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Based on 45 years of experience conducting research and development into spacecraft instrumentation and 13 years' experience teaching Systems Engineering in a range of industries, the Mullard Space Science Laboratory at University College London (UCL) has identified a set of guiding principles that have been invaluable in delivering successful projects in the most demanding of environments. The five principles are: 'principles govern process', 'seek alternative systems perspectives', 'understand the enterprise context', 'integrate systems engineering and project management', and 'invest in the early stages of projects'. A common thread behind the principles is a desire to foster the ability to anticipate and respond to a changing environment with a constant focus on achieving long-term value for the enterprise. These principles are applied in space projects and have been spun-out to non-space projects (primarily through UCL's Centre for Systems Engineering). They are also embedded in UCL's extensive teaching and professional training programme.

exd ]-21n19 - TJmmd b qdeqmbe9 (aqm) TJme p indicators are difficult to use. In general, however, MSSL copes well in a resource-hungry environment.

While delivery schedules are often negotiated (the norm for the domain) and space agencies typically include margin in this area, MSSL has not been responsible for any major launch delay.

## Method

UCL Centre for Systems Engineering (UCLse) is a university-wide centre of excellence for systems engineering and is hosted within MSSL. For some time, UCLse has been reviewing experiences from MSSL space projects, and in January 2010, a project was undertaken to formally consolidate these experiences to provide a more coherent expression of best practice in project management and systems engineering. Drawing upon post-project interviews with project managers and systems engineers, the focus of the project was an intensive three-day workshop in which UCLse staff and programme managers reviewed the experiences and identified the influences that had made the greatest impact on the outcomes of MSSL projects. From an initial brainstorm of issues, a shortlist of common themes was identified, and from these themes it was found that a set of five orthogonal 'principles' were needed to cover the most important issues. During the workshop the names and an approximate description of the principles were agreed, with the exact wording and furth

