AN INTEGRATED PROCESS FRAMEWORK FOR ENGINEERING ENDEAVOURS

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ABSTRACT

With the exponential increase in the complexity of modern products, the enterprise which creates the product also increases in complexity. Projects to realise engineering products are often fraught with delays, budget overruns and unsatisfied clients.

The study sets out exploring the domains of systems engineering, project management and quality management, by extensively referencing industry standards and international good practice in the quest of unravelling conflicts and uncertainties. Selected concepts and business processes of each domain are studied to arrive at an understanding of the objectives and scopes of those processes. This understanding enables the integration of these business processes and concepts by utilising the widely-used plan-do-check-act (PDCA) cycle. The business processes of each domain are divided into the four PDCA quadrants and integrated models of those quadrants are presented.

The four quadrants are synthesised into a single framework which shows the project management, quality management and systems engineering processes performed during a single project phase. This Engineering Management Framework may be tailored for the design and realisation of any complex product, given adequate planning, understanding of the challenges and knowledge of the subject matter.

Key words: Systems Engineering, Project Management, Quality Management.

INTRODUCTION

The field of modern engineering of complex products is fraught with ambiguous terminology, conflicting methodologies and an overflow of information. The cooperative, multi-disciplinary development of such products commands disciplined control and proper integration of the work effort (Kossiakoff, et al., 2011). Therefore, product design, development and realisation utilises various engineering and management processes, in a concerted fashion, resulting in a product which aims to meet the stakeholder expectations.

The fields of systems engineering, project management and quality management are highly studied, well documented and performed throughout the world, yet still riddled with failed products, project delays, budget overruns and health and safety incidents (Pinto & Mantel, Jr., 1990) (Kappelman, et al., 2006). Such issues are often caused by the following challenges (Muller, 2007):

- Unclear, misinterpreted and changing stakeholder expectations (Hull, et al., 2011);
- Lack of clarity regarding the responsibilities of the parties involved in the initiative;
- Difficulty to plan properly due to a poor understanding of the activities to be done;
- Poor communication between the parties involved because of inconsistent use of terms and abbreviations; and
- Poor alignment of the objectives of the parties involved, resulting in a lack of integration of the work effort.

The goal of the study is to understand the objectives of the disciplines and domains involved in the realisation of a complex product and to present an integrated framework which describes the business processes of those domains. This framework is based on industry standards and international good practice and may be adopted and tailored for various industries, environments and projects.

Research Scope

The resulting Engineering Management Framework is structured according to Systems Engineering good practice as documented in international standards (e.g. (IEEE, 2005)) and industry leading engineering organisations (e.g. (NASA, 2007)). To allow for wide adoption, the framework is not industry or product specific and may be adopted, through tailoring and planning, for most engineering product creation endeavours (NASA, 2007).

To adhere to the need for a generic framework, the intricate details of the various engineering and other processes and techniques are not studied extensively, as those details often differ between industries and specialities. The three domains under consideration are explored to the extent that the individual business processes are understood sufficiently to enable integration between them.

Research Objectives

This study aims to unravel the multi-faceted domains by focussing on the following three objectives:

1. Collecting and describing those crucial processes of the systems engineering, project and quality management domains which, if performed correctly, will ensure the success of the work effort and product;
2. Describe the interoperability, interaction and integration between the various processes involved, ensuring a coordinated effort towards satisfying the input requirements; and
3. Creating a standardised model which illustrates the cycle of processes and techniques applied iteratively and recursively during the realisation of a complex product.

Research Process

The targeted framework forms the basis of the engineering management system, which is, similar to other management systems, an extension of the quality management system of an organisation (ISO, 2005). The research is thus structured according to the following requirements of a quality management system, as set out by ISO (ISO, 2008):

- The enterprise shall define the execution and management processes for product realisation and the application thereof;
- Determine the integration of these business processes;
- Define the success criteria of these business processes;
- Ensure adequate resources and information are available for execution and management of these processes;
- Monitor, measure and control these business processes; and
- Implement corrective and preventive actions to achieve success and continual improvement.

Good practice frameworks are utilised to identify the business processes which are necessary for product realisation. These processes are studied using international standards and leading organisation documentation to gain an understanding about the objectives, inputs, outputs and scope of each business process. An integrated framework is then synthesised incorporating the business processes from all three domains.

Research Outcomes

The resulting Engineering Management Framework consists of the following:

- The business processes which are performed in a concerted effort to create a successful product;
- A life cycle model which provides for adequate hold points during the design and realisation of the product;
- A consistent set of terms and abbreviations to improve communication between the parties involved.

LITERATURE STUDY

To understand the objectives and describe the integration between the systems engineering, project management and quality management processes, it will be necessary to study academic and industry literature regarding those fields of study. The literature study is divided into the following sections representing the major fields of study:

1. Consistent language providing standardised terms and abbreviations which enable communication;
2. Systems engineering concepts, techniques and processes;
3. Systems engineering management processes;
4. Project management concepts and processes;
5. Quality management requirements and processes.

