Pergamon

Technovation 21 (2001) 197–207

technovation

www.elsevier.com/locate/technovation

A pragmatic representation of systems engineering based on technological learning

Elias Carayannis [a,*], James Forbes [b]

[a] George Washington University, School of Business of Public Management, 2115 G Street NW, Washington, DC 20052, USA
[b] Logistics Management Institute, 2000 Corporate Ridge, Mclean, VA 22102, USA

Received 1 December 1999; accepted 28 February 2000

Abstract

In this paper, we will argue that the apparent tendency for large engineering projects to produce other than intended results stems not from the particulars of the projects but, more basically, from representing them as overly simplified, highly linear, and often hyper-rational schemes to begin with. We suggest that a key factor in the tendency to go in unanticipated directions is the inherently difficult to predict effect of ongoing sense-making and multi-level technological learning (Carayannis, E., 1999. Knowledge transfer through technological hyperlearning in five industries. Technovation 19, 141)—feedback with a vengeance, so to speak. Further, since this learning is shaped by social context, various stakeholders may well learn differently. Hence, the practice of reliability engineering, logistics engineering, and systems engineering generally, rather than being bad engineering or bad application of good engineering, can instead be reformulated as an ongoing sense-making activity embedded in an adaptive social process. Three case studies serve as archetypes for three fairly common results. The three cases are 'Unexpected Opportunity', 'Failure then Success', and 'Technophobia'. Each case study has two parts. In the first part we present the specifics of the case in abbreviated form. In the second part of each case we place what happened within a common conceptual framework. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Systems engineering; Organizational learning; Knowledge management

1. Introduction

It takes only a casual perusal of the news to recognize that large technical and engineering projects seldom go as smoothly as anticipated. Examples abound of projects that, at some point, seem to go awry. Well known historical examples include the *Titanic* and the collapse of the 4-month-old Tocoma Narrows Bridge. More recent examples include the C-17 aircraft, the B-1 aircraft, the 668-class fast-attack submarine, the advanced tactical fighter, the Hubble space telescope when first launched, the Galileo space probe, the FAA air traffic control system modernization, and information systems projects generally. Why is it that these projects appear to go awry so often? Is it the prevalence of ad hoc processes, mistrust, or enmity instead of rational management and engineering processes as one observer has claimed (Tyler, 1986: 11), the scope of technical difficulty, failure to sit down before system implementation begins and think through all of the implications (Davenport, 1998: 128), or are there alternative explanations?

It is the intent of this paper to suggest a fairly obvious alternative explanation, one that should accord with the experience of engineers who have worked on or with such programs. We will argue that the apparent tendency for large engineering projects to produce other than intended results stems not from the particulars of the projects but, more basically, from representing them as overly simplified, highly linear, and often hyper-rational schemes to begin with. Kline and Rosenberg (1986) (p. 275), in their classic introduction of the chain-link model of innovation (see Fig. 1), have already convincingly argued that innovation, rather than being linear, is "...complex, uncertain, somewhat disorderly, and subject to changes of many sorts". Further, they and others such as Clark (1985) and Drejer (1996) have provided important insights to the reasons for nonlinearity by

* Corresponding author. Tel.: +1-202-994-4062; fax: +1-202-994-4930.
E-mail address: caraye@ibm.net (E. Carayannis).

0166-4972/01/$ - see front matter © 2001 Elsevier Science Ltd. All rights reserved.
PII: S0166-4972(00)00028-6

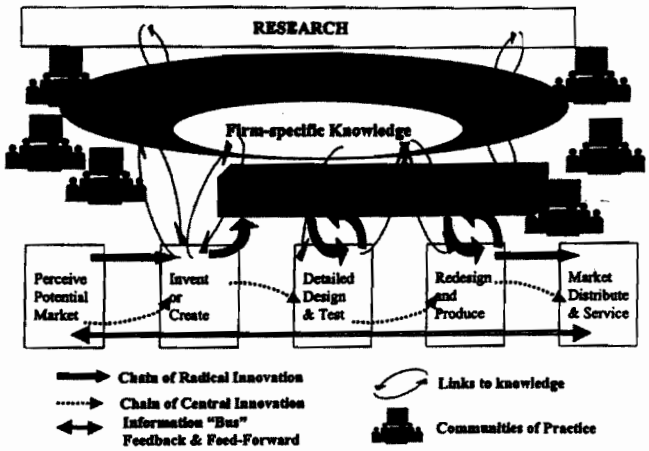

Fig. 1. Chain-linked model of technological innovation.

recognizing that innovation involves a series of changes in a system of hardware, production environment, market environment, and many other elements.

As anyone who has applied systems dynamics will recognize, even linear relationships lead to non-linear behavior when feedback is included. Here we would like to suggest that a key factor in the tendency to go in unanticipated directions is the inherently difficult to predict effects of ongoing sense-making and multi-level technological learning (Carayannis, 1999: 141)—feedback with a vengeance, so to speak. Further, since this learning is shaped by social context, various stakeholders may well learn differently. The natural result is that they can end up with quite different perceptions.

Technological learning is defined as the process by which a technology-driven firm, its suppliers, customers, and competitors (indeed, communities of any kind) create, renew, and upgrade latent and enacted capabilities based on stocks of explicit and tacit resources. It combines both technical and administrative learning processes. Technological learning processes are also organizational transformation processes since individuals, groups, and/or the organization as a whole internalize, with both extrinsic and intrinsic motivation, technical and administrative experience to update organizational decision making routines and the methods for managing uncertainty and complexity (Carayannis, 2000). In the context of large engineering projects, a good deal of this learning involves making sense of the new technologies themselves.

Before continuing the discussion, we note initially that although downside surprises might tend to dominate both the news and anecdotal histories, it is not so much a case of results always being worse as simply being unexpected. We profile here three detailed stories that document the processes for generating, diffusing, capturing, absorbing, and recycling institutional knowledge.

