System Engineering for Faster, Cheaper, Better

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ABSTRACT

The continued thrust to increase competitiveness and shorten time-to-market in industry, and the more recent effort to "reinvent" the procurement process in government, has created sustained pressure to adopt new paradigms for aerospace projects. The banner of "faster, cheaper, better" places emphasis on use of Commercial Off-The-Shelf (COTS) systems and components, Non-Development Items (NDI) (previously developed products that are not commercially available), and advanced, lightweight components.

This paper reviews two successful and two unsuccessful projects, examining the processes they followed compared to the "traditional" approach used from the 1960s through the 1990s. We use a model of the technical aspects of the project cycle (the "Vee") to highlight the essence of the processes followed, as well as the risks to be managed. The results illustrate that, without a valid and comprehensive process, "faster and cheaper" does not automatically lead to "better," and, conversely, that an intelligently tailored process can greatly improve the success rate for "faster, cheaper, better" projects.

INTRODUCTION

"Faster, better, cheaper" is the way the phrase is most widely used. Following the suggestion of Pedro Rustan, project manager of Clementine, we have revised the sequence to be "faster, cheaper, better," because doing the first (faster) usually leads to the second (cheaper), but cannot guarantee the third (better). In fact "faster, better, cheaper" has become the new "buzz word" for the 90s. It follows in the proud footsteps of terms from recent years such as TQM (Total Quality Management), Concurrent Engineering, and Integrated Project Teams. All of these are excellent concepts, and, if properly implemented within the context of an overall project management and system engineering philosophy and process, the improvements in project performance can be dramatic. Out of context, however, these terms become hollow slogans that do little to help the project, the product, the user, or the team. Worse, the slogans can become excuses for deviating from a proven approach without applying the essential project management and system engineering disciplines needed to succeed.

A "faster, cheaper, better" process is essential to our continued competitiveness in an era of tight budgets and global markets. The objective of this paper is to identify the essence of "faster, cheaper, better," to highlight the lessons learned, and to emphasize that success depends on a valid and properly tailored, comprehensive process.

Some who discussed this approach state that success was achieved by using "concurrent processes," and discarding the old patterns (e.g., abandoning the Department of Defense project cycle as well as the concepts developed in the System Engineering Management pre-release standard 499B). Unfortunately these advocates fail to adequately define their new process so that others can understand and apply it.

This paper reviews two successful and two unsuccessful projects. It examines the processes used compared to the "traditional" approach of the 1960s to the 90s. Detailed discussions of traditional project management models are contained in our book (Forsberg et al. 1996) and will not be elaborated upon here. For this paper we will focus on the technical aspects of the project cycle (the "Vee") to understand the essence of the processes followed, as well as to comprehend the risks to be managed in the "faster, cheaper, better" paradigm.

Two well-publicized projects that exemplify the "faster, cheaper, better" approach are the Clementine project (1994) and the Mars Pathfinder mission (1996). Both projects are reviewed here, and the conclusions have been validated through interviews with the Clementine project manager and with key team members on the Mars Pathfinder project. This paper also contains a review of the Buyer Procurement System (BUYER) project that, after three different attempts in a span covering more than a decade, failed in its goal to implement a Commercial Off-The-Shelf (COTS) product for a large software development. The conclusions presented here for BUYER were obtained through interviews in 1996 and 1997 with two of the project managers involved, plus a review of the project documentation. Finally the paper draws on the accident investigation of the Therac-25 radiation machine

(Leveson 1993). The Therac-25 used previously developed products that are not commercially available (Non-Development Items (NDI)). Since both of the failed projects reviewed here used COTS or NDI, the causes of their failures are relevant to this paper, even though neither were initiated under the banner of "faster, cheaper, better."

"FASTER, CHEAPER, BETTER"

When the first satellites were designed and built in the late 1950s, there were no commercial products available for space use. Everything had to be created from scratch, or commercial products had to be adapted for use in an environment for which they were never intended to be used. This led to both performance and reliability problems. The first 12 launches of the Corona satellite (the first US reconnaissance satellite) were all failures (Ruffner 1995). Yet the project survived (a total of 145 launches were made), and today the Corona project is considered very successful and a remarkable achievement. The key to ultimate success of aerospace projects in the early 1960s was the creation and implementation of project management and system engineering processes that were applied to all such development efforts. Procedures were developed based on the best practices of the 1940s, 50s, and early 60s. These defined the "traditional" approach used on most projects to the present time.

As technology matured and lessons learned were applied, our expectations matured as well. Now, almost forty years later, any system failure is considered unacceptable. One of the consequences of the successes of the process models of the 1960s is that in the 70s and 80s they led to more process formalization and often to unnecessarily rigid adherence to a generic (untailored) process.

One view of the traditional approach can be represented as the Technical Aspect of the Project Cycle (or "Vee"), as depicted in Figure 1. This depiction is requirements-driven, and starts with identification of user requirements. When these are understood and agreed-to, they are then placed under project control, and through decomposition the system concepts and system specification are developed. The decomposition and definition process is repeated over and over until, ultimately, lines of code and piece parts are identified. Agreement is reached at each level, and the decisions are placed under project configuration management before proceeding to the next level. When the lowest level is defined, we move upward through the integration and verification process on the right leg of the Vee to ultimately arrive at the complete verified and validated system. At each level there is a direct correlation between activities on the left and right sides of the Vee – the rationale for the shape. Everything on the left and right legs of the Vee are sequentially placed under configuration control, and hence this has been designated the "core" of the Vee. The generalization of the model to include incremental and evolutionary development is discussed in our book (Forsberg et al 1996).