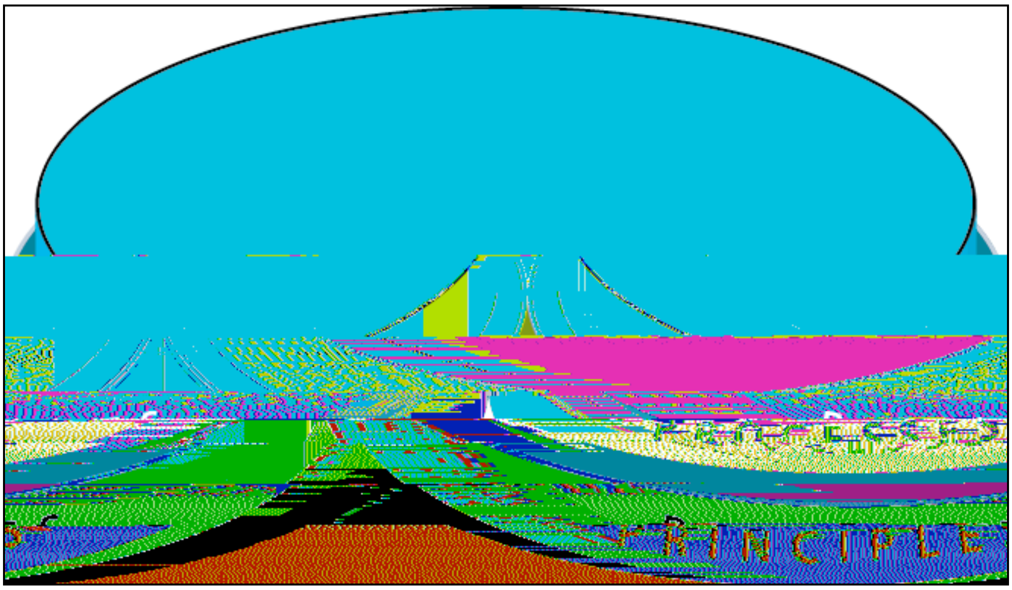

Figure 1. Principles govern process

Processes and standards are valuable, however, to facilitate exchange of information with customers and project partners. Especially in safety-critical systems and demanding environments such as space, very high levels of reliability and quality are essential and standards and common processes help to achieve this. MSSL therefore embraces standards like ISO 9001 (International Organization for Standardization (ISO) 2008), and the European Space Agency's ECSS standards (European Cooperation for Space Standardization 2011). Standards embody the codified knowledge of past generations of expert engineers. If we encouraged all our engineers to challenge standards and processes routinely, we would spend our time forever reviewing techniques rather than applying proven techniques; this would be inefficient at best and dangerous at worst.

What is the right amount of process review to allow? This is analogous to the question 'what is the right amount of tailoring to a process' (INCOSE 2011, 302). The key is to empower 'process innovators' that understand the objectives that different processes are trying to achieve and can bring knowledge or experience to the problem to identify areas for valuable improvement. Sometimes, the best people to suggest improvements will be those experienced in applying the existing process for years – those familiar with the strengths and weaknesses of the current ways of working. Other times, new employees or outsiders (such as consultants) may identify weaknesses with existing practices to which experienced staff have become desensitized.

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Figure 2. Seek alternative systems perspectives

Systems can be defined in many different ways, depending on how we partition the system internally and where we draw the system boundary (Martin 2008), and this flexibility should be explored to maximize our understanding of a system. Sometimes we are encouraged to take a single viewpoint when developing a system, and to make sure that from that viewpoint the system's performance is excellent. When designing a car or an aircraft, for example, the needs of the driver or pilot may seem to outweigh all others from a comfort and safety perspective. Or, a market may be so saturated with similar product offerings that the target customer may be quite specific (such as for technical books or some financial products). In other cases, a trend-setting manufacturer may decide to promote a new product in a particular way, promoting some aspect of form or function above all else. In all of these situations, however, the apparent focus on one stakeholder is an illusion.

In reality, all products' designs represent a compromise between offering performance in one dimension and offering performance in another.

consistent manner between projects in a range of industry sectors. TRAK, for example, has a set of five ‘perspectives’ (enterprise, concept, procurement, solution and management) each with a number of ‘viewpoints’ (22 in total). Although the business case is weak for MSSL to adopt a formal architecture framework developed for a different domain, MSSL is exploring the idea of using a basic set of standard viewpoints that encourage different perspectives to be considered; consistent with the idea that ‘principles govern process’, however, flexibility to explore additional perspectives will be maintained. In parallel, MSSL is taking an interest in the emerging European Space Agency Architecture Framework (Gianni et al 2011).

## *Principle 3: Understand the enterprise context*

System developments are undertaken by an organization (usually a business) because they give benefits to that organization. It is essential to understand the organization’s objectives and constraints when determining the optimal solution. The system development system (the combination of enterp1 (nt)eec(l) 4 (l) 4 naortord splycn ttdevelom /F1.n t specialist engineering

- A masters-level programme of education that is aligned to our research interests

- An outreach programme that encourages future interest in space through the dissemination of our research and technology interests

- A professional training programme in Systems Engineering, Systems Engineering Management and Project Management.

We should also look outside our own enterprises to understand the external environment. What is the competitive landscape, for example? When bidding for a project, what will be the likely competing bids, and how can we maximize our perceived value relative to theirs? For a new product development, how might competitors react? For competitor new product developments, how should we respond? Systems engineering managers in a commercial organization should be alert to the possibility of exploiting technology developed elsewhere, or selling or licensing technology to competing organizations, with at least a basic understanding of the concepts of value-creation, cost-benefit analysis, and intellectual property.

