THE NECESSITY FOR SYSTEMS ENGINEERING WITHIN THE OIL AND GAS INDUSTRY.

Institution of MECHANICAL ENGINEERS

Produced by:
The Upstream Oil and Gas Technical Activity Committee of the Institution of Mechanical Engineers

Improving the world through engineering

> System engineering provides the oil and gas sector an opportunity to deliver a more efficient and cost effective industry, while simultaneously creating a better understanding of the interdependencies and relationships between different parts of the product cycle, supply chain, regulators and upcoming skills gaps.

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This report has been produced in the context of the Institution's strategic themes of Education, Energy, Environment, Healthcare, Manufacturing and Transport and its vision of 'Improving the world through engineering'.

Published October 2018.
Design: teamkaroshi.com

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EXECUTIVE SUMMARY

Systems Engineering has been shown to be an effective discipline in formalising engineering project methodology for the purpose of minimising risk and maximising quality for a given spend. It is now routinely and successfully deployed in many industries, having begun in aerospace and been adopted by rail, defence and other capital-intensive industries. Recognition of the discipline is growing and a number of universities now offer Systems Engineering modules or courses to reflect the change in demand for the skills. Systems engineering, however, has not been widely adopted in the oil & gas industry, despite recognition of the potential benefits. Many reasons have been cited, including a lack of suitable material to identify an approach that would be applicable to the oil & gas industry.

This report investigates the applicability of a Systems Engineering approach to the oil & gas industry. A definition of Systems Engineering for use within the oil & gas industry is developed through the assessment and adaptation of the guidance provided by the Systems Engineering professional body: the International Council on Systems Engineering (INCOSE). Further to this, it explores the application of oil & gas-specific Systems Engineering via an exemplative case study. The necessary competencies required by industry employers and employees are discussed, and areas of further development for the benefit of the application of Systems Engineering in the oil & gas industry are investigated.

DEFINITIONS

The following definitions are used in this document

Term	Explanation
CAPEX	Capital Expenditure
FMECA	Failure Mode, Effects and Criticality Analysis
INCOSE	The International Council on Systems Engineering
MCDA	Multi-Criteria Decision Analysis
OPEX	Operational Expenditure

INTRODUCTION

The purpose of this report is to begin to address and elevate what has long been recognised as a need within the oil & gas industry: a way in which a Systems Engineering approach might be applied to deliver a more efficient and cost-effective methodology for designing and managing oil & gas assets and equipment.

The following topics are discussed:

- An introduction to Systems Engineering
- The potential benefits
- The current state of understanding within the oil & gas industry
- A suitable competency structure
- The next steps for the industry

This report does not address the needs of the industry completely, and notes that there is still much work to do – the Systems Engineering approach represents a new way of thinking about project delivery that requires cultural as well as organisational changes. The potential benefits, however, are significant.

WHAT IS SYSTEMS ENGINEERING?

All major engineering projects are systems, or even systems of systems – complex, interdependent constructs with multiple functionality. An offshore oil platform has numerous systems: the physical structure itself, the process systems, subsea elements, control and instrumentation, accommodation, safety systems and many more; so much so that the whole assembly could be regarded as a system of systems. It has long been understood that these separate elements are systems that have interfaces with other systems, and that these interfaces must be managed carefully from the conceptual and design stages. This is one of the reasons why Systems Engineering is frequently poorly applied within the industry – there is a widespread belief that the ability to design various systems and manage their interfaces already constitutes Systems Engineering. As this report discusses, it does not.