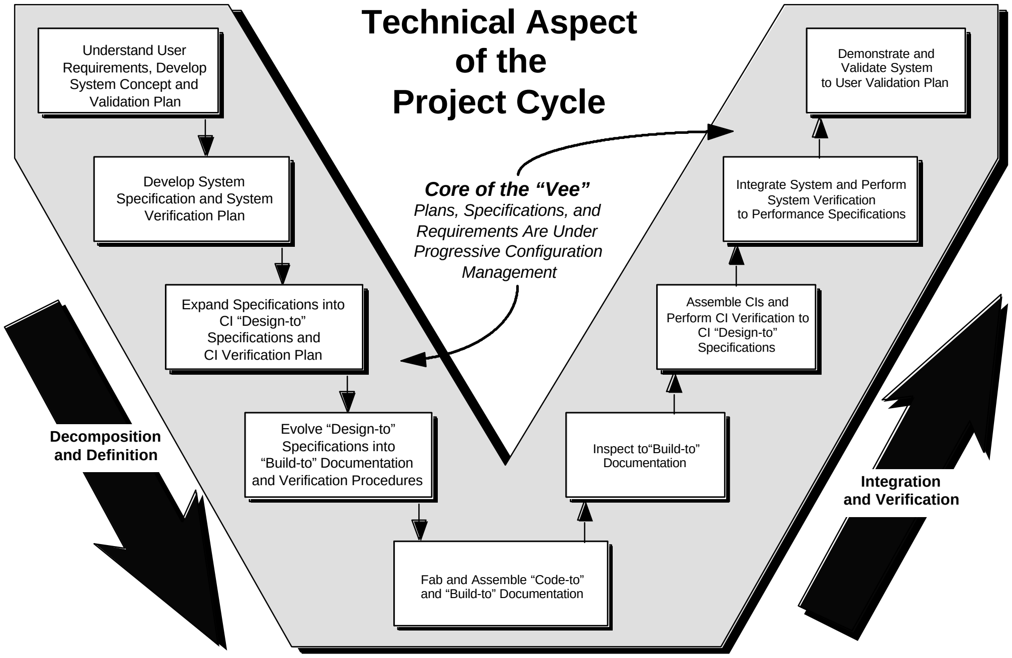


Figure 1 – The Technical Aspect of the Project Cycle (The "Vee")

While the core of the Vee is sequential, concurrent development is an essential part of the process. The concurrent "off-core" analyses, investigations, developments, and tests are engineering studies necessary to manage opportunities and risks inherent in higher level "on-core" requirements (Figure 2). These studies ensure that the higher level requirements can be met, and that the team is not committing to develop an "antigravity device." Upward iteration with the user ensures that the solutions being considered will be acceptable in the completed system. Upon approval the higher level "on-core" requirements become part of the baseline, but the supporting engineering studies *do not*; they are documented, however, as a part of the decision support process.

Today the management processes that led to past successes are viewed with suspicion and are being targeted as the villains in the drive to produce the next generation of systems. Under management pressure several projects have adopted the banner of "faster, cheaper, better," and have had significant success. To say that they were successful because they used previously developed products (Commercial Off-The-Shelf or prior non-commercial designs) misses the point; from the late 1960s to the present there has always been pressure to use previously developed products. What is new today is the range of useful products available for incorporation into the next generation of aerospace systems. However, these recent projects did break the 1970 and 80-era rigid interpretation of the traditional approach by creatively tailoring the project management process to their specific needs. Their legacy is important to us all. Their lessons apply to all projects, commercial as well as aerospace. We must examine how we can use their success to improve on the "traditional" project management and system engineering approach.