Large technical and engineering projects are generally thought of as being managed through systems engineering activities. Since systems engineering includes a number of disciplines, to give focus to the discussion that follows we will use examples from the sub-disciplines of reliability and logistics engineering. In these two areas, as in systems engineering generally, results generally do not always agree well with what was intended, i.e. they tend to go awry. The paper will argue that the practice of reliability engineering, logistics engineering, and systems engineering generally, rather than being bad engineering or bad application of good engineering, can instead be reformulated as an ongoing sensemaking activity embedded in an adaptive social process. When so viewed, what presently appear to be perverse outcomes are, instead, natural and expected, potentially even manageable.

2. Outline of the paper

We begin with three mini-case studies that will serve as archetypes for three fairly common results. The three cases are 'Unexpected Opportunity', 'Failure then Success', and 'Technophobia'. Each case study has two parts. In the first part we present the specifics of the case in abbreviated form. In the second part of each case we place what happened within a common conceptual framework.

In the second part of the paper we will expand on the common conceptual framework and discuss some of the implications for systems engineering.

3. Case studies

3.1. Case A—unexpected opportunity

3.1.1. Background

Technology Development Command (TDC) contracted with Aerospace Company (AC) to develop a new air-launched attack missile (ALAM). The ALAM contract included specific reliability requirements that missiles had to achieve after they were delivered to Offensive Air Command (OAC).

Since OAC did not have a reporting system that would record reliability-related data, AC developed and delivered such a system as part of its contract. The plan was that technicians belonging to OAC would do the data entry. For each maintenance action they would record the date, the serial number of the missile itself, the serial numbers of major components when those components were replaced, and the actual work they performed (e.g. removal from and return to storage, results of scheduled tests and inspections including passes and failures, modifications, and repairs). The data were then uploaded to a central computer at one of AC's plants. When OAC

first understood what they were being asked to do they were bitterly opposed—seeing the situation as one where they were being asked to commit significant amounts of their technicians' time to entering data into a system from which they received no benefit. Although the possibility of contractor entry of the data was discussed, TDC took the position that it did not make sense to pay to keep a contractor employee full time at each missile storage location just to do data entry. In the end TDC prevailed but the dispute left a bad aftertaste for everybody.

The next part of this story requires a partial understanding of how missile maintenance is managed. OAC technicians generally removed (or 'broke out') missiles from storage for one of three reasons: upload on an aircraft, scheduled automated surveillance testing, and installation of design modifications. Because of the large labor content associated with breakouts, OAC's technicians tried to minimize the number they did. A fly in this ointment, however, was the arrival of a modification kit from MSC.

Managers at MSC would check their records to find out which operational base had the most unmodified missiles and, when they received a modification kit, send it to that base. When the base received the kit the base had a limited amount of time to install it on an unmodified missile. In the event that a base did not install a kit within the allowable time window they were subject to various forms of managerial harassment by both their own headquarters and MSC—hence they had motivation to get the kits installed expeditiously. Whenever possible, the technicians would try to modify a missile that they were breaking out for some other reason. As fortune would have it, however, the more typical circumstance was that either there were no missiles due breakout or, if there were, they would already have been modified. This meant that a missile had to be broken out for the sole purpose of installing the modification kit. Technicians were not fond of such extra break-out opportunities.

Within a few months after the reliability data system was in place, modification managers at AC and MSC realized that they had an unplanned-for capability. Now they knew not just which base had the most unmodified missiles but exactly which missiles were unmodified and when those missiles were due a scheduled breakout. As a result of this visibility, when a modification kit was ready MSC would ship it to a missile base that was about to break out an unmodified missile. The ability to reap scale economies by combining modification kit installation with scheduled inspections had important consequences. First, OAC was able to reduce missile maintenance staff requirements by over 40% and apply those authorizations to other high priority needs. Second, whereas with past data systems data entry had been haphazard at best, OAC's technicians now were incentivized to place emphasis on accurate data entry. And third, when several years later TDC began development of another missile system, OAC 'demanded' that it come with a reliability data system.

3.1.2. Discussion

In order to appreciate what was going on here one has to see data systems from the viewpoint of maintenance technicians. The technicians' view, based on their experience, was something like that portrayed in Fig. 2. After a technician would complete a maintenance task he or she would spend inordinate amounts of time entering cryptic maintenance codes on paper forms to document the maintenance. The completed forms were then entered by a clerk into a local computer system and transmitted to a distant mainframe. Feedback was limited to criticism for the errors that the technicians may have made in recording the data—or that the clerk may have made but the technician had to correct anyhow. From time to time an engineer or manager from TDC or MSC visited the bases and explained how important the data were to engineering and logistics analysis. But this explanation came across as remote to the technicians; the analysis the engineers described never seemed to see the light of day once completed.

What we have just described is the construction, through learning, of a shared if tacit working model of the world (Bowlby, 1973: 203) which included a representation of maintenance information systems. The working model or, alternatively, structural metaphor (Lakoff and Johnson, 1980: 61) highlighted certain aspects of the concept 'maintenance systems' and permitted the maintenance technicians to generate a set of learned rules (Lindenberg, 1989: 175) governing values (Carayannis, 1999: 148) or stock of standard procedures for reducing equivocality (Hall, 1984: 908) and forecast how a new information system would behave. Key governing values were that they were administrative nuisances and provided little if any benefit. Thus, that was their forecast for the new system. Since the staff at headquarters Offensive Air Command were chosen from the community of senior field technicians, the headquarters

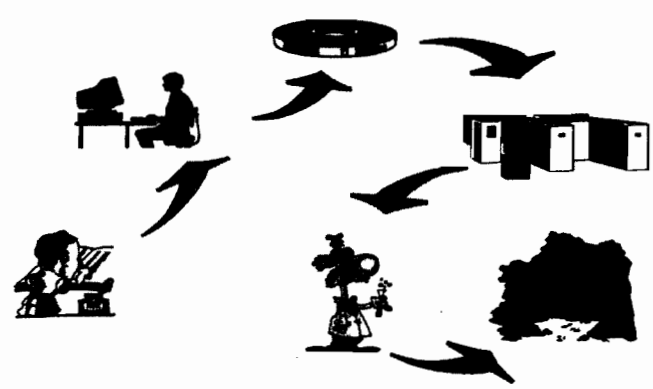

Fig. 2. Model of maintenance information systems.

shared the same working model, the same governing values, and the same forecast. Later—after the new maintenance information system was in place and being used to synchronize missile modification kit work with other work on missiles to their benefit—they modified their working model and values through double-loop learning (Argyris and Schon, 1978: 2–3) as a result of experience. The modified working model and values then became the basis for forecasting the behavior of future maintenance information systems.