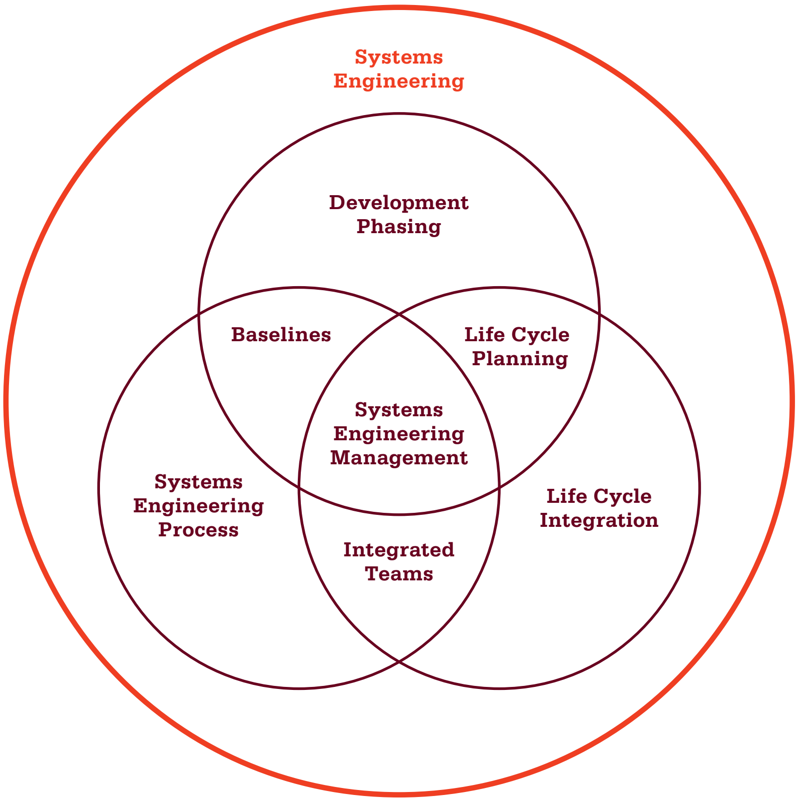
A true Systems Engineering approach requires that the asset is designed not only in space, but also in time. Every stage of its existence, from concept to disposal, must be addressed, including detailed consideration of how it is to be operated, maintained, upgraded, recycled and disposed of. Not only must these aspects be considered, they must be optimised alongside the optimisation of the physical design, with the ultimate aim of minimising the complete cost of ownership and maximising the return on investment. Philosophically, this is very different from undertaking a stand-alone reliability analysis or undertaking a maintainability review, and requires a different way of thinking, with different tools. This has long been recognised by those industries where Systems Engineering has been adopted as a standard practice, and is inculcated in engineers from the earliest stages of their careers.

The American Apollo programme made it to the moon; the Soviet N-1 rocket, designed for the same mission, exploded four times on the launch pad before being abandoned. One difference was that NASA was an early adopter of Systems Engineering principles, with dedicated Systems Engineers overseeing every part of the project life cycle. Even today, the NASA Systems Engineering Handbook is essential reading for everyone in the discipline.

This recognition of the importance of what are often dismissed as operational and life cycle support costs is generally what distinguishes Systems Engineering from merely engineering the system. It is identified quite succinctly in **Figure 1**.

Although perhaps quite simplistic, **Figure 1** provides a reasonable overview of the complete integration of all aspects of the facilities to address the full spectrum of the system's (and sub-systems') life. It starts with understanding the operational or business requirement, and matures to integrate all aspects of operations, availability, reliability maintenance, logistics, training, infrastructure etc. Indeed, current and projected variations in market pricing information could also be used to drive the long-term needs from the facilities.

Figure 1: Systems Engineering Overview



DRIVING FORCE

"We usually find oil in a new place with old ideas. Sometimes, we find oil in an old place with a new idea, but we seldom find much oil in an old place with an old idea."

This is a much-used quote from Parke A Dickey, to provide an insight into one of the drivers behind the market for system improvement and asset redevelopment within the oil & gas industry. With oil & gas reserves becoming more difficult to locate, to access, to maintain and to decommission, interest in technology development, and critically the approach to technology development, is unlikely to decrease.

Later that year the pump failed and almost three months of production was lost while a replacement was sought. No analysis to assess this risk had been completed.

An example of this process can be found in the United Kingdom Continental Shelf (UKCS). A number of major drivers for this region exist, including the area's importance as a part of the UK's energy equation.

Although the basin is mature, with peak production having been reached around 1999/2000, there is still much that can be done to prolong the life of many existing assets. Any ability to extend the life of an asset also defers the extremely expensive decommissioning liabilities, offering an additional incentive.