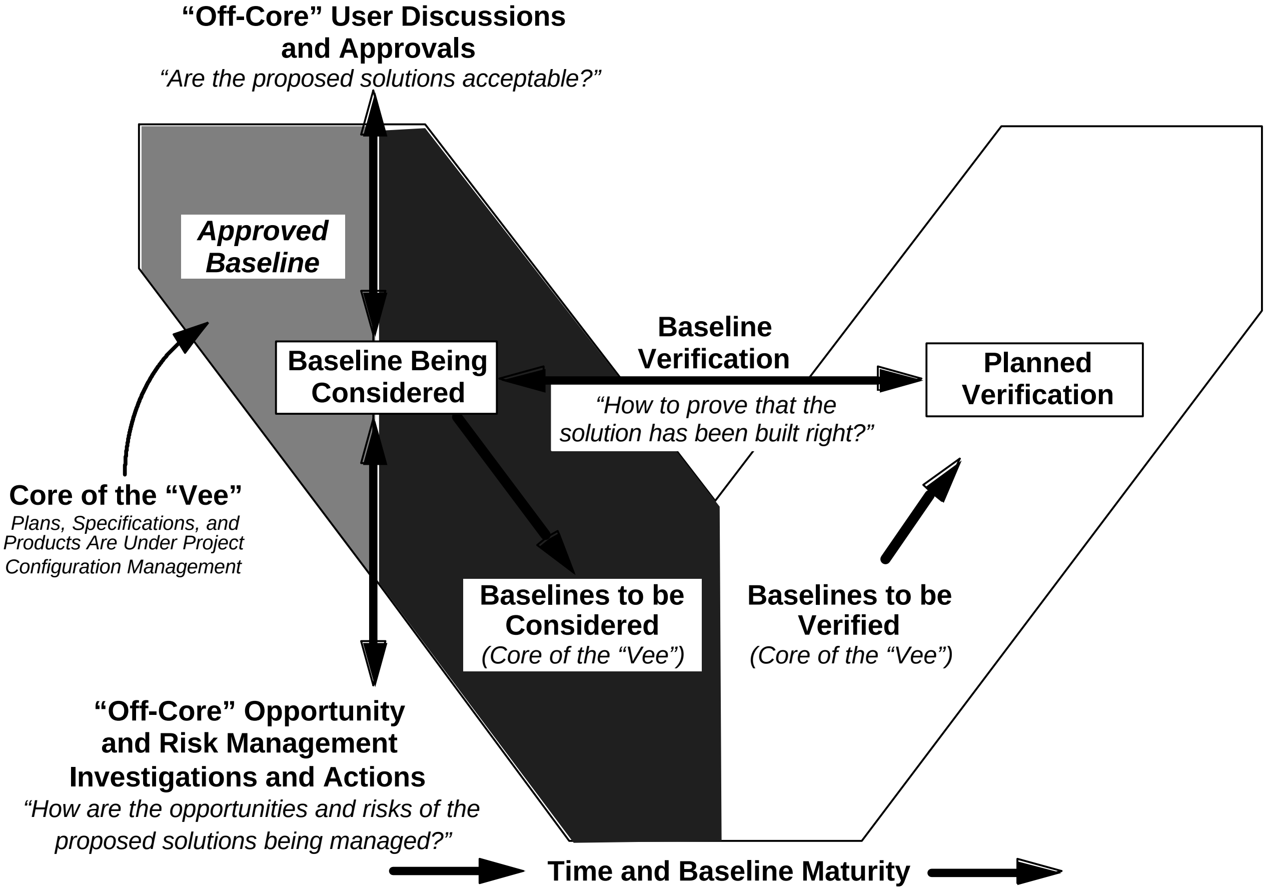


Figure 2 – Critical Aspects of Decomposition and Definition Emphasizing "Off-Core" Opportunity and Risk Management

CLEMENTINE

According to the project manager, the Clementine spacecraft was smaller (508 pounds dry weight), built faster (22 months), and cheaper ($80 million) than any previous deep space mission (Rustan 1995). The spacecraft, launched in 1994, had the mission objectives of photographing the earth, the moon, and an asteroid (Lenorovitz 1994). It met two of these three objectives, and the radar returns from the lunar South Pole strongly suggested the presence of ice in a large lunar crater. (This exciting discovery and the 1.8 million multi-spectrum pictures from the moon have rekindled national interest in manned lunar missions.) A fourth objective of this project was to prove that using a streamlined acquisition and management process, and maximizing the use of COTS, would substantially reduce the development cycle and development costs. These objectives were successfully demonstrated.

While the macro-objectives for the Clementine project were fixed, the detailed capabilities of the spacecraft were determined by what could be achieved with available equipment. So while “faster, cheaper, better” was the goal, the lower level requirements were not determined by the mission, but rather by existing capability. In fact the project team relied on traditional high-reliability piece-part and component procurement to achieve the necessary reliability levels. For instance, according to the project manager (Rustan 1995), “commercial diodes, transistors, and integrated circuits were prescreened prior to selection (approximately 4% of all diodes, 3% of all transistors, and 1% of all integrated circuits failed the screening test). …Sensor reliability analysis was conducted using the MIL-HDBK-217F reliability standard to identify potentially weak elements for replacement.” These traditional risk management activities are the “off-core” opportunity and risk identification and mitigation efforts discussed earlier (Figure 2).

The Clementine team used existing products for over half of their subsystems. Since the team did not need to develop the pre-existing designs, the “Vee” for a COTS component in their system would descend only to the component level as shown in Figure 3. However, off-core analysis and testing was necessary to investigate problem areas and to determine required modifications to achieve desired performance.

