A SYSTEMS ENGINEERING APPROACH TO PROGRAMME EVALUATION IN TECHNOLOGY-INTENSIVE DOMAINS

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Now that society is well into the Information Age, some general trends are particularly evident to engineers and others in technology-intensive domains of human endeavour. These trends stem from people's desire for an ever-higher quality of life, driving a quest for optimisation, sustainability, reliability and safety. Failures in technological projects receive increasing criticism, making the situation worse by creating a risk-adverse culture that extends programme schedules and inhibits creativity. Despite this, the demand remains for increasingly complex projects to be undertaken yet with the realisation that the success of such projects depends more on the management and related programme issues and less on the engineering details. Herein lies the dilemma. Technology-intensive domains demand evaluation of their programmes, yet have no real experience of 'soft' approaches. Evaluation techniques from 'soft' domains with little understanding of technology may be quickly dismissed as 'not sufficiently quantitative' and thout a systems (engineering) basis'.

This paper proposes an open inquiry evaluation method derived from a Systems Engineering approach to complex problem solving. This method is akin to the proven process used in the engineering discipline of *Test and Evaluation* to validate 'hard' products of the systems engineering process. With this background, it is proposed that such a technique is easily understood and appreciated by the critical reference group in technology-intensive domains. This technique was trialled in an evaluation of the Test and Evaluation programme of a Commonwealth government department; and may be a useful approach for evaluating other high-technology programmes.

Test and Evaluation, technology, quantitative, evaluation, engineering

1. INTRODUCTION

In technology-intensive domains, the engineering profession dominates the organisational culture (not unexpectedly) providing the organisation with a ‘hard science’ culture based upon numbers, facts and artefacts. Until fairly recently, matters considered the realm of ‘soft science’ such as human factors, stakeholder viewpoints and opinions, and aesthetics were largely ignored in such technology-intensive organisations. However, as society has progressed from the Industrial Age into the Information Age, the engineers and others in technology-intensive domains of human endeavour have experienced new emphasises. These emphasises stem from peoples’ desire for an ever-higher quality of life, in turn driving a quest for optimisation, sustainability, reliability and safety.

The major effect on engineering outcomes of these new pressures and emphasises have been an increased criticism of failures in technological projects. This has created a risk-adverse culture that extends programme schedules and inhibits engineering creativity. Despite this, the demand remains for increasingly complex projects to be undertaken yet with the realisation that the success of such projects depends more on the management and related programme issues and less on the engineering details. Herein lies the dilemma. Technology-intensive domains demand evaluation of their programmes, yet have no real experience of ‘soft’ approaches. Evaluation techniques from ‘soft’ domains with little understanding of technology may be hastily dismissed as ‘not sufficiently quantitative’ and ‘without a systems (engineering) basis’.

2. THE PROBLEM SPACE

The problem space in technology-intensive domains is defined by the nature of the organisational culture and its difficulty in adapting to the external emphasis imposed by the need to operate in the Information Age. Evaluation of programmes in these domains is difficult due to the professional difference between evaluators and the critical reference group in such technology-intensive domains. This delta in intent between the two groups adds another dimension to the problem space.

2.1. The Information Age.

The shift from the Industrial Age to the Information Age came as a result of a fundamental change in the social landscape and the emergence of enhanced information infrastructure. These fundamental changes have affected everyday life and brought about a quantum leap in the pace of change, as well as presenting significant challenges in legal, social, economic and political circles. The US National Council of Research suggested the changes were caused by three particular technological advances: the increased use of information in digital form, the rapid growth of computer networks, and the creation of the World Wide Web (National Research Council, 2000). Several authors (Gartz, 1997), (Clark and Fujimoto, 1991), (Schulz, Igenbergs et al., 2001) have suggested global society has become tremendously more complex in almost every aspect in the past decades. The ease of information availability has seen several trends in society emerge, particularly the desire for an ever higher quality of life which in turn demands increasingly complex projects to be undertaken in the technology-intensive domains of human endeavour (Cook, Sydenham et al., 2001).

2.2. Technology-Intensive Domains.

The shift from the Industrial Age to the Information Age has been accompanied by a maturing of the technology-intensive domains of human endeavour. This maturing has resulted from a realisation that the technical complexity and cost of programmes in these domains had increased dramatically, and yet spectacular programme failures still occurred. Systems Engineering (SE) had developed as the 'silver bullet' to solve many of these of problems, with SE borne from the need for a methodology to handle large programme complexity in the technology-intensive fields of defence weapon systems and aerospace. Cook (Cook, 2000) contends that SE's success in mitigating technical programme failures attracted increased attention throughout the 1990s, with recent evidence of an increasing trend to apply SE to a wider range of domains.

