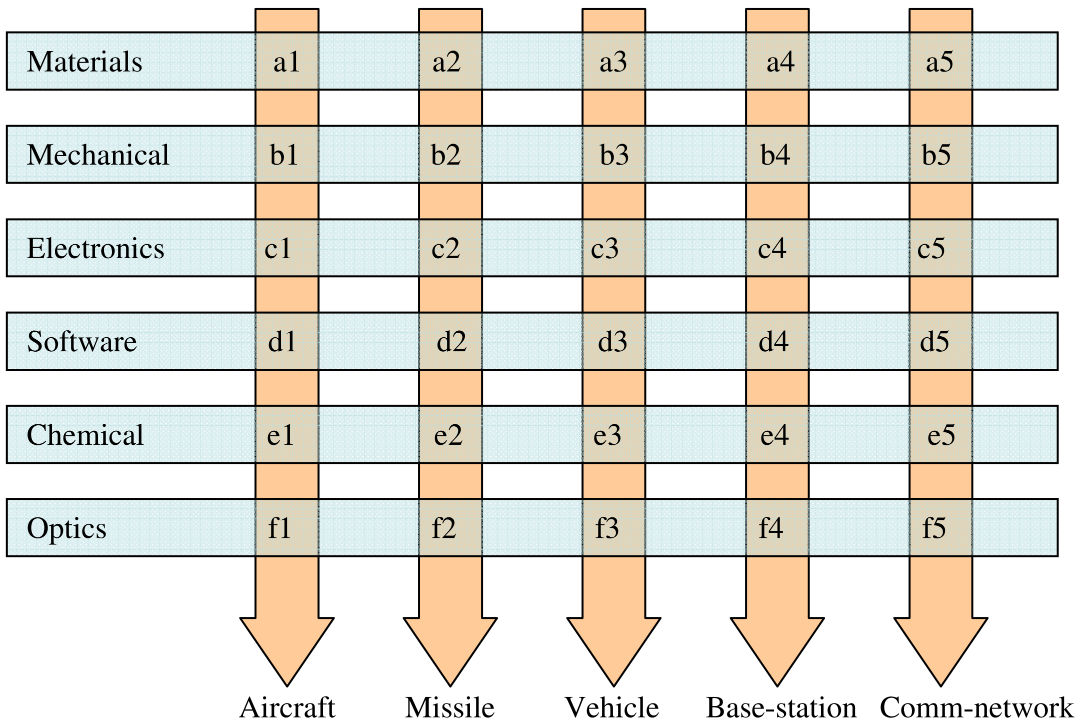

Figure 2. Combination of disciplines to deliver systems

The system is assembled using different combinations of the traditional engineering disciplines. Although the mix is different for each system, the scope is very similar across the board. As a result, companies employ a wide mix of engineers. During their careers, some remain discipline specialists while others migrate to orthogonal project management roles. The consortium training courses have in the past largely concentrated on the latter group since they have the greatest need for innovative training opportunities.

Effective operation of a matrix structure, especially with rapidly changing technology, demands very efficient communication. At senior management levels, fluency and accuracy tend to be good. The harder task is to understand the specialist's language and to recognize latent problems as they emerge. One of the unexpected benefits to arise from the group dialogs in the training courses is that informal communication channels are developed and the contacts can be productive and long-lasting.

Skills mapping

The cooperative interactions of discipline specialists described in the last section gives one viewpoint of what's needed to create a system. However, there is another perspective that must also be managed. Technical specialists must be able to dialog with each other and no matter their roles, they must all follow the company and international protocols for reporting and safe operations. The first requirement can be managed by offering short courses that provide insights into each discipline for non-specialists. Results will be reported elsewhere. For the second requirement (conformance to standards), we have used a skills mapping process. As an example, figure 3 indicates some results of an analysis to determine which groups might need access to training in the conventions and standards for data representation. Each job category was classified into those who might require training, those who should already be experts and those who were unlikely to need the skills in the normal course of their job.