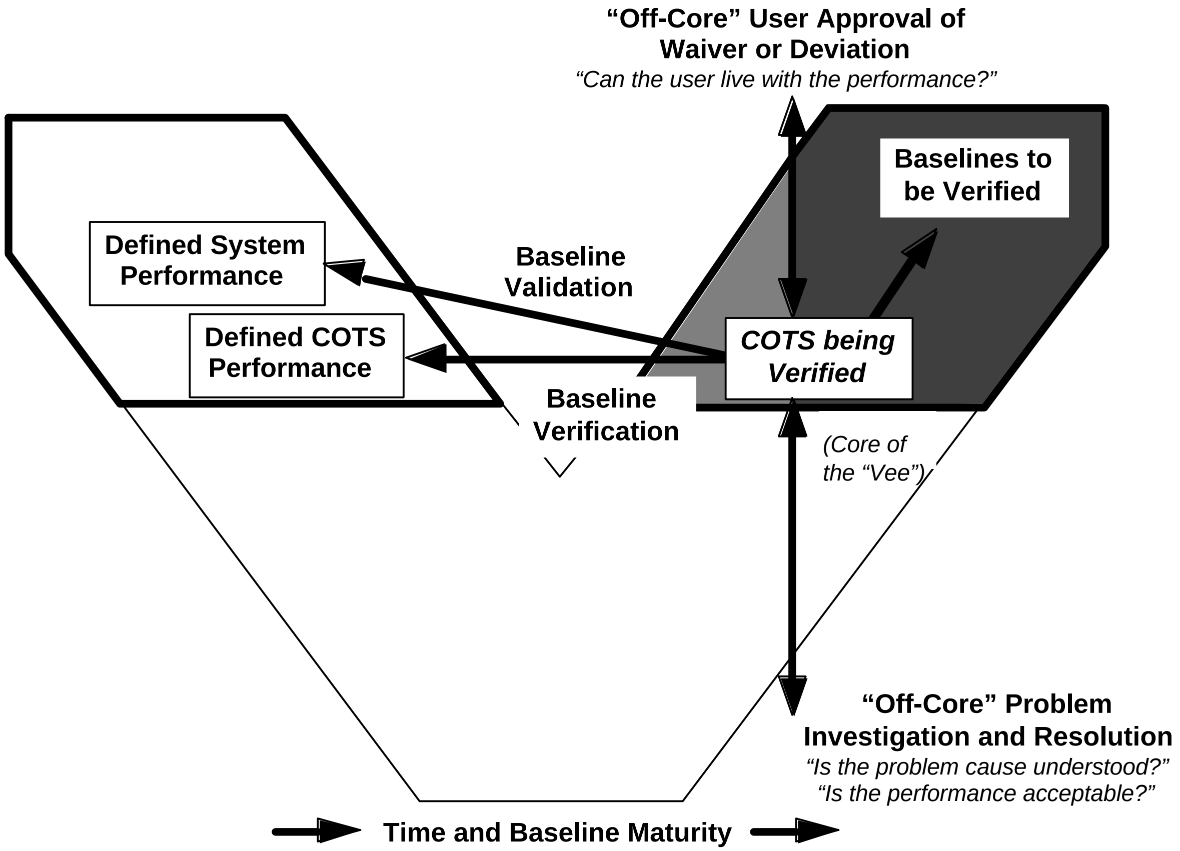
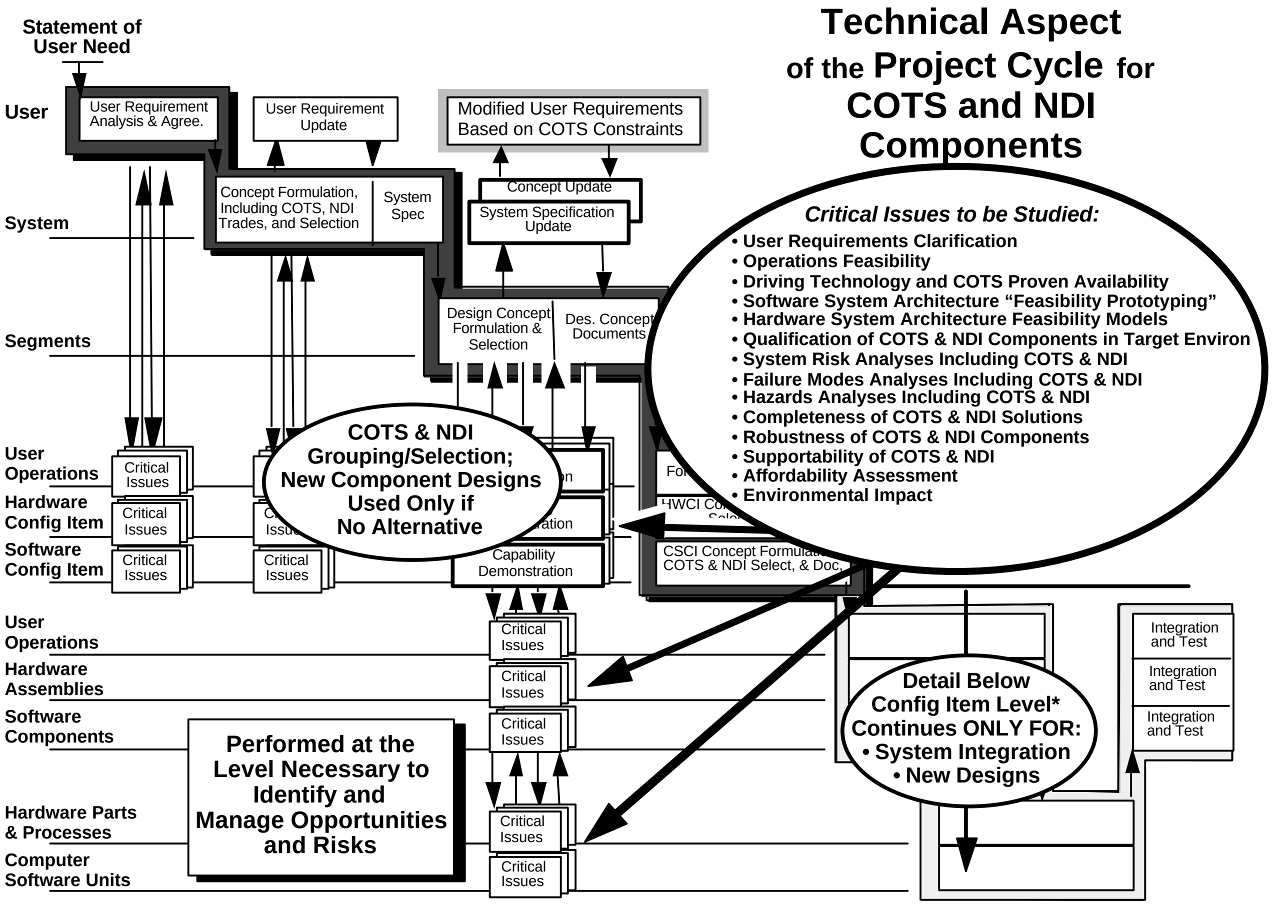


Figure 3 – Critical Aspects of Integration and Verification for a Commercial Off-The-Shelf Component

Many of the details of the critical issues to be studied in the off-core analyses for COTS and Non-Development Items (NDI) on Clementine are illustrated in Figure 4. It is important to note that the “Vee” for system design and integration should have reached the lowest level of decomposition (depicted in Figure 5), but for Clementine it did not. The pressure to meet the January 1994 launch date, which had been set in January 1992, caused some software testing to be restricted in scope. Incomplete low-level testing failed to detect the software error that caused the spacecraft to miss its third objective of photographing the asteroid. The Clementine team allowed schedule pressure to override proven software development discipline. In every project one must always balance technical risk versus project schedule.



* This chart uses the Configuration Item level for illustration; COTS & NDI can be used at any level.