3.2. Case B—failure then success

3.2.1. Background

On one of its primary aircraft, Operational Command routinely flew 9 to 12 hour missions. As a result of increasing age, system reliability of the analog technology avionics suite had dropped to just over 3 hours mean time between failure (MTBF). Even though redundancy compensated to some extent for hardware failures, the increasing number of mission failures attributable to unreliable avionics was of growing concern. Also of concern was the increasing cost of avionics maintenance due to the high failure rate. In response to Operational Command's concerns, Technology Development Command (TDC) initiated a program to develop a replacement avionics suite based on digital technologies. TDC contracted with Large Aerospace Company (LAC) to develop the new system. The new avionics suite included multiple computers, dual inertial platforms, Doppler radar, and a radar altimeter—all of which were integrated with each other, the existing search radar, and sophisticated software-based navigation programming. Program managers in TDC specified 33 hours MTBF in the development contract and featured the 10-fold increase prominently in their briefings and correspondence.

Development of the new avionics suite occupied about 4 years; initial production and installation of modification kits took another 24 months. When enough flight test hours had accumulated on the initial production aircraft to compute system reliability of the new avionics suite, the achieved reliability averaged 12.5 hours MTBF. Test Command compared the 12.5 hours to the promised 33 hours, declared the reliability results a failure, and issued a scathing report on the program. Four years later when production was complete, average field reliability had improved modestly to 13 hours MTBF. Operational Command, in contrast to Test Command, counted the achieved avionics reliability among its most important successes.

3.2.2. Discussion

Clearly there is something awry if 33 hours MTBF is promised, 12.5 hours is delivered and declared an abysmal failure, and then nearly the same value, 13 hours, is touted as a important success. Understanding the story behind these numbers and their differing interpretations is instructive.

Differing definitions of 'failure' account for part of what was going on (Table 1; Types 3, 4, and 5 were not accidentally left out of this table—their meanings have been lost to history during the last 25 years). Operational Command and Test Command, when they assessed the reliability of the original main avionics suit were concerned with *all* failures. This is natural enough: it does not matter to an aircrew trying to complete a mission if somebody is unable to duplicate a failure on the ground later or if they discover that a failure was induced through a maintenance mistake. Technology Development Command and LAC, though, had a different view of failures. When they entered into a contract for the new avionics system, they had in mind design reliability (Type 1). This is also natural enough since inherent failures were a recognized part of the designer's domain; failures not inherent in design were viewed as outside his or her domain. Such simplification to reduce complexity is normal in reliability engineering (Ascher and Feingold, 1984: 63). In the case of both Operational Command/Test Command and TDC/LAC, members of those organizations had "...created a sensible rendering of previous events stored in the form of causal assertions" (Weick, 1979: 166) and then made this rendering binding on the current situation. Operational Command and Test Command rendered failures based on mission impact; TDC and LAC rendered them based on perceived ability of the designer to influence reliability outcome.

It is also important to note that the distinctions at issue were more tacit than explicit. Contracts, briefings, test reports, and other documents referred only to MTBF, not what MTBF 'meant' or the kinds of failures that were counted when computing it. This also is fairly natural since for each of the four communities the community-specific meaning of MTBF and associated counting rules had become part of the tacit, taken-for-granted, cultural knowledge (Berger and Luckmann, 1966: 68) of that community and were outside the community's direct awareness (Rioch, 1970: 59; Wassmann and Dasen, 1998). Because the tacit nature of the meaning was outside awareness, each community, without realizing it, had assumed that anybody else would attach the same

Table 1
Failure types

Type	Description
1	Inherent failures (i.e. inherent in the design)
2	Induced failures, typically caused by a person (e.g. wrong lubricant, dropped)
6	No defect, could not find anything wrong

Table 2
Results summarized

Circumstance	MTBF value	Frame of reference	Evaluation
Actual on old system	3.5	Types 1, 2, 6	Limitation on combat capability
Requirement on new system	33	Type 1	Almost 10-odd improvement (comparing type 1 to types 1, 2, 6)
Actual (operational test) on new system	12.5	Types 1, 2, 6	Program failure (comparing types 1, 2, 6 with type 1)
Actual (field) on new system	13	Types 1, 2, 6	Program success (four-fold improvement over previous system)

meaning it did to the symbol 'MTBF'. Thus, the communities were unknowingly talking past each other.

Even though their assessments were separated in time, Test Command and Operational Command were also, for all practical purposes, talking past each other even though they shared the same counting rules. Operational Command reached its conclusions by comparing 3.5 hours to 13 hours—a four-fold improvement it was glad to have. Test Command had compared 12.5 hours worth of oranges to 33 hours worth of apples without knowing it was doing so. All of this is summarized in Table 2.

3.3. Case C—technophobia

3.3.1. Background

At the beginning of the decade, Using Command was starting to get concerned about the age of one of its primary cargo aircraft types and came to the conclusion that it was time to start a new development program. The procedures for starting a new development program required that Using Command develop a need statement. One section of Using Command's need statement for the new cargo aircraft read, in part:

> Reliability and Maintainability for the mature system will equal or exceed the best of in-service cargo aircraft.