A small operator took over a North Sea FPSO and commissioned a reliability assessment of all rotating equipment. The lead engineer identified one item – a water injection pump – as a major concern. It had no history of failure, but was crucial to production, so it was recommended that a spare was acquired at a cost of £2m. The request was declined.

It is therefore in the UK's interest to ensure the continued development of the UKCS basin. As there are no major reserves expected to be found in this region, smaller pockets must be exploited, which necessitates the development of transferable technology. It stands to reason that, while not taking an eye off the capital costs, focusing on designing for the full life cycle and minimisation of operational expenditure will extend the region's economic life, with innovation and technology likely to be essential elements of the long-term solution.

The critical enablers required to realise this solution include reduced capital costs for new and upgraded facilities, reduced life cycle costs, and the development of new equipment, systems and processes.

To do this, the development of robust methods of designing, applying and integrating these factors is equally critical.

APPLICATION TO EXISTING ASSETS

Systems Engineering principles can also be applied to legacy assets not originally designed to that approach. Specifically, the operational support optimisation tools that are used in design can also be used for existing equipment, by applying the same approach of specifying a series of desired requirements, modelling the systems, and then selecting an approach that best meets the requirements. Existing assets also benefit from known operational data, and some of the examples given later in this report show how the approach has successfully been applied.

THE RELEVANCE AND BENEFITS OF SYSTEMS ENGINEERING

Systems Engineering has long been viewed by some people within the oil & gas industry as a tool for the specification, design and realisation of any new or developing product. However, attitudes to Systems Engineering vary from an essential approach of major benefit, to one that over-optimises a specific solution within a limited revenue stream.

INDUSTRY SURVEY

To gain a better understanding of how Systems Engineering is perceived in the oil and gas industry, a survey was undertaken. It took the form of an online questionnaire, circulated by members of the IMechE Upstream Oil & Gas TAG to their contacts and beyond. 59 complete responses were received to the following questions:

1. How well do you think that Systems Engineering is understood within your workplace?
2. How closely to a Systems Engineering approach is the average project run within your workplace? (Covering the seven stages of Systems Engineering (state the problem, investigate alternatives, model the system, integrate, launch, assess, re-evaluate) across a number of feedback loops)
3. On average, how satisfied are the key stakeholders (the customer, the engineers and the management team) with the delivered product?
4. How often is a project delivered within time, within cost and to the correct level of quality?
5. How beneficial do you perceive a Systems Engineering approach to be if applied to projects within the oil and gas industry?
6. How much of an increase in development time or cost do you believe applying a Systems Engineering approach to require?

Responses were multiple choice, with the range “Not at all”, “Poorly”, Average”, “Well” and “Excellently”. Respondents were also invited to give written responses to the question “Please provide any benefits or draw-backs you perceive in the systems approach”.

The survey was supported with detailed interviews with individuals within the industry, from a range of backgrounds including senior executives at operating companies to specialists in implementing systems methodologies. The findings from this research are referred to through this report.

INDUSTRY ATTITUDES

The findings from the first survey question are shown in **Figure 2** below.

Figure 2 provides an overview of the perceived current understanding of Systems Engineering, and its perceived benefits. It follows that:

- Many do not believe that Systems Engineering is well understood in the industry, yet
- The associated benefits from developing this understanding are large

Many conversations have been had with a cross-section of industry personnel, with discussions frequently reverting to concerns that the major driver is to design and engineer facilities to the lowest possible capital cost, with little regard given to life cycle cost. This has been heightened since the oil price crash in 2014, which has resulted in a resurfacing of low-cost design (similar to the CRINE era) rather than designing for low cost. Indeed, project managers have often cited that OPEX costs are not their consideration, because they are focused on delivering projects within their capital budget.