Figure 4 – Critical Issues to be Studied for Commercial Off-The-Shelf (COTS) and Non-Development Items (NDI)

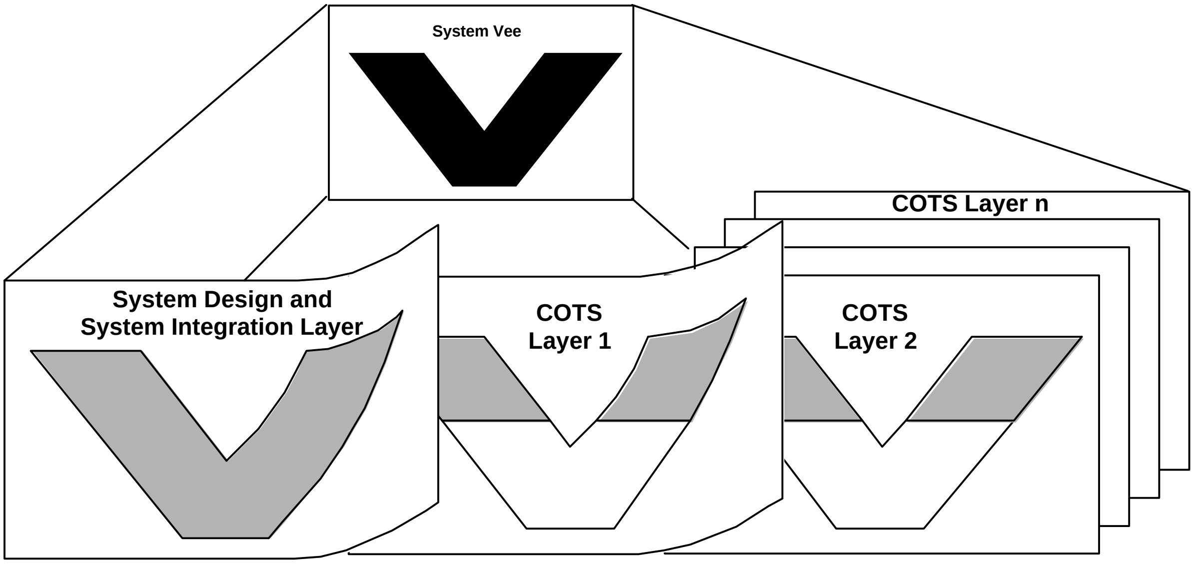


Figure 5 – The Vee, In Layers, for a COTS System.
The "Full-Depth" Vee is Required for Component Interfaces.

When asked to describe the top five factors contributing to Clementine's success, the project manager, Pedro Rustan, replied:

1. Empowerment, where the project manager has full authority (executive management stayed out of the way)
2. Leadership
3. Availability of a significant amount of hardware from previous projects which could be used in this project
4. Managerial, technical, and financial skills and motivation
5. Burning desire to succeed!

In an earlier article (Rustan 1994) he also identified several other factors necessary to the success of his project:

6. Collocate the team (including all the engineers and technicians) for all essential functions.
7. The project manager should control the procurement process; the government contracting officer should be responsible to the project manager.
8. Build and test an engineering model.
9. Reduce component traceability, formal quality control, and documentation procedures.
10. Use a small team with clearly defined responsibilities.

A comparison of Rustan's points with the operating procedures for the Skunk Works, a highly efficient aircraft development organization, shows a significant commonality (Rich 1994, p. 51-53). The operating rules for both Clementine and the Skunk Works are also completely consistent with the *essence* of good, traditional project management. The reason they succeeded is not that they abandoned obsolete processes, but rather that they intelligently tailored and streamlined the project management and system engineering processes to their needs.

MARS PATHFINDER

Like Clementine, the Mars Pathfinder project also introduced several new approaches to project implementation. Key was the early and comprehensive use of computer modeling and simulations (Smith 1997) during the study period, which allowed efficient concurrent engineering. The team also focused on integrating previously developed products. Some items such as a heat shield for Mars atmospheric entry are not commercially available (as yet). To take advantage of prior experience developed twenty years earlier on the Viking missions, heat shield design and fabrication experts were recalled from retirement. The Mars Pathfinder team successfully reduced the development cost by about one-half, compared to similar projects, and shortened the development schedule from five years to three years.

The Mars Pathfinder mission is one of the first NASA projects to be developed under the "faster, cheaper, better" paradigm. Discussions with Dr. Robert Shisko at JPL confirmed that there was a well-developed project management process and risk mitigation activity for the entire project development span, even though it was a departure from the approach used on previous large JPL projects. Dr. Shisko stated, "They implemented new things, combined in new ways, with the following highlights:

1. Flatter management structure, which shortened decision times,
2. Collocation of the entire team,
3. Greater authority given to subsystem managers,
4. Necessary documentation was created, but in a non-traditional, less formal way,
5. Preference for test over analysis during development,
6. The focus on "cheaper" caused careful management of cost and schedule reserves."

In addition the team had a well-defined quantitative risk analysis process. For instance, they modeled the entry, descent, and landing sequences, and used Monte Carlo analyses to provide data for risk management decisions. Although the team did not express it this way, the details of Figures 3, 4, and 5 apply here.

The observations by Dr. Shisko match very closely the areas emphasized by Rustan (Rustan 1994) in his article on spacecraft project management. Moreover the topics highlighted match exactly the intent of the tailored application of sound project management principles (Forsberg et al 1996).

THE BUYER PROJECT

Although not initiated under the banner of "faster, cheaper, better," the Buyer Procurement System (BUYER) project focused on one of the key avenues of success for "faster, cheaper, better": the use of Commercial Off-The-Shelf (COTS) products.