The right-hand chart on Fig. 3 illustrates what Using Command got in the way of reliability of the engines for the new aircraft. Reliability certainly exceeded the best of the in-service cargo aircraft—by nearly a five to one margin. But, as illustrated by the specific fuel consumption comparison on the left-hand chart, it was not just reliability that improved from one generation of engine to the next, the engine was less expensive to operate in general, as was generally the case, by the way, for the entire aircraft.

Ten years after it had published a need statement for a new primary cargo aircraft, Using Command decided that increasingly challenging mission requirements being placed on one of its other cargo aircraft required the addition of a new sophisticated avionics system incorporating various state-of-the-art advances in forward looking infra-red and related night vision technologies. The requirements document that Using Command published at that time read in part:

> All modified/added aircraft systems or equipment must either meet or exceed the R&M [reliability and maintainability] values obtained by the same system or equipment installed on similar aircraft.

[Text in brackets added]

In the interim period between the two documents, all of the individuals who prepared the first document had long since departed. In fact, most of Using Command's staff positions had seen at least three incumbents come and go during this time frame.

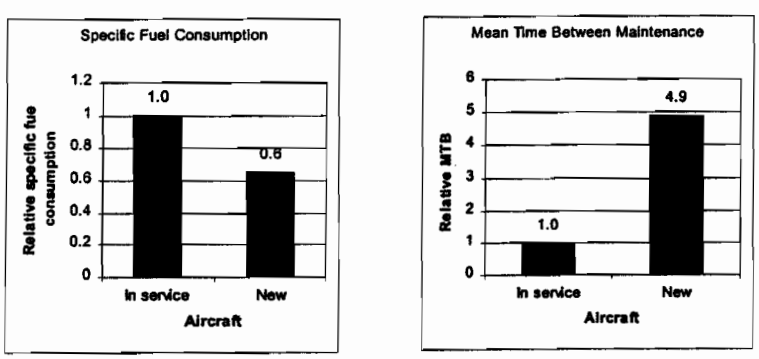

Fig. 3. In-service aircraft compared with new aircraft.

3.3.2. Discussion

There are two noteworthy contrasts in the case described above. The first (actually a *lack* of contrast) is between the language used in the two requirements documents. To put it charitably, both documents reflect a conservative view of what technology had to offer. Further, although separated by 10 years, the conservative view expressed in the two documents—even the choice of words—is nearly identical. If the documents had been authored by the same individuals such similarity of language might possibly be expected even with the separation in time. But as noted above, this was not the case—none of the individuals involved in authoring the need statement were still on the staff of Using Command when it wrote and published the requirements for the new avionics system.

The second contrast is between the conservative reliability results anticipated in the requirements document for the new cargo aircraft and that which was delivered. It should be noted that there was no evidence of reliability gold-plating in the development program. The achieved reliability was simply a reflection of the state of engine technology. Thus, Using Command's institutional memory led it to predict a future quite different from the one that appears to have arrived.

In the discussion under Case A, Unexpected Opportunity, we already described how the construction of a shared, tacit working model of the world permits forecasting how the future will behave. The similarity of language in the two requirements statements suggests that, even though Using Command's staff had changed over the decade bracketed by the two documents, the institutional working model (Carayannis, 1999: 147) had not. That much perhaps is straightforward. Why the working model is conservative has a more subtle explanation. First, the language quoted above was written by Using Command's logisticians and it is the experience of one of the authors (Forbes) that logisticians generally seem to embrace conservative working models. Although certainly not definitive, Adler and Clark (1991) (p. 277), in the context of discussion of the learning curve, and Kelly (1994) (p. 408), in the context of information systems, provide insight into why this might be so when they both note that performance-related engineering changes and new technologies typically are disruptive to established processes. Since a fundamental objective of logistics management is integration of the processes within the logistics system (Bowersox et al., 1986: 267; Copacino, 1997: 10), not a simple undertaking to begin with, the working model of logisticians with respect to performance-related development emphasizes the aspect of disruption. Logisticians, inclined by experience toward technophobia, would see the development of the new airlifter and the development of the new avionics suite as just that, *development*, forecast disruption, and in their requirements statements emphasize prevention of disruption (i.e. not making things any worse than they already are). Further, the corroborating feedback from prior technology introductions would also naturally reduce aspiration levels (i.e. generate conservative requirements) (Lant, 1992: 624).

4. An alternative to rational-model-based engineering

Each of the case studies summarized above served to illustrate the kinds of disconnects encountered in engineering practice between what is advertised and what is achieved. Consistently large differences between what is initially recognized as 'the plan' and what is finally realized (or, alternatively, the apparent lack of control and predictability) as well as the alternative representations of results all too often bring into question the nature and credibility of engineering activity. In this section we would like to put forward a conceptual framework that provides a basis for understanding why such differences are natural and to be expected rather than unnatural and to be criticized. If accepted as natural then perhaps that is a step toward accommodation and, possibly, even intervention. We begin by describing the usual, and in our minds problematic, normative representation of engineering.

Blanchard (1981) (p. 14) describes logistics engineering as constituting:

> ...the application of selected quantitative methods to (1) aid in the initial determination and establishment of logistics criteria as an input to system design, (2) aid in the evaluation of various design alternatives, (3) aid in the identification and provisioning of logistics support elements, and (4) aid in the final assessment of the system support capability during consumer use.

Similar representations are easily found for reliability engineering (Zebick and Hoerster, 1986: 63), software engineering (Vick, 1984), and systems engineering generally (Hall, 1962: 89). Normative, espoused systems engineering and the technical disciplines that support it, then, are implementations of instrumental reason and the rational model even when couched in terms of bounded rationality (Eisenhardt and Zbaracki, 1992: 18). (In the balance of this paper, to avoid repeatedly using the cumbersome 'systems, reliability, and logistics engineering' construction, we will simply refer to systems engineering generically unless there is some specific reason for calling a technical field out individually.) The rational model in practice usually comprises the sequence: problem definition, criteria selection, formation of alternatives, comparison of alternatives against criteria, selection of

a 'winner', implementation, and follow-up (Lindenberg, 1989: 175; Oman et al., 1992: 155; White, 1990: 134).