In parallel with the attempts to mimic the success of SE in wider applications there has been a rise of the expectations for optimisation, sustainability, reliability and safety in most human endeavours. With this backdrop, project failures are receiving increasing criticism creating a Catch-22 situation whereby a programme's situation is made worse by creating a risk-adverse culture that extends program schedules and inhibits engineering creativity.

The Information Age has provided an environment in which increasingly complex projects are being undertaken in the technological-intensive domains, and yet it has been realised that their success depends on more the knowledge, skills, intellectual prowess and management acumen of the problem solvers and less on the on technological details of the programme.

2.3. Programme Evaluation and Cultural Differences.

So, corporate knowledge, team skills and management processes have become issues for programme evaluation in the technology-intensive domains. Alas, to paraphrase Cook, in these domains stakeholders have been accustomed to the application of systems engineering principles and methods to large, complex, technical projects and find it hard to envisage tackling a substantial problem (such as evaluating their programme) without a well-established systems engineering framework and set of processes (Cook, 2000). Indeed, evaluators from outside the world of engineering may well have proven techniques for programme evaluation, but may find it difficult to comprehend the technology-intense atmosphere of these domains that is driven by engineering's constant drive for improvement and efficiency. Evaluators may also struggle to be seriously regarded by the technocrats in these domains, as shrugs of 'not sufficiently quantitative' ems engineering basis' highlight the cultural divide between 'soft' and 'hard' fields.

Evaluators need to consider other sources of cultural differences between them and potential critical reference groups in technical domains, such as domain-specific language, context of the target organisational culture, and the particular emphasis for the organisation's programme goals and outcomes. Each knowledge discipline and indeed each profession of human endeavour has developed its own culture, including a specialised glossary and abbreviations. Organisations tend to further refine the context and meaning of their primary field's language, adapted to the business culture in which they operate. These cultural differences combine to form an informal barrier to the programme evaluator, and are considered by this author as a primary region of the problem space in evaluating programmes within technology-intensive domains.

2.4. Organisational Problems.

Any organisation, being a complex network of human personalities, will possess problems due to internal politics that will be exhibited as organisational inertia. This is nothing new, as demonstrated by Machiavelli's observation nearly 500 years ago in his political treatise 'The

"And it ought to be remembered that there is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things. Because the innovator has for enemies all those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new. This coolness arises partly from fear of the opponents, who have the laws on their side, and partly from the incredulity of men, who do not readily believe in new things until they have had a long experience of them." (Machiavelli, 1515)

In technology-intensive domains, this organisational inertia may well balance out the engineering drive for improvement and technical perfection. Evaluation of technical programmes must account for organisational inertia and be aware of the internal politics, if the evaluation is to be effective in its activity and its outcomes.

2.5. Cultural Feasibility.

An obvious result of realising that programme evaluation must tackle the organisational problems outlined above, is the dire need for proposed solutions arising from the evaluation to be culturally feasible. If a solution is not culturally feasible, that is to say, practicable in light of critical organisational problems such as the internal politics, then the solution will be a non-starter. Another way of considering cultural feasibility is the probability a solution or recommendation will be acceptable to the stakeholders.

Indeed, a major consideration in ensuring the solutions will be culturally feasible to technical organisations is ensuring that the evaluation methodology itself is culturally feasible. Technocrats are generally quick to dismiss unfamiliar techniques and methodologies if they consider them to be without a scientific basis. Consider the opinion of one of the great technocrats and scientists, Lord Kelvin (1824 – 1907):

"When you measure what you are speaking about and express it in numbers, you know something about it, but when you cannot express it in numbers your knowledge about is of a meagre and unsatisfactory kind." (University of St. Andrews, 2000)

Cultural feasibility, particularly when manifested as user acceptance, will probably continue to be an illogical barrier for the designers and evaluators and should be considered as part of the problem space for programme evaluation. An example from the technology-intensive (fictional) future of Star Trek is appropriate. In the scene when Dr Leonard 'Bones' McCoy comes on board the newly upgraded Enterprise, even before leaving the teleport deck he complains to Captain Kirk, "… and they've probably changed the sick bay. I know engineers they love to change things" (Livingston, 1979).

3. A SYSTEMS ENGINEERING APPROACH

The origins of Systems Engineering lie in the 'hard' science realm of defence weapon systems development during the Second World War. It's not surprising therefore that in technology-intensive domains definitions of SE have usually been based on the notions of (1) holistic thinking, (2) a systems hierarchy, (3) emergent properties of the system (the sum is more than the sum of the parts'), and (4) emphasis on the interfaces between the hierarchical parts.

