MANAGING COMPLEX TECHNOLOGY PROJECTS

Systems methodologies help meet the formidable challenge of managing increasingly complex engineering systems so they deliver the specified requirements.

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OVERVIEW: A survey of United Kingdom-based industrial companies has identified the development of systems architectures and the use of a robust approach to integrated systems design as important contributors to the successful delivery of today's complex technology and engineering projects. A new conceptual framework, called the four-frames systems view, has been developed as a tool for the management of such projects. This innovative framework brings together different systems-related methodologies and tools in order to reduce risk in project design, implementation and management. The framework is based on a view that different systems methodologies are needed in order to accommodate different levels of complexity. The development of a UAV (unmanned aerial vehicle) system for the civil sector is an initial application of the framework.

KEY CONCEPTS: four-frames systems view, systems engineering, system-of-systems, project management.

Technology and engineering projects are becoming increasingly complex, both from a technical and management perspective. This, in turn, is driving the need for new tools and techniques that can facilitate the design, implementation and management of such programs (1). Although systems engineering (2) and the related subject of systems integration (3) have been developed to meet this need, there continues to be discussion over the most appropriate methods to use when undertaking systems-level research or technology activities. Moreover, this is not limited to engineering—systems approaches are now being extended to biological and financial systems as well as social system applications.

This article describes the findings from an industry survey designed to identify the main industrial problem areas where systems approaches could be brought to bear and consequently add value to the technology and engineering management process for complex projects. (See "How the Survey was Conducted," next page.) The survey results indicated that system architectures and a robust approach to achieving integrated system design were both important factors in the delivery and ultimate success of systems-based technology and engineering projects. The survey also identified that the use of systems integration and system-of-systems approaches had a major impact on the potential success of such complex projects.

The survey further revealed the need for systems engineering capabilities to include both quantitative or mathematical aspects as well as qualitative or descriptive aspects. Within the computer sciences and engineering research domains, the generation of a mathematical formalism in order to provide a representation of a situation is commonplace. The generation of the solution to this formalism then provides an appropriate mathematical model, or algorithm, for the application under investigation. The challenge for systems-based approaches would therefore appear to be the ability to link these algorithmic-type approaches to qualitative frameworks that technology and engineering managers can utilize to add engineering value and reduce technical and management risk.

Managing Complexity
Systems engineering has been evolving for many years and the development of the four-frames system view is an attempt to continue this evolutionary process. This new framework, which has been developed at Imperial College, integrates fundamental systems engineering approaches, such as integrated system design and requirements engineering from the traditional "V approach" (1), with more recent methodologies and approaches, which

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How the Survey Was Conducted

The purpose of the survey was to obtain industrial perspectives on the use of systems methodologies for managing complex technology projects. Twenty-five completed surveys were obtained from a broad range of different UK-based companies (150 surveys were sent out to company contacts of the author). Over half of the completed surveys came from defense organizations but the remaining completed surveys reflected a number of other industrial sectors, including the pharmaceutical, energy, transport and telecommunications sectors. The survey contained 14 questions, including multiple-choice questions and open questions that provided an opportunity for descriptive answers. There were a number of general questions, such as question (a), which sought views on quantitative versus qualitative systems approaches. Chart 1 shows the results.

(a). Which of the following dimensions of systems engineering do you feel is the most important for managing complexity?
   1. Quantitative, mathematical or computational
   2. Qualitative or descriptive
   3. Both

Chart 1

The responses to this question clearly show a preference for systems engineering approaches that embrace both quantitative and qualitative approaches. Question (b) sought to address a specific point on the use of systems modeling and Chart 2 provides the data obtained.

(b). Which of the following areas of multi-scale systems modeling is most relevant to your area of work?
   1. Simulation
   2. Optimisation
   3. Control
   4. Design
   5. Risk analysis and management

Chart 2

Chart 2 highlights significant interest in systems modeling for simulation applications although there is also some interest in risk analysis and management. Simulation of system performance can be a key activity to help reduce project risk and this is incorporated in the four-frames systems view. Question (c) was open-ended to give the opportunity for descriptive answers.

(c). Can you provide a short description of the key challenges that your organisation faces and how systems engineering can help?