On the surface, as an instance of the rational model, the espoused systems engineering viewpoint is positivist and realist. We would like to suggest that the simple, positivist's representation of systems engineering, although a convenient model in pedagogical settings, is a distortion of the assumptions systems engineering's practitioners actually hold. This is hardly a radical stance since others previously have questioned the appropriateness of rationality as a model of choice (Lounamaa and March, 1987: 107). In the balance of this paper, we will discuss an alternative model—one that may better account for the apparently natural prospective and retrospective ambiguity about requirements, achievements, and their relationships.

5. Introducing new technology

To begin with, we would like to emphasize that, in addition to uncertainty and disorderliness as described by Kline and Rosenberg, differences between expectation and achievement are the norm rather than the exception when introducing new technology—that is, things *normally* go awry (Betz, 1987: 61 for technology in general; Gebman and Shulman, 1988: ix for avionics technology). One popular theme in the literature on management of science and technology, picking up on the idea of uncertainty, ascribes the differences between expectation and achievement to factors such as unclear understanding of the future environment, uncertainty over requirements, and uncertainties regarding manufacturing processes (Brody, 1991: 39–44; Tse and Cralley, 1989: ES-1). The general sense is that the science and engineering tools are tine, these things are understandable, they are just not understood at a particular time as a result of incomplete information (often with the thought that what are needed are better tools to preclude such misunderstandings). This is still a realist's view of the problem.

A second common theme asserts that discontinuities introduced by technology (especially when the technology is on a new 'S-curve') will result in the potential consumers of new technology being literally unable to describe what they want (Betz, 1987: 95–96; Burgelman and Maidique, 1988: 26; Foster, 1986: 154; von Hippel, 1986) with the obvious impossibility of matching expectation to achievement. Invention is not enough, there must also be a concerted effort to technologically educate the potential consumers. A third, relatively recent theme, related to the second, describes new technologies as equivocal by nature, requiring "...ongoing structuring and sense making if they are to be managed" (Appleton, 1984: 145–150; Ring and Van de Ven, 1989: 171–172; Robinson, 1988: 325–338; Weick, 1990: 2). The second and third themes are, in the terms of Richard Rorty (1991) (pp. 22–23), a pragmatist's view of the problem. It is the pragmatist's view that is adopted here. Borrowing from John Forrester (1989) (pp. 9–10), systems engineering, from the pragmatist's perspective is a process by which social actors (in this case primarily end-users and engineers) make sense of large, technical projects and come (or do not come) to shared understandings of the implications of a technology. In this we at least partially echo H.K. Klein and R. Hirschheim (1983: 5–24), who, commenting on essentially similar problems with the implementation of decision support systems, have argued for a pragmatist's interpretive approach to that sub-field of systems engineering.

6. Sense-making

The way problems are confronted is directly affected by the language and symbols in which they are couched (Carayannis, 1999: 149; Feigenbaum and Henig, 1994: 186; Ramaprasad, 1987: 141) as well as prior knowledge of relevant categories into which problems might fit (Ramaprasad, 1987: 141). Language, symbols, and relevant categories are all created through collective sense-making. However, painting systems engineering as collective sense-making provides limited insight without an understanding of the process by which sense-making occurs. Thus, creating such an understanding has a practical objective. We begin, however, by considering objectivity and subjectivity because the distinction between the two is at the core of usual notions of science (Searl, 1984: 10).

The traditional conception of the difference between objectivity and subjectivity, dating from Kant, is that the subject (you, I) is the center of awareness and the object is outside of subjective awareness. 'Objective' has to do with things themselves and 'subjective' with thought (Reese, 1980). (Prior to Kant, incidentally, the meanings of objective and subjective were reversed.) As John Searl (1992) (p. 94), by nature a functionalist, notes: "We often speak of judgments as being 'subjective' when we mean that their truth or falsity cannot be settled 'objectively' because the truth or falsity ...depends on certain attitudes, feelings, and points of view of the makers and hearers of the judgment".

These attitudes, feelings, and points of view, however, not only cannot be made to disappear but are the basis of our ability to experience and understand the world (Boland, 1985; Lindenberg, 1989: 178). As Peter Berger and Thomas Luckmann (1966) define it, objectivity, in contrast to Kant's view, is reciprocal inter-subjective typification of conduct. By reciprocal typification Berger and Luckmann mean that two or more actors attach essentially the same meaning to conduct. Conduct to which an actor attaches his or her *own* meaning, not

shared by others, is then what constitutes the subjective (Marshall and White, 1990: 66). In the pragmatist's view, construction of meaning (building a theory to relate facts and events) through the use of language is embedded in social process rather than language conferring specific meaning independent of process. Seen in this light, redefinition of requirements is a continuous social (re)construction of meaning rather than something perverse (Hall, 1984).

Explicit theory, an example of which is the body of rules, principles, and generalizations that constitute systems engineering or any of the technical fields it comprises, is always an abstraction and simplification of a deeper and more complete tacit understanding. Because this is the case, theory is not in a one-to-one correspondence with an underlying tacit understanding (Senge, 1992). Geoffry Vickers (1973) (pp. 103–111) made much the same observation in a discussion of norms, values, and formal rules and regulations as have Wilfred Bion (Rioch, 1970: 56–66) in his work on groups and Chris Argyris and Donald Schon (1978) when they introduced the concept of double-loop learning to correct errors in underlying norms, policies, and objectives (Bernstein, 1983). Another very important consideration is that different communities will produce different theory claims.

Richard Bernstein arrived, in part, at the same destination as we have in his contrast between empiricist and post-empiricist accounts of nature as shown in the first two columns of Table 3 (Bernstein, 1983: 31–33). However, in our minds, it is time to go beyond this simple contrast and dispense with what we see as a false dichotomy between the empiricist and post-empiricist accounts. We indicated in the introduction to this conceptual section that we intended a pragmatist's orientation. Perhaps then, it should not be a surprise that, as illustrated in the right two columns of Table 3, an alternative is available from Piaget's pragmatist approach to cognitive information processing (Bickhard, 1997: 239; Bruner, 1997: 66; Ramaprasad, 1987: 142–144) and, in particular, the process of adaptive learning that is embedded within it.