In more recent times, many authors have proposed definitions of SE and 'system' that attempt to 'soften' this approach. Importantly Checkland's definition of a system as "a whole entity of human activity characterised by hierarchical structure, emergent properties, communication & control" (Checkland, 1998) emphasises the role of the human actors and allows a systems approach to programme evaluation to be considered by technocrats.

3.1. What is a Systems Approach?

Unfortunately, what is meant exactly by the phrase 'systems approach' has not been satisfactorily defined or agreed upon in a scholarly fashion. Several authors (Mar, 1997), (Kasser, 1996), (Stevens, Brook et al., 1998), (Woods, 1993) have discussed definitions of systems engineering, but Cook's (Cook, 2000) (Cook, Sydenham et al., 2001) description of the methodology of systems engineering may best be paraphrased to describe a 'systems approach' as: a hard methodology best suited to problem solving in cases where the following conditions are met:

(1) a holistic viewpoint is used,

(2) the system objectives can be defined at the very beginning of the programme,

(3) the stakeholders can envisage an expected solution,

(4) the process (in taking a systems approach to the problem) can be summarised as moving the system from an initial state S_0 to a different end state S_1,

(5) the environment (technology, organisation, and social policy) is relatively stable, and

(6) the objectives are shared among the stakeholders.

In taking a systems approach to problem solving, including programme evaluation, this author believes the first three of these conditions above are the vital. In taking a holistic viewpoint to the problem, drives a degree of 'lumpiness' in candidate solutions as all the facets to the overall problem need to be dealt with as a whole. A holistic viewpoint also protects the evaluator from getting too involved in detail or indeed getting 'bent around the axle' about sub-issues. Involving stakeholders early in envisaging possible solution sets and defining the objectives upfront are not only keystones in systems engineering processes, but also acknowledged as best practice in Test and Evaluation of complex, technical systems.

3.2. Lessons from Test and Evaluation.

In the technology-intensive domains such as defence systems development, computer networking, software development, and flight test of aerial vehicles, the discipline of Test and Evaluation (T&E) is acknowledged as providing a mature methodology to validate solutions. T&E may be defined as "the process by which a system is compared against technical or operational criteria through testing and the results are evaluated to assess performance against agreed criteria (including design, performance and supportability) to determine the system's fitness for purpose" (Defence T&E Principals, 1998). A practical viewpoint of T&E is that it is a methodology used to answer three crucial questions of a system solution to a complex socio-technical problem (Equid and Harris, 2001): (1) what is the system trying to do, (2) when will we know the goal has been achieved, and (3) who is responsible?

The fundamentals of a good T&E process to answer these questions are:

(a) objectivity and independence of the T&E activity,
(b) a master-planned T&E programme, and
(c) pre-determined Measures of Effectiveness (MOEs).

The MOEs are developed from the Critical Issues determined appropriate for the programme being evaluated. Critical Issues are the 'show stoppers' of the programme, and are phrased as questions. MOEs are statement, holistic in nature and are 'mission' or 'purpose' oriented. Good MOEs are not concerned with the internal details of the candidate solutions, and indeed MOEs should be general, established by consultation with the stakeholders and importantly solution-independent. The reader is referred to Sproles's work (Sproles, 2000) (Sproles, 2001) for a detailed treatment of MOEs, but suffice to say that good, pre-determined MOEs are considered the 'engine' of the T&E process.

An evaluation of a programme in a technology-intensive domain could benefit from being conducted in a systems approach, utilising the fundamental of T&E. Such an evaluation would need to be objective and conducted by an independent agency, have a detailed and well-planned evaluation programme, and be based upon well-framed MOEs developed and agreed upon early in the evaluation programme.

4. A PROPOSED OPEN INQUIRY EVALUATION METHOD

An open inquiry method of evaluation is commonly used in 'soft' domains, and shares much in its approach with that of the technical discipline of T&E. Wadsworth (Wadsworth, 1991) describes an open inquiry method as an evaluation method used to examine a practice in order to extract assumptions and intentions. An open inquiry method is reliant upon who is the enquirer, and is comparative in nature – asking questions such as: how are we going, what are we doing, and what could be done to improve the programme under evaluation? The needs of the critical reference group are implied in the open inquiry, yet it is vital to identify and consider four potential parties in the evaluation: the evaluators, the evaluated, those the evaluation is for (i.e. the critical reference group), and those the evaluation will influence or inspire to act for or not to act against the critical reference group (Wadsworth, 1984).