It is not the aim of this research to present detailed studies of the various business processes, concepts and techniques of the study domains, but rather to gain enough understanding of each to create an integrated business process framework which may be used as reference and guidance to plan, execute and control engineering endeavours.

Standardised Language

One of the greatest challenges faced when attempting to establish a standardised engineering management practice is to avoid confusion and ambiguity caused by inconsistent use of language (Dean & Bentz, 1997). Complete consensus regarding the use and meaning of terms and abbreviations within the fields of engineering, project management and quality management does not exist, let alone across those fields of study. To enable conversation and collaboration within an enterprise, it is essential to establish a single set of terms and abbreviations, based on good practice and industry standards (Winbow, 2002) (Jung, 2009).

To establish such a dictionary of terms and abbreviations and enable consistent use, a list of preferred sources should be drawn up, assisting with the process of introducing new terms and abbreviations to the enterprise. Giving preferential status to a particular publisher will minimise the effort involved with eliminating conflicts between different terms and their associated definitions. The following list of preferred sources was used for the engineering management framework presented in this article:

1. The International Organisation for Standardisation (ISO);
2. The International Electrotechical Commission (IEC);
3. Project Management Institute (PMI);
4. International Institute of Business Analysis (IIBA).

An extensive list of terms with associated definitions and authoritative sources was compiled as part of this study, to establish a standardised and consistent engineering language. These same terms are also used throughout this article and the dissertation that it is based on. The list of terms is not included in this article due to space limitations.

Systems Engineering

Compared to the more traditional engineering disciplines, such as civil and mechanical engineering, systems engineering is certainly a younger sibling, born from the exponential increase in the complexity of modern products (Cogan, 2012). Though it is not clear exactly how and where the practice of systems engineering started, the complexity of aircrafts led the military to adopt a systems thinking and analysis approach, accelerating the development of systems engineering (Cogan, 2012). Many government departments of the United States of America have adopted systems engineering and even made it mandatory for contractors to follow their methodology (INCOSE, 2010).

Commercial entities have also increasingly adopted the systems engineering approach over the decades, due to the following three factors (Kossiakoff, et al., 2011):

- The rapid advancement of technology introduces more technical risk in the development of a product, which requires technical management;
- Fierce competition forces system-level trade-offs to produce superior products; and
- Increased specialisation requires a more modular system which can be designed and produced by different parties, which makes stringent interface management necessary.

With the release of the international standard ISO/IEC 15288 in 2002, systems engineering is now the preferred practice for the development of complex products, especially those requiring multiple engineering disciplines (INCOSE, 2010). It should be noted that systems engineering is concerned with the definition of a product which will satisfy the stakeholder expectations and the validation of the product, but not with the physical creation of the product (U.S. DOD, 1969). However, the verification that the product was created as defined by the systems engineering effort and validation that the product satisfies the original need, does fall within the scope of systems engineering (IEEE, 2005).

The concepts and principles presented by INCOSE (INCOSE, 2010) are adhered to in the framework. The systems engineering process as documented in IEEE Std 1220-2005 (IEEE, 2005) forms the basis of the product design process and the lifecycle processes of ISO/IEC 15288:2008 (ISO, 2008) are referenced.

Systems Engineering Management

Systems Engineering Management, or Technical Management, corresponds mostly to the "control" activity of the systems engineering process of IEEE Std 1220-2005 (IEEE, 2005). Essentially, these management processes are mainly concerned with the planning for and organising and control of the content consumed and produced by the systems engineering process. Therefore, it is not the objective of technical management to manage the resources and effort which produces the output, but provides valuable input to such project management functions.

As an early reference, the U.S. Department of Defence (1969) defined Systems Engineering Management in 1969 as the following:

"The planning and control of a totally integrated engineering effort related to a system program. It includes the system engineering effort to define the system and the integrated planning and control of the program efforts of design engineering, system support engineering, production engineering, test and evaluation engineering."

From the definition it is clear that the systems engineering management processes are present during all stages of the product life cycle. The systems engineering process is not only active during the design phases of the product life, but also during product realisation and utilisation, due to modifications, verifications and validations to be performed (Blanchard, 1994). Therefore, the scope of the various systems engineering processes begins with early project planning and ends when the product is retired and disposed. The cross-cutting technical management business processes as documented in the NASA Systems Engineering Handbook (NASA, 2007) form the basis of the systems engineering management processes.

Project Management

Project Management is thoroughly studied and practiced within most industries throughout the world, as evidenced by the Project Management Body of Knowledge. From large construction projects to small scale business development projects, the domain of project management has been substantially standardised and documented in the widely adopted and referenced Guide to the Project Management Body of Knowledge (PMBOK Guide) (PMI, 2008).