BUYER is a multi-million dollar software system designed to provide procurement support throughout a medium-sized commercial organization. After attempting unsuccessfully to build a "home-grown" system in the 1980s, a decision was made to purchase a COTS product and tailor it to the organization's needs. Three unsuccessful attempts over the past decade led to project termination in 1997. Had the project team used the concepts in Figures 2 through 5, problems would have been revealed earlier and more systematically instead of being a continuous string of surprises. A list of lessons-learned was compiled, from which the following points have been extracted:

- Poor requirements lead to poor plans.
- For COTS software projects, use incremental, phased development.
- For COTS software, pick the product, *then* pick a contractor based on their experience with *that* COTS product.
- Use of COTS products may require performance compromise.
- A COTS product is not really COTS if the vendor is modifying it.
- COTS software is not really COTS if it doesn't run on your target hardware and system software.
- Involve the user in the development process.

In the first two attempts the BUYER project failed because the selected COTS packages did not meet user requirements; in an environment of continuously changing user requirements, however, no development approach could succeed. Support organizations such as procurement often have a difficult time getting firm commitment from senior line managers so that the users will take the requirements development process seriously. In the third attempt to produce a system the team got the necessary management support and produced an excellent fifty-page Concept of Operations document, which finally identified a stable set of implementation-independent user requirements.

The last iteration of the BUYER project failed because, unknown to the team, key software that ran successfully in a commercial UNIX environment was only available in an alpha version for the new target environment (Windows 3.1). The problem was *not* the use of COTS, but rather the incomplete implementation of a good system engineering process. If the team had used good system engineering practices, they would have found the problems early enough to have allowed effective and timely resolution. The project team jumped on an attractive COTS solution, and did not perform off-core studies (Figure 3) to aggressively identify and mitigate risks associated with this opportunity to use COTS. Since they were unaware of problems, the team did not effectively manage the contractors supporting them.

A number of very smart and hard working people devoted years to make the BUYER project a success. They certainly displayed a "burning desire to succeed" (Rustan's success factor number 5 above). In fact the BUYER team did most things right. But, as the old saying goes, "close only counts in hand grenades and horseshoes." This is *not* an example of problems caused by "faster, cheaper, better" concepts; rather, the BUYER team simply failed to follow proven system engineering and project management principles.

THE THERAC-25 PROJECT

The Therac-25 is a computerized radiation therapy machine used to treat cancer patients. It was first used in commercial hospitals in 1982. The goal of the manufacturer was to replace two older models with a new design that was more useful to the hospital, because it combined both low and high-energy modes of operation into a single unit. It was also designed to be cheaper to produce and operate. The Therac-25 project used software NDI (non-development items) in its design. Although not developed under the banner of "faster, cheaper, better," this project is relevant to this paper because use of NDI is a primary means highlighted by management for "faster, cheaper, better" projects, but the risks in the use of NDI are often overlooked.

An excellent study of the cause of the Therac-25 failures (Leveson 1993) reported that "between June 1985 and January 1987, six known accidents involved massive overdoses by the Therac-25 – with resultant deaths and serious injuries. They have been described as the worst series of radiation accidents in the 35-year history of medical accelerators." This 24-page article should be mandatory reading for any system engineer involved in reuse of hardware or software for new applications.

The Therac machines provide two modes of operation: low energy, long time exposures and high energy, short time exposures. The energy settings were controlled by software on a PDP-11 computer. The software had software interlocks to prevent long exposure at high energy levels. For the first three years of operation, the eleven machines performed as expected. However in 1985 a patient in Georgia "received one or two doses of radiation in the 15,000- to 20,000-rad (radiation absorbed dose) range. …Typical single therapeutic doses are in the 200-rad range. Doses of 1,000 rads can be fatal…" After two years of investigation (and 5 accidents later) it was found that a fast typist could enter data and move to a new screen faster than the computer cycle time for polling the screen entry data. Thus input data were lost and so the software safety interlocks were bypassed. This allowed high energy, long exposure times to be accidentally activated.

The Therac-25 development used software from two earlier models (Therac-6 and Therac-20). Both earlier systems used the PDP-11 computers (as did the Therac-25), and both older systems had been in use for a decade without problems. Selected software was used without modification in the new machine. The developer did not recognize that this "previously developed product" was not being used in exactly the same way, however. Both of the Therac-6 and Therac-20 models had software *and hardware* safety interlocks. The new Therac-25 had only software safety interlocks to save cost. After the Therac-25 accident investigation was completed, a re-examination of the Therac-20 showed that the old software had exactly the same failure mode, and the hardware interlock prevented this from becoming a hazard.

Leveson and her co-author highlighted important lessons about software reuse: "A naïve assumption is often made that reusing software (NDI) or using commercial off-the-shelf (COTS) software increases safety because the software has been exercised extensively. Reusing software modules does not guarantee safety in the new system to which they are transferred and sometimes leads to awkward and dangerous designs. …Rewriting the entire software to get a clean and simple design may be safer in many cases." In addition they found that, along with other problems, good system engineering was lacking in the Therac-25 design and development, and proven software engineering practices and processes were not followed. There was no effective peer review during the system development phase.

The Therac development team used previously developed software to save development cost, to save development time, and to create a better product (the same goals sought by advocates of "faster, cheaper, better"). In this case, faster and cheaper did not lead to better.

GENERAL OBSERVATIONS

Product Reliability. How good does the COTS product have to be? A score of 96% (success rate for diodes screened for use in the Clementine) is an excellent test score in school, but is it satisfactory for your project? Consider the consequences of an even tighter 99% successful performance requirement (Harry 1987):

- 20,000 lost articles of mail per hour
- Unsafe drinking water almost 15 minutes each day
- 5,000 incorrect surgical operations per week
- Two short or long landings at most major airports each day
- 200,000 wrong drug prescriptions each year
- No electricity for almost 7 hours each month

Most consumer COTS products fail to some degree, whether we talk about new cars or new Microsoft Office 97 applications. The issue for system engineers to resolve is whether or not the failures are of importance to their project. Most people would refuse medical treatment from a device or medical system which had a reliability level equivalent to current commercial software products sold for use on desktop computers.