4.1. A Quantitative Scoring System.

In order to use an open inquiry method of evaluation in a technology-intensive domain, a quantitative scoring system could be used to add rigour to the process amenable to the technocrats in the three groups belonging to the domain, namely the evaluated, those the evaluation is for (i.e. the critical reference group), and those the evaluation will influence or inspire. If this effect is achieved, then the use of a quantitative scoring system will assist in making the method and the products of the evaluation culturally feasible to the programme under evaluation. A by-product of using a quantitative scoring system is that it adds process to the determination of the MOEs.

4.2. An Example Quantitative Scoring System.

The Measures of Effectiveness (MOEs) to be used to assess the candidate solutions are based on the Critical Issues, re-phrased to indicate a grading scheme. A simple grading scheme could consist of five levels tailored for each MOE. Each level should have a descriptor, to assist the evaluators to maintain objectivity and consistency, and a score (say 0, 1, 2, 3, 4). As all Critical Issues are of equal importance by definition, all MOEs are of equal weighting.

To score an MOE for a particular solution, three basic rules could be followed.

(1) A score of a zero ($c_i = 0$) for any one MOE would discount that candidate solution from further consideration.

(2) Candidate solutions scoring no zeroes ($c_i \neq 0$) have their overall score calculated as the arithmetic mean:

$$\bar{c} = \frac{\sum_1^5 c_i}{5} \qquad (1)$$

(3) Each solution's population standard deviation, $s_{n=5}$, can also be calculated for finer resolution if needed to distinguish between solutions with similar mean MOE scores. A standard deviation of zero (s = 0) should be considered optimal.

4.2. Proposed Model.

Based upon the tenets of the open inquiry method of evaluation, and using a systems approach to problem space, a model is proposed for programme evaluations in technology-intensive domains.

The systems approach needs to be planned before considering the actual options (potential solutions), to ensure the process is objective and legitimate. An Evaluation Working Group (EWG) is established, consisting of the evaluator(s) and stakeholder representatives. The stakeholders to be represented must include both the critical reference group and those the evaluation will influence or inspire to act for (or not to act against) the critical reference group. The group(s) to be evaluated should also be represented if their involvement in the EWG will not skew their results in the subsequent evaluation.

The methodology to develop and assess the options for the programme being evaluated is basically a Systems Engineering Process Improvement regime. Such a regime involves the following steps:

(1) Define the Mission of the programme being evaluated.

(2) Define the Objectives of the programme being evaluated.

(3) Define the Critical Issues of the programme being evaluated. Stakeholder concurrence of the Critical Issues is vital, as these will drive the MOEs developed in the next step.

(4) Define the Measures of Effectiveness to be used, including a quantitative scoring system. If the MOEs are developed by the evaluator(s), then the stakeholders must concur with the MOEs before continuing. Fully developed MOEs that have agreed with by the stakeholders are an absolute necessity at this stage. Progress cannot be made without the MOEs being fully developed, without prejudicing the objectivity and independence of the whole evaluation.

(5) Collect data through structured personal interviews, using a question sheet based upon the requirements of a systems engineering process as set out in ANSI/EIA-632 (Electronic Industry Alliance, 1999).

(6) Identify the Candidate Solutions.

(7) Evaluate each of the Candidate Solutions against the MOEs, following the rule set for the quantitative scoring system developed or agreed upon in Step 4.

(8) Develop recommendations and report findings.

5. IMPLEMENTATION OF THE MODEL - A CASE STUDY

In early 1999, an evaluation of the Test and Evaluation programme of an Australian Government Department was conducted. Since the T&E programme by its very nature was a technology-intensive domain, the challenges of such a problem space as described in this paper were as real as they were obvious to the evaluators.

5.1. Aim of the Evaluation.

The aim of the evaluation was to identify options for the improvement of the process, application and management of T&E within the subject Department in the acquisition of major capital equipment. In considering candidate solutions, six specific areas to be addressed were the organisational structure, the role and responsibilities of the preferred organisation structure, Departmental policy requirements, relevant procedures, training needs, and the utility of information technology applications.

5.2. Method Used.

The open inquiry method, combined with lessons learned from T&E and following the steps of the model proposed in this paper was used to conduct the evaluation. An Evaluation Working Group was formed, consisting of the evaluator, two representatives from the critical reference group, two from the streams to be evaluated (including the evaluation sponsor), and one from primary group that needed to be inspired by the evaluation outcomes.

The EWG defined the Mission of the T&E programme in the Department, and agreed on the four objectives of the programme.