This literature study includes a select few concepts and processes of project management, primarily referenced from the PMBOK Guide, to explore the interaction with the systems engineering and quality management domains and establish an integrated model.

Quality Management

Quality management is the domain of business processes and practices which attempt to ensure that stakeholder requirements are satisfied, by controlling the system which creates the product (ISO, 2005). Therefore, for the development of a complex engineering product, certain quality management mechanisms have to be established in the organisation(s) responsible for the various product design and realisation processes. Therefore, quality management is a constant influence on the system life cycle processes, from requirements analysis to product disposal (Gitlow, et al., 2005). Boardman (1994) created a process model that unifies systems engineering and project management, but viewed quality management as an external factor. The process framework presented in this article includes selected quality management processes as part of the model.

ISO 9001:2008 (ISO, 2008) describes the requirements of a quality management system and the following paragraphs of the standard are related to the engineering of complex products:

- Paragraph 4 – Quality Management System;
- Paragraph 7 – Product Realization;
- Paragraph 8 – Measurement, analysis and improvement.

INTEGRATED MODELS

Many connections and relationships exist between the studied domains and within the domains themselves. The aim of this article is to present an integrated Engineering Management Framework which illustrates these relationships. Utilising the well-known PDCA-cycle (Ishikawa & Lu (translator), 1988), shown in Figure 1, as a rough description of management, the business processes and concepts of the systems engineering, quality and project management domains can be related to each other within each stage of the cycle.

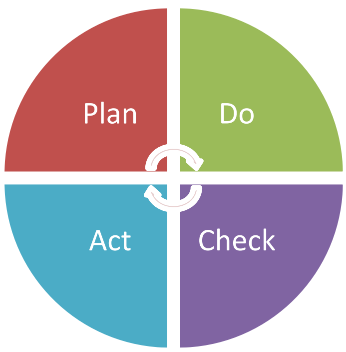

Figure 1: Japanese PDCA Cycle, 1951 (Ishikawa & Lu (translator), 1988)

The elements of the PDCA-cycle shown in Figure 1 will correspond to the following quadrants of the framework:

- Plan equates directly to Planning, incorporating project, technical and quality planning;

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- Do corresponds to both Execution and Control, being simultaneous activities;
- Check is represented as Evaluation in the framework; and
- Action is termed Change Management due to the nature of changes during engineering projects.

Planning

All three the domains of systems engineering, project and quality management have planning aspects to it. As part of systems engineering management, not only is the systems engineering management plan a critical deliverable of the effort, but planning is necessary to perform each of the technical control processes, such as requirements management, information management, etc. (NASA, 2007). Figure 2 shows a hierarchical breakdown of the typical plans created for a project developing a complex engineering product.

This does not necessarily mean that each of the elements on Figure 2 must represent an individual plan record, but rather that due consideration should be given for each planning element, even if the resulting plans are collectively documented in a single record. If each element on the diagram represents an individual record, then the hierarchical lines denotes the structure according to which these plans should reference each other. Therefore, the project management plan should make reference to the systems engineering management plan, which in turn references all the separate technical control plans, such as the configuration management plan.

Planning should be a team effort, consisting of the parties responsible for the project management, engineering and quality management. For each of the elements of Figure 2 the following should be done:

- Define the objectives and the scope of the work to be performed;
- Tailor the business process, supporting documentation and enabling mechanisms for the specific project or job; and
- List and sequence the tasks to be performed and allocate resources (people, tools, money) (NASA, 2007).

Execution and Control

"Do" can be directly translated to execution, but the complexity of the effort necessitates the application of stringent control of the execution. Therefore, execution and control essentially comprises the implementation of the various plans described in chapter 3.1. Execution consists of those elements of the systems engineering process which designs the solution and defines the configuration. Therefore, execution consists of the following processes:

- Requirements analysis;
- Functional analysis and allocation;
- Synthesis;
- System analysis;
- Logistics support analysis;

- Reliability analysis;
- Safety analysis;
- Other engineering disciplines.

Figure 2: Hierarchy of typical plans of an engineering project

The control element then, consists of those business processes which organises the effort involved with and content consumed and produced by the execution processes. Systems engineering, project and quality management all have control elements. Figure 3 shows those control functions, consisting of the following:

- Technical control consisting of the systems engineering management processes, excluding systems engineering management planning, technical assessments and technical decision management (NASA, 2007);
- Project monitoring and control as described in the PMBOK Guide (PMI, 2008);

- Quality control, as a subset of quality management and described by ISO (2008).