The empiricist's view leaves us with the promise of (but ultimate lack of) an ability to predict. The inevitable result is finger-pointing and a search for the guilty—sometimes encouraged by the media—when things do not go as predicted. The post-empiricist's account unfortunately, with its nearly solipsistic readiness to accept nearly everything as relative, is somehow unsatisfying in a world where individuals and organizations do have goals they perceive as worthy and would like to think there is some way to relate choices made today to results tomorrow. We would argue that a pragmatic account based on the cognitive information processing model is an account worthy of attention since it provides for:

- community-determined law-like relations (i.e. logico-mathematical structures) and creation of meaning based on application of established law-like relations, even if they are tacitly held;

Table 3
Empiricist, post-empiricist, and cognitive information processing based accounts

Natural science accounts		Piaget's model of cognitive information processing	
Empiricist	Post-empiricist	Equivalent exposition	Exemplified by
Experience is objective (in usual sense of objective)	Data are not detachable from theory (theory here includes both tacit and explicit aspects)	Previously developed logico-mathematical structures determine what factors and relationships are observed	(Case B) Observation or non-observation of types 2 and 6 failures depending on community to which individuals belonged
If models reflect nature then data will be as we find them	Theories are not models externally comparable to nature, they are the way the facts are seen	If data do not fit deductions then logico-mathematical structures are inductively modified through reflexive abstraction	(Case A) Realization that reliability information system could be used to schedule modification kits
Law-like relations are external	Law-like relations are internal	Law-like relations (logico-mathematical structures) are the inductive generation of information from data by trial and error through reflexive abstraction	(Case A) Modification of working model of reliability information systems as a result of experience with ALAM system
Language of science is exact, formalizable, and literal	Language of science is metaphorical and inexact, if formalize then always distort	When a logico-mathematical structure is sufficiently refined it becomes the reality instead of a model of reality	(Case B) Over time as the failure typology became refined it lost types 3, 4, and 5, and types 1, 2, and 6 became the complete failure reality. Further, only type 1 failures are effected by design
Meanings are separate from facts	Meanings are determined by theory	Perception and meaning are based on a previously developed logico-mathematical structure	(Case C) In logisticians' reality, development *meant* disruption

- inductive (and collective) generation of new and modified logico-mathematical structures when data do not fit those already in existence;
- an explanation why community-determined law-like relations can become so accepted that they become outside a community's direct awareness—i.e. become the reality rather than a representation of reality;
- the possibility of constructive intervention given a concerted effort to understand who the stakeholder communities are and how, not just their perceptions, but their bases for perception differ.

In the context of the three cases presented, the interpretive pragmatist's account provides a perspective within which one program, with one set of quantitative results, can be expected to generate:

- an evolving model of information systems as described in Case A;
- two different interpretations of the results as described in Case B;
- technophobia as described in Case C.

Experience is not objective in the usual empiricist's sense. Rather, objectivity is a function of reciprocal typifications and typifications are created through social processes. Given two or more communities, each will see (i.e. construct) an objectively different result. Note that this is *not* a matter of communities seeing the same thing differently, rather they are seeing different things. In the examples given in the beginning of this paper, there were two or more different communities which had formed different perception spaces. The rational model is unable to provide a satisfactory explanation for this problem since, in addition to assuming that reality is just out there, it inherently assumes a common, stable perceptual space and a stable environment (Bourgeois and Eisenhardt, 1988: 818) within which to arrive at common goals. Such is an unreasonable and in fact arrogant assumption.

An interpretive model incorporating the concepts of cognitive information processing and continuing multi-level learning, by contrast, is useful in understanding the origins of non-linearity, instability, and disorderliness during innovation. It assumes that there may be more than one community and that, through on-going learning, they are adaptive over time. If more than one community, the multiple perceptual spaces in turn result in different norms and attitudes and—as Fishbein (1979) has argued—different subjective norms and attitudes determine different behaviors. The pragmatist's model also 'explains' why technical disciplines such as logistics and reliability engineering evidence what appears to be limited predictive capability. Not only are the rules (or better stated, collections of recipes) of these engineering disciplines a simplification of the tacit models that underlie them but the tacit models themselves change over time. As Vogel (1995) (p. 33) has put it, the objects that science attempts to describe change as science does because such objects are constituted by the communicatively produced and reproduced paradigms within which scientists [and, by extension, engineers] work. Since a fundamental feature of socially-created reality is continuing change (Vitalari, 1985: 250) as a result of continuing multi-level learning and unlearning (Carayannis, 1999: 141), multiple, shifting engineering objectifications will be a constant companion to almost any major development effort. Thus, the proposed model is also the basis for Schumpeter's creative destruction (Berry and Taggart, 1994: 1994), a distinguishing feature of technology.

7. Implications

In summary, value systems, culture, and the behavioral basis for them matter (Lindenberg, 1989: 175–200) to logistics engineering, reliability engineering, systems engineering, and the innovation process generally. More importantly, changing value systems and tacit models evolved by on-going learning matter at least as much. Viewing systems engineering as an interpretive activity embedded in on-going social processes rather than as a 'rational' activity external to social processes provides the basis for understanding why and how these things matter. The primary implication is that rather than attempting to develop improved analytical capabilities—better tools for predicting the inherently unpredictable—an alternative and potentially superior strategy is to recognize that learning is going to happen and, instead, develop strategies for managing multiple-level technological learning as a way to solve complex problems (Carayannis, 1999; Lounamaa and March, 1987: 121). Developing such strategies is a subject that lies beyond what can be presented here.

References

Adler, P.S., Clark, K.B., 1991. Behind the learning curve: a sketch of the learning process. Management Science 37 (3), 267–281 March.