5.2.1. Critical Issues.

The Critical Issues for the T&E programme being evaluated were decided upon as:

- Will the T&E process assess the system against the capability requirement?
- Will the T&E process maintain probity?
- Will the T&E process manage risk for the project?
- Will the T&E process be culturally feasible?

5.2.2. MOEs.

Four MOEs were developed, one for each source Critical Issue. A five-level quantitative scoring system was used, with descriptors for each MOE. As an example, MOE2 Probity of the T&E Process, is at Table 1 overleaf.

5.2.3. Use of the MOEs.

Data was gathered from an earlier Departmental internal survey (conducted in late 1998 with responses from about 90 projects), personal interviews with eight project offices, an extensive literature search and visits with the primary T&E programme staff. With only eight project offices visited (out of the 128 major capital equipment projects being managed by subject department), the sample might well be assessed as statistically insignificant. However, this sample did cover a broad range of project size, the three technology streams of the Department and the full scope of staff experience levels.

For each of the six specific areas to be addressed, two or three candidate solutions were then identified and developed. These candidate solutions were scored against the pre-determined MOEs, and the mean and standard deviation of each solution calculated. Comparison of the grades allowed the preferred solution for each functional area to be nominated in an objective and non-prejudicial manner, to be combined in an overall recommendation package in a comprehensive report to the Department.

5.3. Outcomes.

The evaluation was completed successfully, and was accepted as rigorous and sufficiently quantitative and objective by the technology-intensive organisation.

The main product of this evaluation was a final report to the Department, which included a preferred solution option that addressed the six specific target areas of the critical reference group, six conclusions and eight recommendations.

Table 1. An Example MOE: MOE 2 – Probity of the T&E Process

Grade	Score	Description
Absolute	4	The process audits the T&E master plan against the approved Operational Requirement supplied by the sponsor at regular milestones. Clear guidance documents exist and are used. The supplier does not write the T&E Master Plan (TEMP) and Test Plans. A third party who is not subordinate to the supplier or the Department manages the T&E process.
Total	3	The process audits the T&E master plan against the approved Operational Requirement supplied by the sponsor at regular milestones. Clear guidance documents exist and are used. The supplier does not write the TEMP. Another party approves test Plans written by the supplier. A third party who is not subordinate to the supplier or the project office manages the T&E process.
Complete	2	The process audits the T&E master plan against the approved Operational Requirement supplied by the sponsor at regular milestones. Clear guidance documents exist and are used. The supplier does not write the TEMP. Another party approves test Plans written by the supplier. A third party who is not subordinate to the supplier or the project office approves the T&E process.
Fair	1	The process audits the T&E master plan against the approved Operational Requirement supplied by the sponsor at regular milestones. Clear guidance documents exist and are used. The supplier does not write the TEMP. The Project Office approves test Plans written by the supplier. A third party who is not subordinate to the supplier or the project office audits the T&E process.
Corrupt	0	The process does not audit the T&E master plan against the approved Operational Requirement supplied by the sponsor at regular milestones. Clear guidance

		documents may exist but are not used. The supplier writes the TEMP and/or Test Plans. A subordinate of the supplier or the project office audits the T&E process.

An interesting point to note was that the objectivity of the evaluation was proven during the presentation of the draft final report to the EWG. One of the critical reference group representatives took issue with one of the main recommendations (the number of positions needed to establish a best-practice T&E management group) based upon his own expectation (his ‘gut feel’) of how many staff it would need. When challenged, the evaluation process based upon pre-determined MOEs , descriptors and a quantitative scoring system, stood the test as the EWG could not fault the logic flow or scoring which led to the recommend staffing level.

1. CONCLUSION

Evaluations of programmes in technology-intensive domains provide some unique challenges. The critical reference group and others in high-technology organisations demand evaluators to ‘speak their language’ and be able to jump any cultural divide between the traditional ‘soft’ domain of programme evaluation and the ‘hard’ science background of numbers, facts and artefacts prevalent in the target fields.

An open inquiry evaluation method derived from a Systems Engineering approach to complex problem solving has been proposed. This method parallels the proven process used in the engineering discipline of Test and Evaluation to validate ‘hard’ products of the systems engineering process. The proposed model emphasises front-end effort in pre-determining the Measures of Effectiveness in unison with a quantitative scoring system. The advantage of this model is that such a technique is easily understood and appreciated by the critical reference group in technology-intensive domains. The technique was successfully used to evaluate the Test and Evaluation programme of a government department; and proved to be an objective and quantifiable method of evaluation able to survive scrutiny by the engineering profession.

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