Further to this, many within the oil & gas industry see issues with their current approach to engineering design and application. Issues seen are frequently across three main facets:

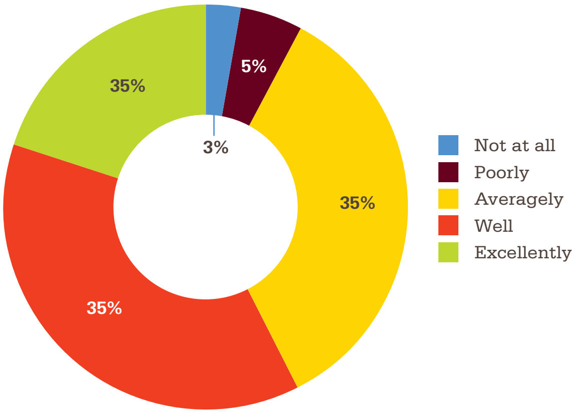
- "I need an approach that captures the range of applications and develops technology accordingly, rather than over-optimising for one application"
- "I have seen projects and equipment in operation see severe delays, redesign, failures and expensive decommissioning; many of which have been run to incorporate a rough systems engineering approach – I need an approach that sees the bigger picture"
- "I need an approach that quickly identifies the minimal change from my existing system for it to adequately function in a new application"

With the market demanding technology with a diverse range of application, to meet a diverse range of well locations and extraction methodologies, a clearer application of systems engineering is required. As discussed further in this report, Systems Engineering can provide a method for problem classification: understanding, prioritising and communicating system requirements. Ultimately, it can facilitate the diversification of developing technology to reach a greater number of revenue streams, and the delivery of systems that are optimised against all stakeholders' aspirations.

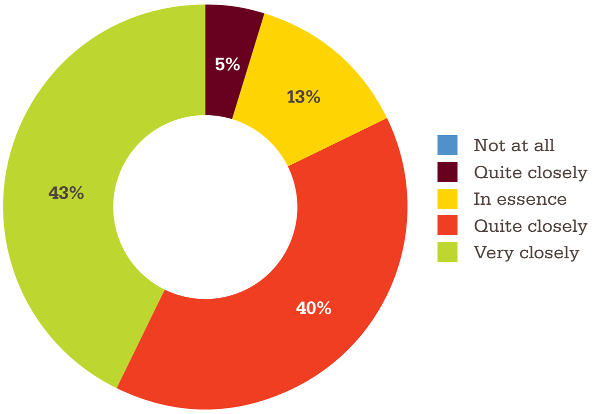
"Can this approach then be tailored to better serve the complexities of oil & gas applications?"

Figure 2: A comparison of perceived current understanding of Systems Engineering to perceived benefits

How well do you think that Systems Engineering is understood within your workplace?



How beneficial do you perceive a SystemsEngineering approach to be if applied to projects within the oil and gas industry?



The short answer to the question is undoubtedly 'yes'. Given that a project-by-project approach is currently taken to new facilities and upgrades, with limited attention paid to life cycle costs, this will require a significant cultural shift.

The survey and interview programme made it clear that there exists some reservation to applying a Systems Engineering approach. Much of this reservation can be addressed in the following three cases:

- Firstly, there is a clear need for an approach that supports engineers and project leads to consider the wider potential application, beyond the first application, of the developing system. A Systems Engineering approach provides a structured and auditable method to identify the potential system operating parameters. It supports the design team to progress, model and review a limited range of design alternatives that could solve a spread of the operating characteristics identified within the problem statement. If all mandatory system requirements have been met, a consideration can be made of the desirable requirements for the system's performance, and an educated understanding of the potential operating parameters of the system can be gained.
- Secondly, there is a clear need for an approach that integrates the requirements of all stakeholders, so that the bigger picture is captured. The Systems Engineering approach described above offers a framework for the capture of the requirements of the full range of stakeholders. Moreover, it can be coupled with a multi-criteria decision analysis to support the identification of optimal designs through the weighing of desirable requirements' relative importance. This not only allows for the bigger picture to be captured, but enables the design to be optimised against it.
- Thirdly, there is a clear need for an approach that supports the identification of minimal system change to meet new applications. The aspiration to adapt products efficiently to new applications has resulted in great numbers of previously unforeseen issues being thrown up, and this is true across all industries. This is a major concern of any change management team, and is bolstered by the knowledge that many issues are not found until the product is in service, where solutions are often more difficult and costlier to implement.