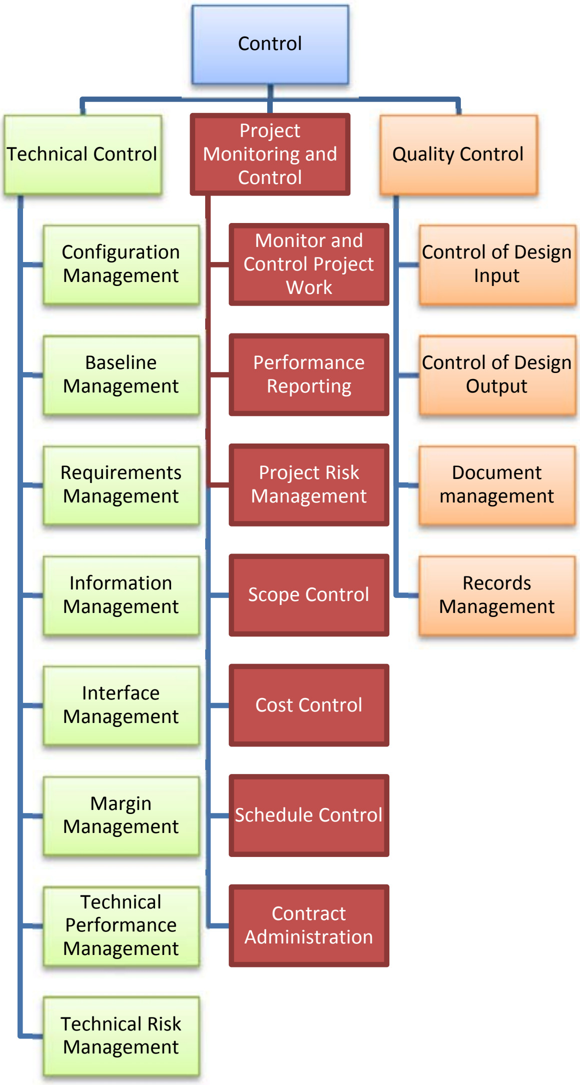

Figure 3: Technical, project and quality control

Evaluation

After a product design or realisation phase or activity, the output produced by the various processes is evaluated to confirm satisfaction of the input requirements. This evaluation corresponds to the "check" element of the PDCA-cycle shown in Figure 1. Verification confirms whether the output of a process satisfies the input criteria and validation confirms whether the product will meet the original need. The following verification and validation methods are made use of during the design and realisation of a product:

- Design review
- Technical assessment
- Inspection
- Test

- Demonstration
- Functional configuration audit
- Physical configuration audit

By utilising the concept of configuration equilibrium as presented in the INPO Configuration Management Process Description (INPO, 2005), the different verification and validation methods can be explained. Figure 4 shows the seven evaluations, between the requirements, information and actual system. As shown, design reviews and technical assessments are usually performed by comparing the output product configuration information to the design requirements (IEC, 2005). The remaining five methods require the actual product or a prototype to be performed.

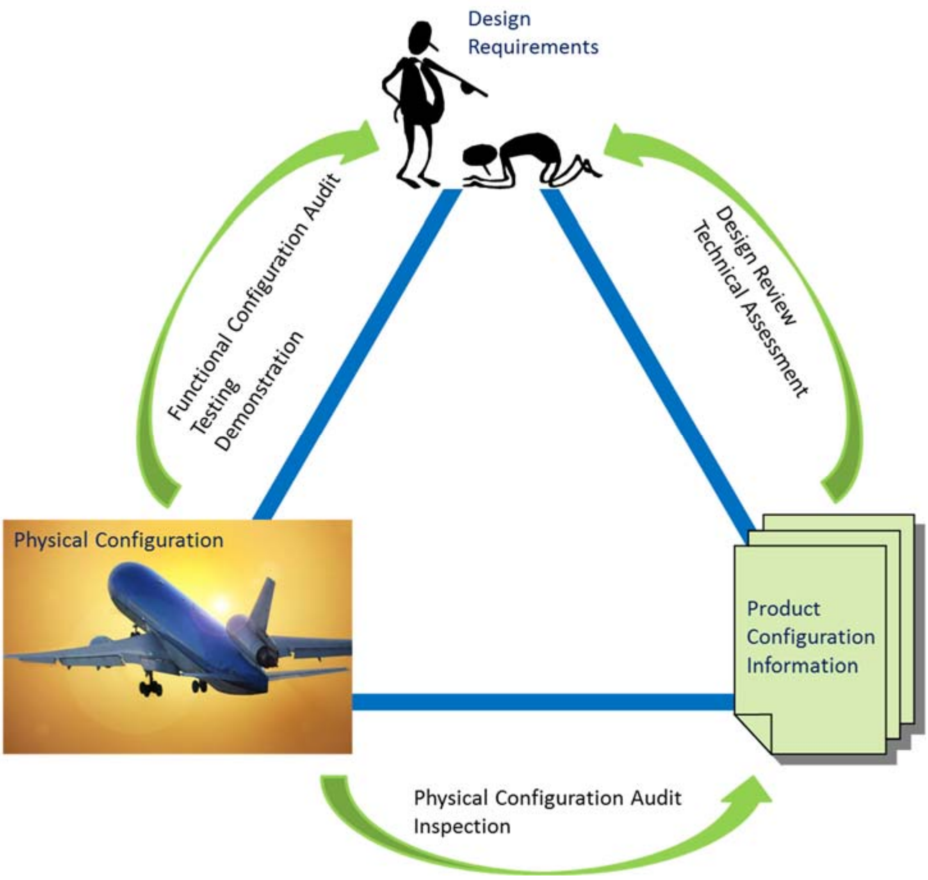

Figure 4: Confirming the configuration equilibrium

Figure 5 shows the verification and validation feedback loops for a typical product design and realisation life cycle; validations are shown in red and verification loops in blue. The typical methods utilised for the specific verifications and validations are also shown.