Many replies to this question focused on common needs, such as the management of increasingly complex projects. This increasing complexity was associated with a number of different factors, including the development of new technologies and a greater prevalence of networked organizational structures to deliver complex programs.

Many answers also mentioned the specific problems associated with systems integration of new technologies on existing platforms. This was especially the case for defense companies, for example, involving “through life capability management” of military platforms and the subsequent requirement for technology insertions to extend the operational life and capability of the platform.

Finally, the development of tools and techniques to manage the complexity of system-of-systems was a common requirement.

A number of themes can be discerned from the survey, such as the ongoing challenges around systems integration and the complexity of so-called system-of-systems. Interest in systems engineering research included both quantitative and qualitative aspects; mathematical systems that do not include descriptive or semantic elements are less favored.

Within the area of systems modeling, the main focus of interest appears to be on simulation of real-world events, although there was also interest in the provision of a systems capability that reproduces experimentation as part of a low-cost solution, e.g., using modeling and simulation to reduce product development costs.

Interestingly, the survey highlighted that there are many different perspectives on what constitutes systems engineering, but despite these differences there was agreement on the need for more robust systems tools, models and techniques for the management of complex technology projects.—S.P.P.
have been designed to address the increasing complexity associated with the need for systems integration and system-of-systems.

Additionally, the framework references a theoretical foundation, through the systems theory level, which seeks to emphasize the need for skills, expertise and experience of systems practitioners. It is also linked to the enterprise level, which addresses the need to provide a bridge between technology management approaches and traditional business management.

Systems engineering and project management are systematic methodologies that have been designed to manage technical and organizational complexity; however, the failure of complex technology projects can be linked to both technical and social causes (4). Furthermore, the increasing complexity of large technical systems can be associated with larger organizational structures as well as greater numbers of dependencies and distributed networks of people and organizations that are related to the system under investigation.

This increased complexity, together with the nonlinear nature of technology-based projects and the tighter connectivity between subsystems, is leading to a greater risk attached to the delivery of projects and programs. For example, in the defense sector, there are numerous cases where program costs have not been properly controlled on high-value platform procurements programs. These cost increases have often arisen due to the increasing complexity of technologies in general but specifically through rapid advances in information and communications technologies.

The discipline of systems engineering and traditional approaches to integrated systems design, such as the “V approach,” form a solid basis for tackling these complexity issues, but the challenges do remain. One approach to meeting this need is the adoption of greater modularity of the complex system (5). However, modularity can simply increase complexity through introducing further interconnectivity within the technology system.

**Four-Frames Systems View**

The four-frames systems view is a conceptual framework that has been designed as a tool for the management of complex technology projects. The tool differs from other approaches by providing a route map for managers to help reduce technical and management risk for complex projects. This route map is based on a progression through the different frames and by reference to the two levels (systems theory and enterprise) so that effective systems management routines and behaviors are established. The use of this approach cannot guarantee the success of any technical project but it should help to reduce risks and help the manager of complex technology projects to “cover as many bases as practicably possible.”

The four-frames systems view is based on four descriptive frames, which allow increasing levels of complexity to be managed (see diagram, next page). Each frame contains its own subset of tools and techniques that can be used to manage complexity and reduce project risk. Although this approach infers a linear progression through the frames in a sequential manner, it is recognized that in certain applications this may not be possible. In this case, the activities associated with each frame should be undertaken in a sequence that is contingent on the properties of the particular technology project.

Certain technology projects may only require progression through a subset of all four frames; for example, the development of a new structural bearing for an automotive application may require systems engineering to be carried out in the first two frames; integrated system design (Frame 1) and systems architecture development (Frame 2). However, significantly more complex engineering systems may require progression through all four frames.

For example, the development of an aircraft avionics software package will need to involve all four frames in order to cope with the high degree of complexity within the system. In such a case, the overall architecture will need to be designed in conjunction with the effective use of integrated system design as part of the engineering process (Frames 1 and 2). The software package will need to be integrated with existing hardware and software configurations, such as the engine management system that controls the performance characteristics of the aircraft engine (Frame 3). It will also need to be aligned to other (partially and non-federated) systems, such as the aircraft maintenance systems (Frame 4).