Suitable investment in the modelling and integration stages of a Systems Engineering approach have been shown to 'left-shift' the identification of issues, meaning that they are found and dealt with at an earlier stage, with an associated cost benefit. However, the optimum approach for the identification of minimal system change is to work from a product that was designed using a structured, auditable Systems Engineering approach. Of course, this may not be achievable for a given product now, but the controlled review and development of products to a documented set of mandatory and desirable requirements, allows for detailed change interrogation and re-assessment of a follow-on product, via the same modelling techniques.
As the modelling and in-service performance of the original product are known, the new system aspects can be more reliably integrated, and the new modelling results can be suitably adjusted, with the result that an educated assessment of the new product against the new set of requirements can be made. Therefore, the impact of change – both good aspects and bad aspects – is more likely to be understood at an earlier stage in the design. Thus the 'minimum change' option can be better considered alongside the associated impacts.

From the three cases discussed above, it follows that the benefits of a Systems Engineering approach can roll on from project to project, when applied consistently.

A DEFINITION OF SYSTEMS ENGINEERING FOR OIL AND GAS

If it is accepted that a systems approach would be beneficial to oil & gas projects, then how should it be implemented and what are the differences with current practice? This section adjusts the definitions and methodology outlined by INCOSE[1] to produce a definition tailored to the oil & gas industry.

SYSTEMS LIFE CYCLE MODELS

Underpinning all approaches to Systems Engineering in the design phase, is the idea of a project development life cycle. There are a great many different varieties, and the Systems Engineering Body of Knowledge[2] divides them into three categories:

1. Pre-specified and sequential processes are appropriate when the required capability is known before design starts and there is no requirement for capability upgrade during the development process.
2. Evolutionary and concurrent processes are used when an initial operating capability is achieved, and then upgrades are implemented based on the outcomes of the initial operating stages.
3. Interpersonal and unconstrained processes are used when a system is in a state of continuous development and improvement.

The last of these model classes is best suited to electronic or software systems, where there are continuous changes to the operational environment. Large capital projects usually follow the first approach, where requirements are specified before any design effort begins, and this report will focus on this type of model.

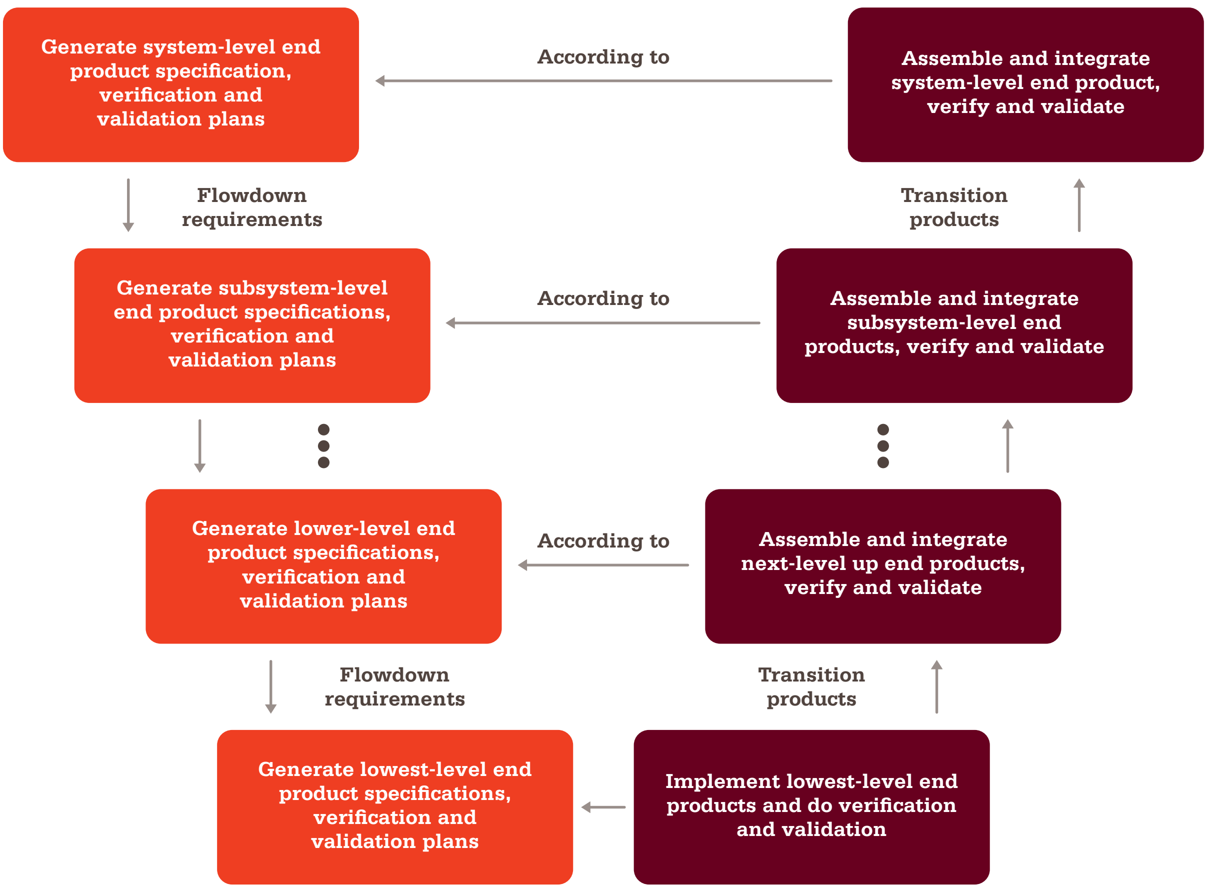
However, it should be noted that some oil & gas projects do include an initial operating stage, and for those situations the models described below may not be appropriate.