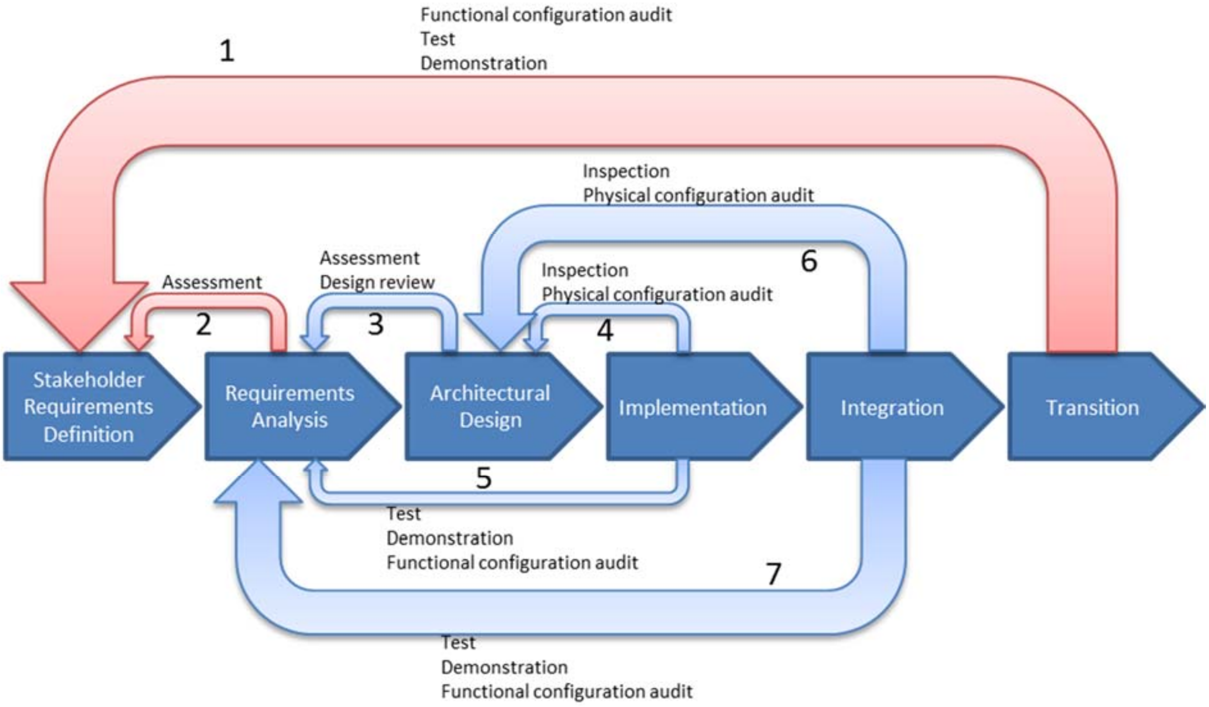

Figure 5: Verifications and Validations

The validation feedback loops are indicated in red, showing the following two validations to be performed:

1. The systems requirements generated by the requirements analysis are validated against the defined stakeholder requirements; and
2. The product is validated after transition to confirm whether stakeholder requirements are satisfied.

The following verifications are shown in Figure 5:

3. The configuration documents produced by the architectural design is verified against the system requirements;
4. The implemented product is verified against the configuration documents;
5. The implemented product is verified against the system requirements generated by the requirements analysis process;
6. The integrated product is verified against the configuration information; and
7. The integrated product is verified against the system requirements.

Change Management

Projects constantly go through changes of various types, such as changes to the project scope, budget, timelines or changes to the design requirements (Nicholas & Steyn, 2012). The ability with which a project can manage this inevitable change may act as insight into its possibility of success (Rowell, et al., 2009). Change control in engineering projects is usually initiated as a result of findings of the evaluation processes and corresponds to the "act" quadrant of the PDCA-cycle shown in Figure 1.

During the design and realisation of a product, numerous configuration changes are initiated or requested due to technical risks, design issues, nonconformities, etc. It is a requirement of ISO 9001:2008 that such changes are recorded and controlled to avoid unauthorised changes compromising the product configuration (ISO, 2008). Figure 6 shows a simple diagram which illustrates the difference between normal technical control changes to requirements, information and interfaces and changes which cross established configuration baselines.