Appleton, D.S., 1984. Business rules: the missing link. Datamation 15, 145–150 October.

Argyris, C., Schon, D.A., 1978. Organizational Learning: A Theory of Action Perspective. Addison-Wesley, Reading, MA.

Ascher, H., Feingold, H., 1984. Repairable Systems Reliability: Modeling, Inference, Misconceptions and Their Causes. Marcel Dekker, New York.

Berger, P.L., Luckmann, T., 1966. The Social Construction of Reality. Anchor Books, New York.

Bernstein, R.J., 1983. Beyond Objectivism and Relativism: Science, Hermeneutics, and Praxis. University of Pennsylvania Press, Philadelphia, PA.

Berry, M.M.J., Taggart, J.H., 1994. Managing technology and innovation: a review. R&D Management 24 (4), 341–353.

Betz, F., 1987. Managing Technology. Prentice-Hall, Englewood Cliffs, NJ.

Bickhard, M.H., 1997. Piaget and active cognition. Human Development 40, 238–244.

Blanchard, B.S., 1981. Logistics, Engineering & Management. Prentice Hall, Englewood Cliffs.

Boland, R.J. Jr., 1985. Phenomenology: a preferred approach to research in information systems. In: Mumford, E., Hirschheim, R., Fitzgerald, G., Wood-Harper, T. (Eds.), Research Methods in Information Systems: Proceedings of the IFIP WG 8.2 Colloquium, September 1984. Manchester Business School: Elsevier Science Publishers, pp. 193–201.

Bourgeois, III, L.J., Eisenhardt, K.M., 1988. Strategic decision processes in high velocity environments: four cases in the microcomputer industry. Management Science 34 (7) July.

Bowersox, D.J., Closs, D.J., Helferich, O.K., 1986. Logistical Management. MacMillan Publishing Company, New York.

Bowlby, J., 1973. Attachment and Loss. Basic Books, London.

Brody, H., 1991. Great expectations: why technology predictions go awry. Technology Review July, 39–44.

Bruner, J., 1997. Celebrating divergence: Piaget and Vygotsky. Human Development 40, 63–73.

Burgelman, R.A., Maidique, M.A., 1988. Strategic Management of Technology and Innovation. Irwin, Homewood, IL.

Carayannis, E.G., 1999. Knowledge transfer through technological hyperlearning in five industries. Technovation 19, 141–161.

Carayannis, E., 2000. The strategic management of technological learning. In: The Handbook of Technology Management, CD-ROM Version: IEEE/CRC Press.

Clark, K.B., 1985. The interaction of design hierarchies and market concepts in technological evolution. Research Policy 14, 235–251.

Copacino, W.C., 1997. Supply Chain Management: The Basics and Beyond. APICS, Falls Church, VA.

Davenport, T.H., 1998. Putting the enterprise into the enterprise system. Harvard Business Review July-August, 121–131.

Drejer, A., 1996. The discipline of management of technology, based on considerations related to technology. Technovation 17 (5), 253–264.

Eisenhardt, K.M., Zbaracki, M.J., 1992. Strategic decision making. Strategic Management Journal 13, 17–37.

Feigenbaum, H.B., Henig, J.R., 1994. The political underpinings of privatization: a typology. World Politics 46 (2), 185–209.

Fishbein, M., 1979. A theory of reasoned action: some applications and implications. In: Nebraska Symposium on Motivation., pp. 66–116.

Forrester, J., 1989. Planning in the face of power. University of California Press, Berkeley.

Foster, R.N., 1986. Innovation; The Attacker's Advantage. Summit Books, New York.

Gebman, J.R., Shulman, H.L., 1988. A strategy for reforming avionics acquisition and support. RAND, Santa Monica.

Hall, A.D., 1962. A Methodology for Systems Engineering. Van Nostrand Reinhold, Princeton.

Hall, R.I., 1984. The natural logic of management policy making: its implications for the survival of an organization. Management Science 30 (8), 905–915 August.

Kelly, M.R., 1994. Productivity and information technology: the elusive connection. Management Science 40 (11), 1406–1425 November.

Klein, H.K., Hirschheim, R., 1983. Fundamental issues of decision support systems: a consequentialist perspective. Office: Technology and People 2, 15–42.

Kline, S.J., Rosenberg, N., 1986. An overview of innovation. In: Landau, R., Rosenberg, N. (Eds.), The Positive Sum Strategy: Harnessing Technology for Economic Growth. National Academic Press, Washington, DC.

Lakoff, G., Johnson, M., 1980. Metaphors We Live Byy. The University of Chicago Press, Chicago, IL.

Lant, T.K., 1992. Aspiration level adaptation: an empirical exploration. Management Science 38 (5), 623–644 May.

Lindenberg, S., 1989. Choice and culture, the behavioral basis of cultural impact on transactions. In: Haferkamp, H. (Ed.), Social Structure and Culture. Walter de Gruyter, Berlin, pp. 175–199.

Lounamaa, P.H., March, J.G., 1987. Adaptive coordination of a learning team. Management Science 33 (1), 107–123 January.

Marshall, G.S., White, O.F. Jr., 1990. The Blacksburg Manifesto and the postmodern debate: public administration in a time without a name. American Review of Public Administration June.

Oman, R.C., Damours, S.L., Smith, T.A., Uscher, A.R., 1992. Management Analysis in Public Organizations. Quorum Books, New York.

Ramaprasad, A., 1987. Cognitive process as a basis for MIS and DSS design. Management Science 33 (2), 139–148 February.

Reese, W.L. (Ed.), 1980. Dictionary of Philosophy and Religion: Eastern and Western Thought. Humanities Press, Atlantic Highlands, NJ.

Ring, P.S., Van De Ven, A.H., 1989. Formal and informal dimensions of transactions. In: Van De Ven, A.H., Angle, H.L., Poole, M.S. (Eds.) Research on the Management of Innovation: The Minnesota Studies. Harper & Row, Grand Rapids, MN.