Although the model does not explicitly include feedback mechanisms, it is recognized that feedback is an essential...
part of the control cycle for technology projects. Therefore, progression according to the four-frames framework may be accompanied by appropriate feedback loops. For example, once the system architecture has been developed for a particular IT system (Frame 2), before systems integration can occur (Frame 3), additional systems design and testing may need to be carried out (Frame 1) in order to enhance the system architecture (Frame 2).

Systems Theory Level

Within the framework, the four frames are supported by the systems theory level. This level provides the generic systems skills, techniques, semantics, and language, together with the requisite understanding of systems methods, which are required for any systems-based technology project to be undertaken. Appropriate systems techniques could include approaches to systems diagramming, such as systems maps (useful for mapping stakeholders), fishbone or Ishikawa diagrams (useful for displaying linear systems relationships) and multiple-cause diagrams (useful for displaying non-linear and cyclic systems relationships). In order for the engineering system to be implemented, both the project manager and the project team will need sufficient awareness and relevant experience in the application of systems tools and approaches.

The systems theory level can be further enhanced by the use of systems dynamics. Originally developed in the 1960s (6), this discipline provides conceptual tools and techniques to help understand the structure and dynamics of complex systems (7). Tools such as multiple-cause diagrams are used to map the structure of complex systems and to investigate the dynamics of these systems. There have been applications in various areas, such as supply chain management and disease epidemics as well as industry and market changes. System dynamics helps provide the context for system modeling, which is focused on developing an understanding of a particular problem area connected with the functioning of the system. As part of the modeling process, the mathematical formalism of the model will be based on the theory of dynamic hypothesis, which essentially provides a description of the system behavior.

Enterprise Level

Within the framework, all four frames are linked to the enterprise level. This connection emphasizes the importance of managing engineering systems in the context of the overall organization: its structure and composition, aims and objectives, as well as strategic and operational characteristics. This linking to the enterprise level also
**Systems Engineering**

The 2004 INCOSE (International Council on Systems Engineering) handbook describes systems engineering as "an interdisciplinary approach and means to enable the realisation of successful systems," where a system is "an integrated set of elements that accomplish a defined objective. These elements include products (hardware, software and firmware), processes, people, information, techniques, facilities, services and other support elements."

Although this definition is comprehensive, in order to highlight the key features of this discipline, it is useful to provide some of the underlying principles, and these are as follows:

- Systems engineering is about managing complexity and achieving an operational capability. Complex systems could include the manufacture of an aircraft, ship or automobile or the development of a telecommunications system.
- Central to the systems engineering approach, especially for very complex systems, is the need to establish an overall systems architecture that provides the framework for the systems engineering activities to take place, which in turn leads to delivery of the operational capability.
- The systems engineering approach involves the decomposition of the system into smaller subunits or subsystems and then the management of these subsystems through an appropriate system life cycle.
- The systems engineering process is iterative by nature and encompasses generic phases in the resulting system life cycle, such as requirements specification or capture (requirements management), analysis, design, implementation, integration, acceptance, and evaluation.

needs to ensure that not just the technical aspects of any project are considered. There needs to be clear recognition of any social dimensions of the work system. Examination of the social dynamics within the system should take account of the cognitive or human sciences aspects, as failure to fully understand the human component of any subsystem can hurt performance of the overall system.

The enterprise level analysis should not be limited to the organization itself but should also include its partners, both suppliers and customers. This holistic view of the enterprise should address the needs of both internal and external stakeholders.

**Frame 1: Integrated System Design**

The first frame involves the integrated system design process and essentially incorporates the traditional systems engineering V approach. Progression of the engineering project according to the V approach ensures that the requirements are fully captured and subsequently incorporated into the system development phase, which is followed by validation, verification and testing of the system.

During the requirements capture stage, it is important to have a defined set of requirements from the outset of the development process. These requirements can form the basis for the customer/supplier relationship and for subsequent decision-making. Failure to have properly defined requirements, or alternatively where the requirements are subject to frequent change, can have a detrimental effect on the system development process.

As part of the integrated system design process, the manager of the technology or engineering project will...
need to ensure that the user requirements are adequately captured and properly recorded in project planning documents. These requirements can then be used as the basis for quality assurance (QA) activities that are undertaken later in the project life cycle. Such QA activities will be further supported by a number of underpinning aspects, such as appropriate organizational structures and control systems, which will need to be aligned so that the system performance and quality standards are realized.