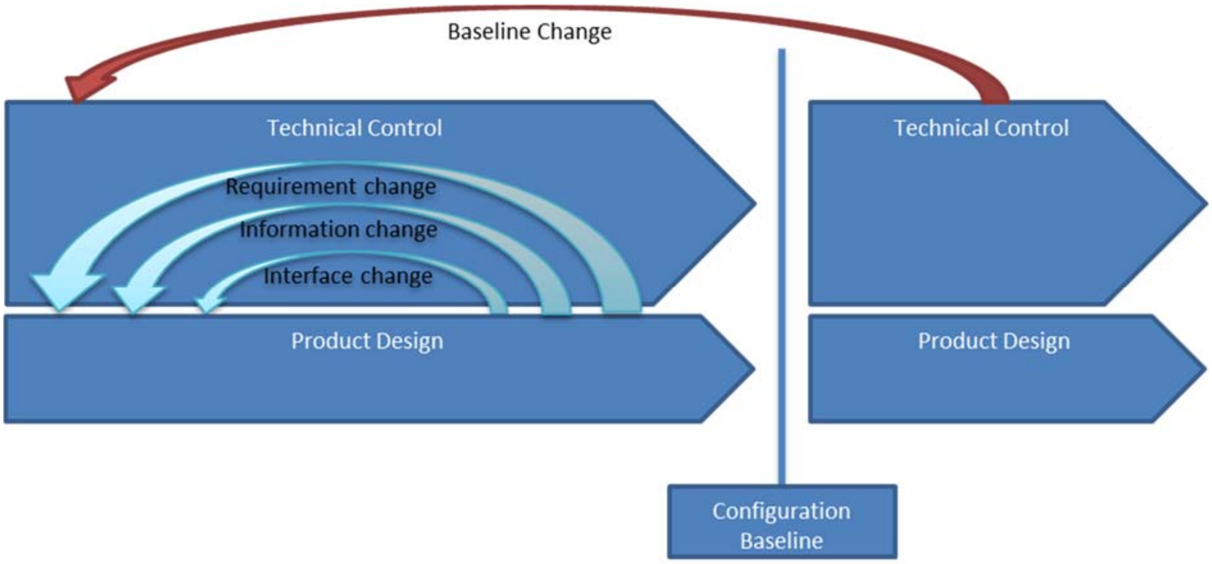

Figure 6: Technical control vs. baseline changes

Ideally, further work should always be based on a baseline to ensure that all parties utilise a consistent set of approved information. During a particular design stage, requirements and records are generated, reviewed and released for use. Further work, within the same stage of design, is then based on the results of those released requirements and records. It is the role of requirements management and information management, as part of technical control, to ensure that only released information and requirements are used for further work and that changes to currently released items are thoroughly evaluated and controlled. However, if for any reason a change to the configuration information of a previous baseline is to be changed, then the complete impact of such a change will have to be assessed to gain an appreciation for the amount of rework to be done. For any of the above changes, if it is determined that the changes will have an impact on the project scope, schedule or budget, the project change control process should be initiated.

Integrated Lifecycle Model

A single lifecycle model which integrates the project, system and design life cycle stages can be created by applying the following principles:

- The result of the project is the product;
- Systems engineering is a method of design and development;
- The product is a system; therefore the product and system lifecycles are the same.

By applying these principles and comparing the system life cycle processes of ISO/IEC 15288:2008 (ISO, 2008), the design stages of IEEE Std 1220-2005 (IEEE, 2005) and the project life cycle of PMBOK (PMI, 2008), a translation table can be created, as shown in Table 1.

Table 1: Lifecycle translation table

Project Management	System Lifecycle Stages	System Lifecycle Processes
Idea		
Project Charter		
Project Management Team		
Scope Statement		
Plan		Project Planning Process
Baseline		
Progress		Stakeholder Requirements Definition
	System Definition	Requirements Analysis
	Preliminary Design	Architectural Design
	Detailed Design	
	Fabrication, Assembly, Integration and Test	Implementation
	Fabrication, Assembly, Integration and Test	Integration
Acceptance	Fabrication, Assembly, Integration and Test	Verification
Approval	Fabrication, Assembly, Integration and Test	
Handover		Transition
		Validation
	Production	Operation
	Support	Maintenance
	Retirement	Disposal

From this translation, a single standardised life cycle model with the following phases is created:

- Project Preparation, including the project, technical and quality planning and the definition of the stakeholder requirements;
- Conceptual Design, with the systems engineering process resulting in a system specification;
- Preliminary Design, recursively applying the systems engineering process to the various subsystems, resulting in several subsystem specifications;

- Detailed Design, finalising the designs of all configuration items to prepare for implementation and integration;
- Implementation and Integration, in the form of fabrication, coding, production and construction and the planned verification of each configuration item and the system;
- Transition, including the hand-over of the verified product to the owner or customer and validating if the initial expectations were met.