The COTS product being reviewed for a specific application may not be suitable for its "new use" as it comes "off the shelf." System Engineering has the obligation to evaluate the risks and to decide on the appropriate actions. As the Therac-25 accidents revealed, assessing the suitability of a COTS or Non-Development Item (NDI) solution is non-trivial.

Shortened Project Development Schedule and Reduced Cost. Project teams for both Clementine and Mars Pathfinder tout their success in reducing project schedule from the traditional five or six years to an "amazing" two to three years. What is new? America's first operational fighter jet, the P-80, was developed from concept to first flight (in 1945) in 143 days (Rich 1994). The U-2 went from concept to first flight (in 1955) in just eight months. The SR-71, still one of the most advanced aircraft in the world in 1998, thirty-six years after its first flight, was developed from concept to its first flight (in 1962) in thirty two months. The SR-71 also pushed the state of the art in many areas, including the structural use of titanium. The Corona project, America's first reconnaissance satellite, took three years and 11 months from project start to the first totally successful flight (in 1960); this span includes 13 launches before full success was achieved. The Corona program was started before any man-made objects were put into orbit so everything from concept to reliability was first of a kind. These four projects share a common trait in that all had a national mandate and resources (which had to be continuously justified) to get the job done right.

The P-80, U-2, and SR-71 were all developed in the Lockheed Skunk Works (Rich 1994). The Corona was developed in a Skunk Works-like environment, with Kelly Johnson, founder of the Skunk Works, as an advisor (Aronstein 1997). While Lockheed seems to be the only organization to sustain a Skunk Works for an extended time (fifty years), Aronstein discusses three other independent aerospace Skunk Works operations (two American, one German) which embodied the same rules and outstanding successes (Aronstein 1997, Appendix C). The Skunk Works concepts were also common and effective in the computer industry. IBM, Control Data, and Intel all maintained significant Skunk Works-like operations.

One of the characteristics of the Skunk Works is that it is a small part of a larger organization and they were able to "skim off the cream of the crop" for engineering and manufacturing talent. No organization can have all its projects operate in this way, so there is a challenge in making the Skunk Works concepts work in general. However the principles of a thoughtfully tailored system engineering and project management process, a small, empowered, collocated team, and tailored documentation, to name a few areas, can apply to any project. The factors highlighted as elements in the success of Clementine and Mars Pathfinder are consistent with the Skunk Works guidelines. The Skunk Works operating principles are indeed a model paradigm for the "faster, cheaper, better" projects to follow.

One of the consequences of the successes of the process models of the 1960s is that they led in 70s and 80s to more formalization of process and often to unnecessarily rigid adherence to a generic (untailored) process. As noted by Cialdini (Cialdini 1993), Ralph Waldo Emerson in his essay "Self-Reliance" said, "A *foolish* consistency is the hobgoblin of small minds." There are many instances in the experience of the authors and our colleagues where unthinking adherence to process led to wasted time and money. In the 1970s and 80s projects typically stretched out many years and costs grew significantly. Average project spans are shown in Table 1.

Decade	**Average span from Project Start to Initial Operational Capability**
1960s	74 months
1970s	104 months
1980s	107 months
1990s	97 months

Table 1 – Average Project Span for Major Defense Acquisition Programs (Acquisition Reform 1997)

In the early 1990s the Department of Defense mandated that DoD standards and specifications be replaced by commercial ones - even though commercial counterparts do not always exist; the objective was to break down barriers between the DoD and the commercial market place. A side benefit is that it forces everyone to break the constraints of their old paradigms and rethink the processes from scratch. That is also one of the challenges the "faster, cheaper, better" advocates have given us. The key is that any process must be tailored to the project at hand, and the system engineer must thoughtfully perform this tailoring.

The penalty for inappropriate deviation from the process can be severe, however. The GOES NEXT project, which started in 1985, was designed to provide the next generation of weather satellites with the first launch planned for 1989. A five-year development should have been more than adequate. The first launch actually occurred in 1994, five years late and with a five-fold increase in costs (to $1.2 billion). The GOES NEXT management team decided early in the development that since satellite production was almost routine they could skip the study period. They also used a "qualification by heritage" concept that (as later discovered) was not always appropriate. The consequence was that critical development issues, which should have been found in the off-core studies (Figures 2 and 4), were not discovered until the project was well into the implementation phase. Use of COTS or NDI would not have mitigated this failure to follow the process.

Another example of the consequences of inappropriate tailoring of the project cycle is found in the Lewis spacecraft launched by NASA in August 1997. This spacecraft was not simply the first of a new generation – it was to be a pathfinder in a new way of doing business. Two of the business objectives were to validate a new approach to acquisition and management of spacecraft systems, and to reduce cost and development time of space missions for science and commercial applications. Developed under the banner of "faster, cheaper, better," the Lewis spacecraft achieved the first two. Lewis was launched on 23 August 1997. The first problem was found 20 minutes after launch. All contact with the spacecraft was lost on 26 August 1997. There are specific engineering and operational causes of the failure. However, from the system engineering process standpoint, one of the primary causes was the abandonment of informal peer reviews two years prior to flight. The contractor reduced the number and scope of internal reviews to save costs, and could do so because the customer did not require them. From the perspective of our model, they did an inadequate job of the off-core risk management. The lack of peer reviews allowed the risk areas to go unchecked to orbit.

Creeping elegance is another culprit in derailing a project. Reaching back two hundred and fifty years, the history of the development of the maritime chronometer is an excellent object lesson for us in our modern era. This critical device could have saved literally thousands of sailors' lives in the 1700s, but John Harrison, the inventor, refused to release his design for forty years, because he had "not perfected the details" (Sobel 1996). In that forty year span, Harrison created five working models that were field-tested and met all requirements, but each time he saw a way to improve the product before its release.