Frame 2: Systems Architecture Development
The systems architecture is essentially a representation of the systems components (e.g., both the hardware and software subsystems for a new IT system) and an expression of the relationship or connectivity between these subsystems. Establishment of the architecture allows a comprehensive understanding of the system to be developed. This understanding can be enhanced further through more detailed systems studies, such as the use of modeling and simulation. For example, the manufacture of an aerospace subsystem, such as a mechanical actuator, could involve simulation of the performance characteristics of the actuator.

Previous studies have identified the need to establish information systems architectures that include high-level business strategies in addition to computer code (8). This approach highlighted parallels between information system architectures and real-world scenarios, such as the design and construction of buildings. A descriptive model was developed that provided new tools and techniques, which can inform the architecture development process. The model included consideration of the business perspective and the information system perspective, depicted as data columns. The four-frames systems view is an attempt to reinforce this type of linking of the technical and architecture development activities with the enterprise level, which includes organizational aspects as well as business strategy.

Frame 3: Systems Integration
This frame highlights a particular case for systems that are highly complex and where there can be specific difficulties with the implementation of the system once it has been designed, validated and tested. Operational testing of the system can require the integration aspects to be addressed; however, integration with existing systems as well as with other new systems can become problematic for different types of engineering projects. Systems integration was identified by the industry survey as a major source of problem areas in complex technology projects. In this context, the development of versatile and robust mathematical models and algorithms, together with descriptive frameworks that allow systems integration to be achieved, continues to be a major challenge for systems-oriented academic researchers and systems practitioners.

Ultimately, the success of any systems integration activity will be based on the ability of the system to deliver the required functional capabilities. The integration process is likely to benefit from a thorough appreciation of the system attributes together with an understanding of how the system will function in relation to the environment outside the system’s defined boundary (this may include the wider system of interest view). Similarly, in military terms it may be useful to relate the system to the appropriate concept of operations, in order to ensure that the system performs effectively once it has been integrated with other systems and subsystems.

Various generic tools can be used in support of the systems integration process, including modeling, simulation and visualization techniques. Furthermore, applying a network-centric approach to systems integration can have particular benefits. Such a framework could involve regarding each system as a node on an information network. Consequently, the integration and resulting management of these systems can be achieved through the use of established network management models, such as root cause analysis, active network management or agent-based techniques (9).

Frame 4: System-of-Systems Management
The system-of-systems (SoS) approach addresses specific issues associated with systems implementation and management for highly complex systems. In this case, such systems may be only loosely federated with each other or alternatively may be non-federated; they are therefore not considered as a series of systems and corresponding subsystems. Effective SoS management can require a more in-depth analysis of the requirements because there are multiple systems to consider and the requirements engineering can become significantly more complex (10).

Establishment of a requirements matrix can help this process and the increased number of systems can lead to the need for a broader consideration of a larger group of stakeholders. The literature on SoS management appears to be fragmented but there are studies that have highlighted the need for new processes and techniques to be developed in order to cope with the increased complexity of SoS-type situations (11).

In order to identify some of the key issues that may arise as part of a systems-based technology project, and consequently to highlight how to effectively use the four-frames systems view, it is suggested that a number of questions be posed in relation to the project (see "Questions To Ask," next page). These questions should help the project team to identify which systems-based tools and techniques will potentially be of most benefit and thereby provide an initial checklist for planning complex technology projects.
Application of the Framework

To illustrate the utility of this framework, the four-frames systems view will be applied to an emerging business opportunity that is technologically intensive and has complexity both on a technology and organizational level. The application is the development of unmanned aerial vehicles (UAVs) for commercial uses, such as cargo transport or environmental monitoring.

The first frame of the framework (integrated system design) can be applied to the development of the UAV platform. Initial identification of the system requirements, such as the load capacity, range and endurance of the vehicle, together with propulsion and other performance characteristics will establish the vehicle’s operating parameters. The established V approach can then be used, from requirements capture and management to system development and then validation, verification and acceptance testing. This initial systems work represents traditional approaches to systems development.