## *Principle 4: Integrate systems engineering and project management*

Project management and systems engineering management are highly overlapping endeavours. In both cases, their general scope is the fitness for purpose of the end product and the efficiency of its production. Different organizations define differently the responsibilities of project managers, programme managers, systems engineering managers and chief scientists. Nevertheless, there needs to be cooperation and coherence in the management structure, which recognizes the differing approaches of (systems) engineering and (project) management. While project management is typically based around a deterministic breakdown of the required activities and the creation and delivery of a causal network of such activities against defined timescales, engineering often involves iterative development with concurrent progress across a broad front. This difference can lead to real difficulties when reporting progress. Projects are systems, and need to be managed with a similar blend of science, heuristics (rules of thumb based on lessons learnt and best practice) and creativity. Too often, projects are seen deterministically, when in fact there are major sources of uncertainty (threats and opp ( ) Tj 1 (r 4(t)s)  cm BT 45 0 0 45 0 0 Tm /F1.0 1Tf ( ) Tj  -3 7 (45 0 1 ) ] 0 1 ( )   -3 7

Sometimes, such as when consortium building, the value to be obtained from early investment is primarily derived from an increased probability of winning a contract to supply a system; this value may never manifest. But even here, the consortium-building process may lead to valuable follow-on opportunities with project partners. Other times, the value may be derived from a reduced risk of project failure; more thorough planning can help to anticipate many problems that would normally be encountered in manufacturing or, worse, in service. It is difficult to retrospectively justify expenditure on the basis of avoidance of failure, but just as with insurance, the value is real. Long-run investment in capability ensures that when projects start, the tools and knowledge at the project team's disposal allow progress to be made relatively quickly.

The cost of space science missions can be very large (typically in excess of $500m) and can increase very significantly in the face of unforeseen technical difficulties. In order to ensure appropriate technical maturity across the lifecycle ESA (European Space Agency) and NASA gate their development process with the use of Technology Readiness Levels (TRLs). While this provides a useful check on the latter end of the process, it actually adds relatively little to what was already a well-understood process. However, it has had a particular impact upon the earlier stages, especially at the point of mission commitment where TRLs are expected to be greater than 5. MSSL needs to bring forward compelling and enabling technologies to a level of maturity that are of sufficient maturity to be selectable in a future mission. This involves often a very long-term programme of technological factors were user involvement, executive management support, clear statement of requirements, and proper planning. The most significant determinants of project cancellation were the above success factors, a lack of resources or unrealistic expectations. Of the five principles described in this paper, only the first – principles govern process – does not directly address the key factors described by the Standish Group research. Yet one of the strongest conclusions of the Chaos Report was that software

## Biography

Dr. Michael Emes is Head of the Technology Management Group at MSSL and Co-director of UCLse. He researches technology management tools and theory, risk management, modelling, and the intersection of systems engineering and management. He teaches postgraduate courses at UCL and industrial training courses in the areas of systems engineering, design, modelling and management and is Programme Director for the MSc in Systems Engineering Management. Before joining UCL, Michael was a strategy consultant working on projects in retail, e-commerce and transport. He has a first-class MEng in Engineering, Economics and Management from St. John s College, Oxford, and a PhD in Spacecraft Engineering from UCL.

Professor Alan Smith started as an instrument scientist for the Medium Energy X-ray Experiment which flew on-board the European space agency mission EXOSAT. In 1990 he joined MSSL, initially as Head of Detector Physics but later to become Programme Manager and eventually Director and Head of Department and vice-Dean for Enterprise. In 1998 he was made a Professor of Detector Physics. While at UCL he has been Director of UCL s Centre for Advanced Instrumentation Systems, a Co-director of the Smart Optics Faraday Partnership and is founding Director of the Centre for Systems Engineering (1998-present).

Dr. Raúl Leal is the Business Development Manager for the Technology Management Group at MSSL. His academic interests are in systems engineering, modelling and estimation. He has taught for twelve years at postgraduate and undergraduate levels with positions in Mexico, at Kings College London and now UCL. Dr. Leal has over six years experience doing consultancy and training for industry a 674.8 cm BT 0 1 ()3 (n) 2 (c) 3 (e) ] TJ E74.8.68 cm BT 02a c 45 0-14244 -3 ay w44 3 (t) oiynd 3 (t) T