Rioch, M.J., 1970. The work of Wilfred Bion on groups. Psychiatry 33 (1), 56–66 February.

Robinson, J.B., 1988. Unlearning and backcasting: rethinking some of the questions we ask about the future. Technological Forecasting and Social Change 33, 325–328.

Rorty, R., 1991. Objectivity, Relativism, and Truth. Cambridge University Press, Cambridge.

Searl, J.R., 1984. Minds, Brains, and Science. Harvard University Press, Cambridge, MA.

Searl, J.R., 1992. The Rediscovery of Mind. The MIT Press, Cambridge, MA.

Senge, P.M., 1992. Mental models. Planning Review March–April, 5–10.

Tse, E., Cralley, W.E., 1989. Management of Risk and Uncertainty in Product Development Processes. Institute for Defense Analysis, Arlington, VA.

Tyler, P., 1986. Running Critical. Harper & Row, New York.

Vick, C.R., 1984. Introduction: a software engineering environment. In: Vick, C.R., Ramamoorthy, C.V. (Eds.), Handbook of Software Engineering. Van Nostrand Reinhold, New York, pp. xi–xxxii.

Vickers, G., 1973. Values, norms and policies. Policy Sciences 4, 103–111.

Vitalari, N.P., 1985. The need for longitudinal designs in the study of computing environments. In: Mumford, E., Hirschheim, R., Fitzgerald, G. (Eds.), Research Methods in Information Systems: Proceedings of the IFIP WG 8.2 Colloquium, September 1984.

Vogel, S., 1995. New science, new nature: The Habermas–Marcuse dabate revisited. In: Feenberg, A., Hannay, A. (Eds.), Technology and the Politics of Knowledge. Indiana University Press, Bloomington, IN.

Von Hippel, E., 1986. Lead users: a source of novel product concepts. Management Science 32 (7), 791–805.

Wassmann, J., Dasen, P.R., 1998. Balinese spatial orientation: some empirical evidence of moderate linguistic relativity. Journal of the Royal Anthropological Institute 4, 689–711 December.

Weick, K.E., 1979. The Social Psychology of Organizing. McGraw-Hill, New York.

Weick, Karl E., 1990. Technology as equivoque: sense-making in new technologies. In: Goodman, Paul S., Sproull, Lee S. and Associates (Eds.), Technology and Organizations. Jossey-Bass Publishers, San Francisco, CA, pp. 1-44.

White, J.D., 1990. Images of administrative reason and rationality: the recovery of practical discourse. In: Kass, H.D., Catron, B.L. (Eds.). Images in public administration. Sage Publications, Newbury Park, CA.

Zebick, H.E., Hoerster, M.G., 1986. R&M in a systematic trade study

process. In: Evans, R.A., Stiehl, G.L. Jr. (Eds.), Proceedings of the Annual Reliability and Maintainability Symposium. The Institute of Electrical and Electronic Engineers, Las Vegas, NV, pp. 61–68.

Elias G. Carayannis is on the faculty of the School of Business and Public Management of the George Washington University in Washington DC, as well as Director of Research on Science, Technology, Innovation and Entrepreneurship, European Union Center, SBPM, GWU and faculty member of the GWU SBPM Environmental Studies Center. Dr. Carayannis was previously on the faculty of the Anderson Schools of Management of the University of New Mexico where he was co-developer of a Management of Technology MBA curriculum.

Dr. Carayannis received his PhD in Technology Management from the Rensselaer Polytechnic Institute in Troy, New York in 1994, his MBA in Finance from Rensselaer in 1990, and his BS in Electrical Engineering from the National Technical University of Athens, Greece, in 1985. Dr. Carayannis' teaching and research activities focus on the areas of strategic government–university–industry technology partnerships, business/war gaming and technology roadmapping, technology transfer and commercialization, international science and technology policy, technological entrepreneurship and regional economic development.

Dr. Carayannis has had several articles published in both academic and practitioner, US and European journals such as the Journal of Engineering and Technology Management, International Journal of Technology Management, Technovation, Journal of Technology Transfer, R&D Management, Growth and Change, The Review of Regional Studies, International Journal of Global Energy Issues, International Journal of Environment and Pollution, Le Progres Technique, and Focus on Change Management.

He has consulted for several technology-driven government and private, large as well as small organizations such as the NSF SBIR, the NIST ATP, Sandia National Laboratories' New Technological Ventures Initiative, the General Electric Corporate Training & Development Center, Cowen & Co, First Albany International, Entreprises Importfab, and others.

He is fluent in English, French, German, Greek, and has a working knowledge of Spanish. He is a citizen of the United States of America and the European Union.

James Forbes is a certified professional logistician with over 25 years of experience in policy analysis, technology management, program management, reliability and maintainability (R&M) analysis, operations research, life cycle cost, and operational logistics. As an Air Force officer, he had extensive experience assessing the impact of technology on organizations and managing technology-driven change. He participated in the management of the B-1A, B-1B, B-52 Offensive Avionics System/Air Launched Cruise Missile, and Small Intercontinental Ballistic Missile acquisition programs. Since entering the private sector, he has conducted numerous technology-related studies. These included a study of the existing formal and informal logistics policy for space systems (for which he used an interpretivist framework), application of fuzzy-set theory to perform the first comprehensive life-cycle cost (LCC) analysis of on-orbit maintenance, application of network analysis methods to parameterize the logistics performance of a new flight control system technologies, and numerous studies of logistics-related information systems and associated standards. He led the research that resulted in the US Department of Defense initiating a deliberate program of reliability, maintainability, and supportability investment. He is currently providing analytic support to the US Federal Aviation Administration as they undertake a similar program. He is also leading a large study effort to characterize total ownership costs for United States Coast Guard Deepwater assets (i.e. all Coast Guard aviation and all cutters that operate more than 50 miles from the coast). A major focus of recent research has been the development of improved methods for choosing between public and commercial sources of product support. He is currently completing a doctoral program in technology management at the George Washington University.