THE V-MODEL

The classic systems life cycle model for pre-specified scenarios is the V-model, which exists in a variety of forms and is specified in a great many standards. Essentially, the two arms of the V are specification on the left and verification on the right, which gradually come together as the design reaches maturity.

Systems Engineering is an engineering discipline whose responsibility is creating and executing an interdisciplinary process, to ensure that the customer's and stakeholders' needs are satisfied in a high-quality, trustworthy, cost-efficient and schedule-compliant manner throughout a system's entire life cycle.

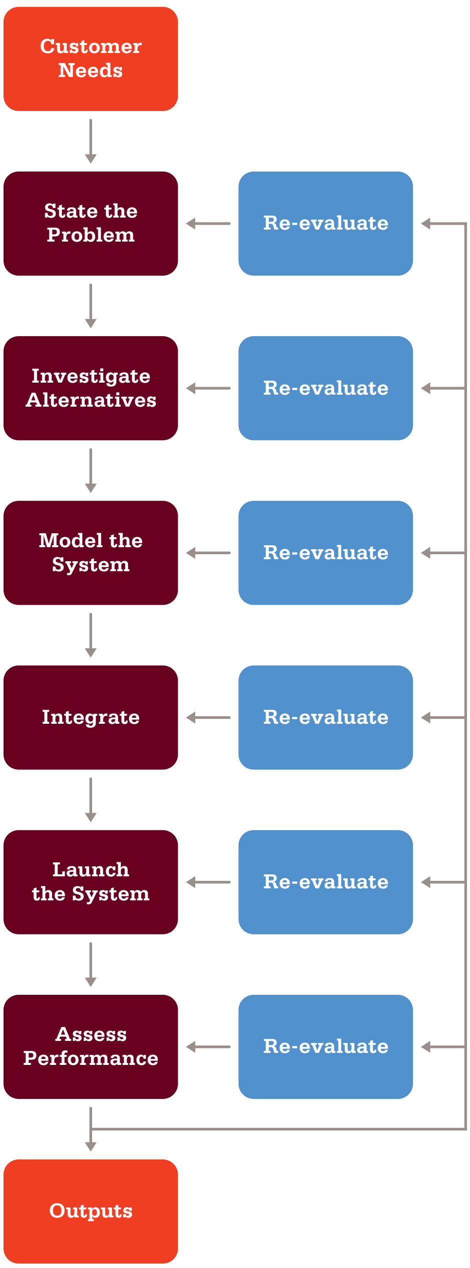
Figure 3: The V-model as implemented by the US Department of Defence



Another example, described in detail below, is the seven-stage SIMILAR process[3]. This is also a V-process, as at every stage it re-evaluates the effectiveness of the design against the requirements.