The second frame involves rigorous development of the systems architecture and, in this example, could start once the initial system has matured sufficiently, i.e., before the first frame is complete. In order to understand how the air vehicle will operate, a detailed systems architecture will need to be established, which includes an understanding of how the platform’s subsystems (e.g., software subsystem, propulsion, landing gear, etc.) interact with each other and how they contribute to the performance of the overall UAV system.

The systems architecture will need to incorporate validated data and information on the UAV’s flight characteristics, guidance and control aspects as well as various information and communication technologies, such as sensor integration systems. Modeling and simulation can be carried out on the performance of the UAV, involving development of a real-time synthetic environment (12) that is based on a mathematical description of the system attributes. The synthetic environment can be used to model the operation of the UAV and then, when the UAV is operational, real-time data from the UAV can be used in the computer simulation to further enhance the UAV’s performance.

Progression to the third frame can occur once a robust systems architecture has been developed and the performance of the UAV is fully understood. The third frame will require integration of the UAV’s subsystems and with related systems (e.g., the ground-based control system) which together would represent an operational UAV system. The integration process will ensure that the connectivity of the UAV subsystems is fully achieved and the system delivers the operational capabilities.

This process would need to address hardware and software considerations, with the latter being dependent on associated interface protocols, etc. Integration of system software could be achieved through the application of critical, metrics-based success factors (13). This approach benefits from allowing decisions on system conformity and acceptability to be taken as part of the planning.

Finally, progression to the system-of-systems (SoS) frame will be required in order to integrate the operational UAV system with non-federated or only loosely federated systems. In the case of an application for cargo transport, for example, there will be a need to manage the UAV system in the context of airport operations. The airport itself can be considered a system-of-systems, which would include the air traffic management, cargo handling, law enforcement, and homeland security systems as well as the airport’s management systems.

Questions To Ask

1. Will the engineering system be open or closed, i.e., to what extent is there an interaction with the external environment?
2. Are there any quantitative or algorithmic-based models that have suitability and relevance to the engineering system?
3. Does the engineering system have a social or people-oriented dimension that needs adequate coverage?
4. Has an initial view been formed on where the main areas of complexity will arise within the engineering system and its subsystems?
5. To what extent is the engineering system based on a comprehensive integrated system design process, including requirements engineering, system development and testing?
6. How adaptive does the system architecture need to be; will the success of the engineering system depend on the level of adaptability of the architecture?
7. Will the engineering system need to be integrated with existing systems or other newly developed systems?
8. Will the engineering systems need to be managed in the context of other loosely federated systems, thereby representing a system-of-systems?
9. Do the project team members have the required systems skills and understanding of system theories, tools and techniques?
10. Have the enterprise level aspects of the engineering system been properly considered?
Specific SoS activities could include linking together multiple information and communication networks using the Pajek Plot network analysis tool (14). However, in order to retain flexibility and for technology upgrades to occur, there may be a need for such networks to be only loosely federated together. This would retain flexibility, so that software and hardware enhancements can be undertaken for individual networks (system level), without compromising the capabilities of the entire communication apparatus (SoS level).

The four frames view is underpinned by the systems theory level. In this example, at all stages of the systems development program, it will be essential for the people involved to have adequate systems skills and experience. Moreover, and in relation to the framework's enterprise level, a clear and attractive business case will be required in order for UAVs to be developed for application in the civil airspace. With UAVs already in operation in the military environment, as both surveillance and combat platforms, their application in the civil sector would benefit from previous research and technology investment in the defense sector. The use of civil UAVs for cargo transport will be dependent on service demand and consequently integration with customer relationship management (CRM) systems will be needed.

**Future Work**

This conceptual framework is an innovative approach to help improve the level of understanding of the problem areas and the resulting trade space for engineering projects. It has not been designed to be overly prescriptive but is instead a tool that should be of benefit in the planning, implementation and management of complex technology and engineering projects.

Further research will be required in order to provide additional linking mechanisms for the different approaches to systems methodologies. Future work could include an extension of the four-frames systems view in order to incorporate a quantitative dimension and thereby help provide a bridge between algorithmic-based solutions and more descriptive engineering frameworks. It is also recommended that a set of performance metrics be developed to help measure the effectiveness of systems frameworks. The generation of a numerical measurement tool that could be applied to the different parts of the four-frames systems view would offer the potential to assess its effectiveness for different technology and engineering projects.

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**References**