Conversely, the Clementine project manager insisted that the team use the existing capability of the COTS products to drive the system capability. The desire to "improve" on the COTS products was prohibited. As noted in the BUYER lessons learned, use of COTS products may require performance compromise. The system engineer must control the requirements management process.

CONCLUSION – BACK TO BASICS

The success of the "faster, cheaper, better" approach confirms the original purpose of the process models as represented by Figures 1 through 5. Nothing in the actual experience of the projects reviewed here contradicts the value and intent of the traditional view. In fact they forcefully remind us that any process must be *understood, tailored appropriately, and aggressively managed.* The multi-segment model (Figure 5) can be combined with an incremental or evolutionary approach to suit the needs of a project. Pro forma application of the process will be destructive to all involved. *Avoid foolish consistency.*

When we started the study of projects implementing the "faster, cheaper, better" paradigm, we expected to find a new way of doing business. We planned to map that new process against the "traditional" project management process to highlight the differences. In fact what we found was that the project champions had thoughtfully tailored the old way of doing business to eliminate waste and overturn irrational or unnecessary barriers. The Clementine project manager has explained how he managed the process (Rustan 1994). NASA JPL has presented their project management approach for the Mars Exploration Program (Shirley 1996; Staehle 1996). All are consistent with the project management process previously discussed (Forsberg et al. 1996).

The real breakthrough by the project teams on Clementine and Mars Pathfinder was to apply appropriate tailoring of the project cycle, and effective implementation of concurrent engineering on the off-core opportunity and risk identification and mitigation studies. In the failed projects cited earlier, many smart people worked very hard to achieve success; however, to save time and cost, they omitted key steps which lead to their downfall. You have to understand the project management and system engineering process before you can successfully tailor it. To tailor without understanding is to invite disaster.

Properly applied, the experience of the past four decades is entirely relevant to today's drive for "faster, cheaper, better." The Skunk Works experience is also relevant to our goals here (Rich 1994; Aronstein 1997). Thoughtful application of the principles underlying the traditional project management cycle and system engineering management process will yield success if we are alert to the need for tailoring and implement an aggressive opportunity and risk management policy. The Clementine and Mars Pathfinder projects have proven it can be done. The other projects cited illustrate the risks if the process is not carefully tailored. System engineers now need to be proficient in the approach so the successes can be repeated and failures avoided.

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REFERENCES

Acquisition Reform Benchmarking Group, "1997 Final Report, Part 2 – Measuring Cycle Time Improvements," Prepared for the Under Secretary of Defense (Acquisition and Technology), 30 June 1997 (www.acq.osd.mil/ar)

Aronstein, David C., and Albert C. Piccirillo, *Have Blue and the 117A*, American Institute of Aeronautics and Astronautics, Reston, VA, 1997

Cialdini, Robert B., *Influence, The Psychology of Persuasion,* William Morrow and Company, Inc., NY, NY, 1993

Forsberg, Kevin, Hal Mooz, and Howard Cotterman, *Visualizing Project Management*, John Wiley & Sons, NY, NY, 1996

Harry, Mikel J., "The Nature of Six Sigma Quality," Motorola Inc., Government Electronics Group, 1987

Lenorovitz, Jeffrey, "Clementine to Mark U.S. Return to Moon," *Aviation Week and Space Technology*, p. 66-67, January 17, 1994

Leveson, Nancy G. and Clark S. Turner, "An Investigation of the Therac-25 Accidents," *IEEE Computer*, p. 18-41, July 1993

Rich, Ben R. and Leo Janos, *Skunk Works*, Little, Brown and Co., Boston, MA. 1994

Ruffner, Kevin C., Editor, *Corona: America's First Satellite Program*, CIA History Staff, Center for the Study of Intelligence, Washington, DC. 1995

Rustan, Pedro L., "Spacecraft Project Management," *Technology Management*, Vol. 1, p. 17-23, 1994

Rustan, Pedro L., "Clementine: Measuring the Results," *Aerospace America*, p. 33-38, February 1995

Shirley, Donna L., "'Mars on $300K a Day': The Mars Exploration Program," NASA APM-23 Fast Track Study, p. 2-14, November 1996

Smith, David B. and Mike Vertal, "Flight Project Reengineering: A Modeling Approach'" presented at the seventh *International Council for System Engineering (INCOSE) Symposium*, August 1997.

Sobel, Dava, *Longitude*, Penguin Books, NY, NY. 1996

Staehle, Robert, "Pluto Process Improvement Initiatives," NASA APM-23 Fast Track Study, p. 53-57, November 1996

BIOGRAPHIES

Dr. Kevin Forsberg draws on 27 years of experience in System Engineering, Project, and Proposal Management and fourteen years of successful consulting to both government and industry. His experience ranges from research projects, to development efforts, through to full-scale production implementation. Training and consulting have been provided to many organizations including AT&T, Lucent, GTE, SAIC, TRW, Lockheed-Martin, Chiron, CIA, NASA, and other government agencies.

Dr. Forsberg is co-founder of the Center for Systems Management. He is co-author of a book, *Visualizing Project Management*, J. Wiley & Co., 1996, and has over forty published articles in referred journals.

Awards

NASA Public Service Award, for outstanding contribution to the Space Shuttle Program

Agency Seal Medallion, CIA, for pioneering effort in project management training

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Mr. Harold A. Mooz draws on 22 years of experience in System Engineering and Project Management and 16 years of successful consulting to both government and industry. Training and consulting have been provided to AT&T, Bell Labs, GTE, TRW, Lockheed, Emerson Electric, CIA, NASA, and other government agencies. Mr. Mooz has developed leading industry training programs and has trained over 5000 high technology project managers.

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