By adding the system lifecycle processes of ISO/IEC 15288:2008 (ISO, 2008), a detailed lifecycle model can be created for engineering endeavours, as shown in Figure 7.

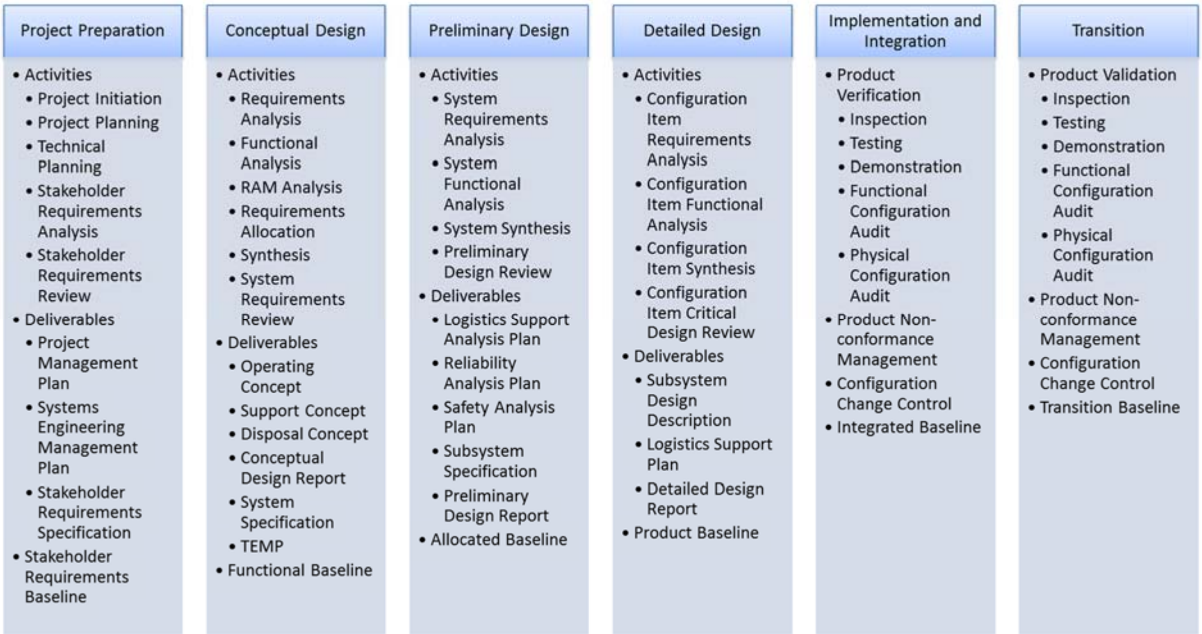

Figure 7: Detailed description of the consolidated lifecycle model

Engineering Management Framework

It has been shown that systems engineering and project management may be complimentary, if applied with good understanding of the responsibilities and tools involved (Sharon, et al., 2011). Figure 8 shows the engineering management framework for a single project phase, by integrating the domains of project management, quality management and systems engineering. Bahill and Briggs states that systems engineering is more successful when involved from the start of the project or project phase (Bahill & Briggs, 2001). Figure 8 shows that technical planning, including systems engineering management planning, provides input into the project planning.