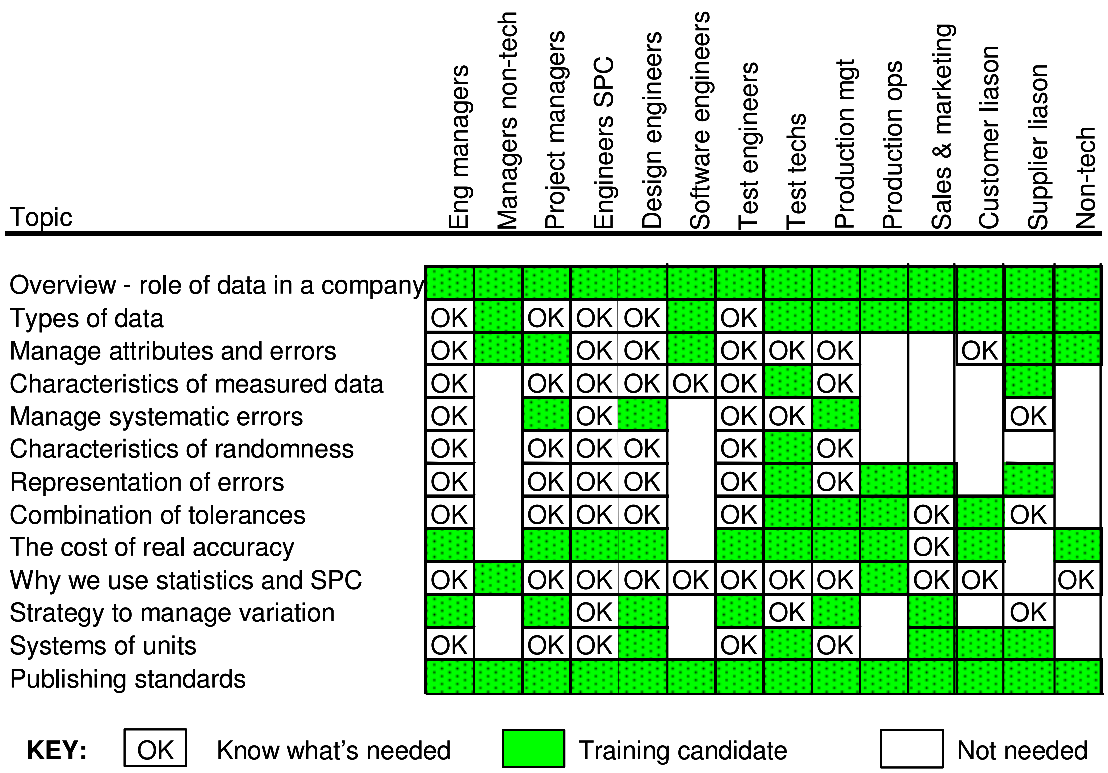

Figure 3. Training requirements analysis

One useful by-product from this activity was that the groups who figure most strongly in the 'OK' categories are also the people who can probably develop and deliver the training. Thus the process identifies needs but also the potential providers of solutions.

Manage life-cycle features of systems

Perhaps the most important issue to emerge from over 1000 man-days of executive training on complex systems is the question of how to manage system longevity. It is useful here to make a distinction between products which rarely go beyond their designed life, and systems where component parts can be changed and upgraded until almost no part of the original system remains. Examples of the former category are most consumer goods - even if they are complex. In the latter category, we have systems for functions such as enterprise-level scheduling, cellular networks and advanced weapons. This is not an intellectual distinction because system development is usually done within a series of projects. Each project delivers a defined set of requirements and rarely is there enough resource to design-in scope for later evolution and development. As a result, no development stage can afford to prepare for the next. However, if a retrospective accounting process is done over many generations of development, the silo development approach is clearly more expensive and wasteful.

There is no magic answer to design long-lived systems. Tight project constraints and highly focused resource applications will not change. However, the features of system design can be broken down into a number of requirements and the features of each can be analyzed and prioritized. The familiar topics are:

- manufacturability,
- testability,
- reliability,
- maintainability,
- usability,
- sustainability
- cost viability

For obvious reasons, these system lifetime goals are called the " … ilities". All have familiar and well-developed design and operational methodologies associated with them. The important lesson we have learned is that it need not be expensive to design these functions well. The key requirement is to be aware of them and make sure they are considered at the appropriate time in the product cycle. This is an important function of the technology executive and is a central point in the consortium's certificate program.

There are four other " ilities" that have been subject to less study and invariably give rise to serious discussion in case studies:

- Extendibility – substitute new modules to meet evolving requirements but still retain the low overhead of a point solution.
- Flexibility – adapt a good solution for one application to another. This requires good design-simulation-manufacturing interaction.
- Scalability – add modules to change functionality and move to larger scale markets.

- Tolerance to ripple risk – decisions made today can have interactions and repercussions many years later. The conventional concepts of risk in project management have to be substantially extended to handle this effect.

The procedures outlined in this section are not solutions but they do indicate how existing training and study processes can readily be extended to tackle some of the more serious design issues associated with next generation systems.

Outcomes and progress

The high-level industry training activities outlined in the last section have resulted in a number of requirements that serve as goals for future development:

- Specialists need a much better appreciation of what other specialists can do, how to communicate and how to recognize opportunity and constraints.
- The intense, data-driven environment of the networked supplier-customer matrix requires training on common themes but adaptability to individual groups.
- Success and experience in one product or technology area should be adapted and quickly applied to other areas.
- We need a much better process to clarify technology readiness levels and incorporate the results in roadmaps to be used throughout the supply chain.
- Individuals are accountable for their own skills and competencies. However, they need a structured process to plan their own personal development.
- There is a complementary challenge to adapt academic programs. A long-term outcome from this project will be to extend some of the course materials into university programs.

None of these topics has conveniently available training solutions. For the topics addressed in this project, we are still at the initial levels of the evolution chain so all solutions will require substantial innovation. We use market-derived requirements, content combinations, demonstration tools and delivery methods. The next series of course developments will cover:

- Definition of 'systems of systems' requirements
- How to prepare and use technology roadmaps
- System reliability (components, software and architectures)
- Project management dialects
- Manage distance activities (meetings, communication, clarity, culture)
- Resource estimating
- Prioritized decision-making and assessment
- Comparison of tools for design, simulation and operations
- Explain new technologies and their impact indicators
- Auto-coding and software re-use
- Alternative paths to system realization

The advantage of having a smoothly-operating consortium pays off in delivering such a broad-based plan. Processes are already in place to identify the required expertise and manage the balance between the different thrusts and measure their effectiveness. There is also an important 'trickle down' effect. Topics that appear first in high-level leadership courses steadily diffuse out to a wider range of participants to mimic the way technology is spread throughout the industry. The trends are also seen in detail by the academic collaborators and the relevant sections are quickly incorporated into academic courses.

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