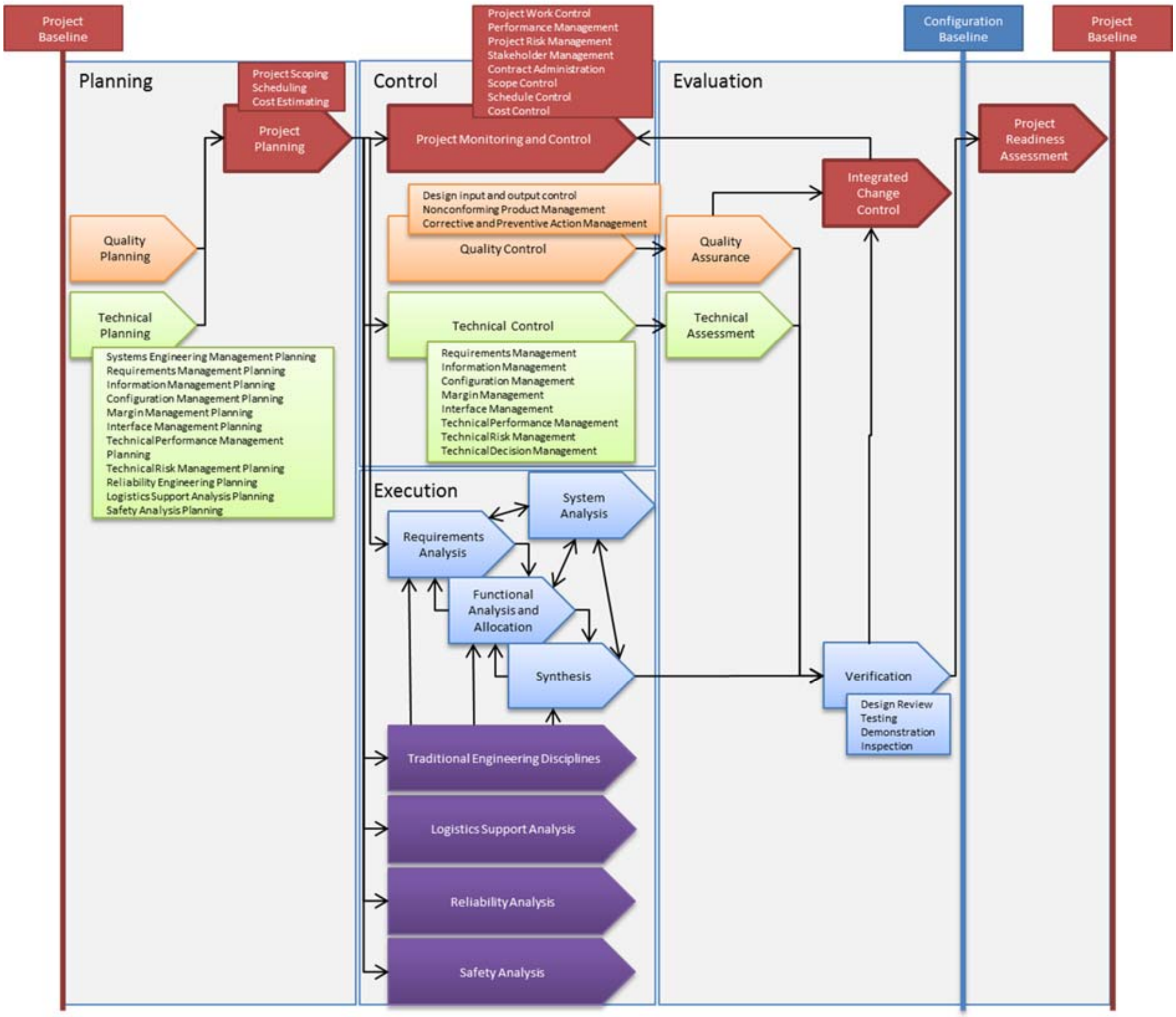

Figure 8: Engineering Management Framework

The “control” quadrant represents the project, quality and technical control processes as depicted in Figure 3. “Execution” shows the systems engineering process, excluding the control function, in close proximity with the various engineering design disciplines and analyses. In the evaluation section, quality assurance, technical assessments and verification are shown. Technical assessment is highlighted separately due to its role of supplying updated data on the technical performance measures tracked as part of technical control. Finally, integrated change control is shown, representing the project and technical changes.

CONCLUSION

A business process framework which integrates systems engineering, project management and quality management concepts has been created by adhering to the following key principles:

- Applying the domain-generic PDCA-cycle to show the relationships of similar business processes;
- Understanding the objectives of the various business processes across the three domains;

- Clearly stating the scope of each business process to avoid overlap and duplicated functionality;
- Consolidating life cycle phases where necessary to simplify the phase gates and control mechanisms; and
- Avoiding confusion and ambiguity by establishing a terms and abbreviations dictionary based on industry standards.

The plan-do-check-act cycle is a convenient way of framing a management framework. The Engineering Management Framework follows the four steps, translated as the following:

- Plan: the collaboration of technical, quality and project planning to arrive at a complete understanding of the challenges and how those challenges will be faced by the project team;
- Do: translated to execution and control showing the application of the systems engineering process in collaboration with design analyses, engineering disciplines, project, quality and technical controls;
- Check: evaluating the design output requirements and information to confirm whether input requirements are satisfied and whether the product will meet stakeholder expectations; and
- Act: translated as integrated change control to cater for the numerous requirements, information, configuration, scope, schedule and budget changes inherently part of the development and realisation of every complex product.

The presented Engineering Management Framework should be tailored for each application of it. Such tailoring is achieved by matching the outputs of the business processes to the objectives and deliverables of the project. Depending on the complexity of the project, it may be found that certain life cycle phases or business processes may not have to be performed as formally as for uncertain and unpredictable project. By following such a tailored framework, the domains of systems engineering, project and quality management will complement each other, instead of degrading into animosity often caused by a lack of understanding of the responsibilities of the parties involved, the outputs of the various business processes and the language used within the different domains.

The presented framework is industry and product generic, which may be adopted and tailored for the realisation of any complex product. However, to successfully tailor the framework for a specific application may require practitioners with extensive knowledge of the involved business processes and experience in the field of adoption. Therefore, it is recommended that further research is conducted to created industry specific Engineering Management Frameworks which will decrease the reluctance to adopt such a standardised process framework. Increased adoption of such frameworks may lead to improved application of systems engineering, project management and quality management good practice and principles, ultimately increasing the chances of project and product success.

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