This process may not look that different from the pre-FEED options studies routinely undertaken in the industry today, and project stage-gate processes. However, there is one crucial difference in the systems approach: every stage of the asset life cycle is considered within this process.

Figure 4: The Systems Engineering 'SIMILAR' process



Problem Statement

In its simplest form: what must be done?

There is an art to identifying what the real task of a system is, and this must be carefully considered to allow the requirements derived from this problem statement to be truly reflective of the nature of the problem. An example may include the outcome of the operation of the system, and identification of the range of environments in which the desired outcome must be achieved.

For example, within what depths does a system for the flooding of a pipeline need to operate? What is the maximum size of the system, to allow it to be shipped to location? By when does the system need to be operational? How is it to be inspected and maintained? Where might it be tapped into? How will it be removed? These pieces of information can all form part of the problem statement.

Requirements for the design, manufacture, operation, maintenance and decommission of the system will be drawn from this problem statement, and so it is important to consider as large a pool of stakeholders as is feasible, including end-users, operators, manufacturers, maintainers, suppliers, acquirers, owners, regulatory agencies, victims, sponsors and others. In a system as complex as an offshore oil platform, there would be hundreds if not thousands of requirements, giving criteria not only for performance but also for maintenance, repair and disposal.

A discussion of the mandatory and desirable requirements can then be had to specify the concept of the system. Mandatory requirements must be met, to ensure that the system is fit for purpose. Desirable requirements are traded off and balanced to form a system that is optimised across all stakeholder desires. Regarding the earlier discussion of the transferability of developing technology, it is within the desirable requirements that this trade-off begins to take form, and a fair assessment of the impact of widening the operational environment of the system can be understood.

Investigate Alternatives

Alternatives can be identified at any level of the design. This could include conceptual alternatives that approach a problem via a different technology that requires large system redesign, or modification that could optimise an aspect of the design, or expand its applicability.

For example, what existing oil separation units exist? Is this approach valid for the new application, with some modifications? This may reduce up-front costs, but will a more efficient design with emerging technology increase profitability, when development, assurance and timescale delays are taken into account?

There are many approaches for the consideration of design and concept alternatives, including top-down concept development and problem-oriented concept development. In most circumstances, however, there exist desirable requirements that conflict with other desirable requirements, where it is not immediately obvious how priorities identified by different stakeholders should be weighted. Structured methods of weighting desirable requirements, however, exist. A common approach is a developed form of multi-criteria decision analysis (MCDA) such as analytic hierarchy process (AHP), which is conducted iteratively as decisions are made and more data becomes available.

For complex systems, alternative designs that can be identified throughout the design process, from concept designs to detailed designs, help to reduce project risk, clarify the problem statement, and allow for innovation and development of technology and system application.

Model the System

Modelling a system involves a diverse range of considerations and approaches, to ensure that all requirements are being considered. Many types of system models can be used, such as physical analogues, analytic equations, functional flow diagrams and computer simulations. A good project plan is one that has been created with the feedback of all key stakeholders, to identify and schedule the inputs required for all areas of modelling.

As an example, consider the design of an additional combustion chamber at a natural gas power station. Known previous performance data can be used to inform concept equipment and component design requirements, such as structural and material part requirements, and identify areas of design focus. As the design progresses, local loads and thermal and vibrational environments begin to be understood. Therefore, early fatigue and thermal stress simulations can be revised, and previous confidence margins and predicted equipment energy consumption reduced. Reliability predictions and maintenance periodicities can be re-assessed, and desirable requirements previously expected not to be complied with, can be given consideration.

Modelling tools such as simulation techniques and indicative tests perform an essential step of the design process prior to in-service or 'digital twin' data generation. Where inputs are unknown, approximations and sensitivity analyses allow for the design process to develop before operational inputs are finalised.

It is within this stage that desirable requirements can begin to be compared, and weightings allocated. As with all stages of the Systems Engineering process, the results of this stage should be used to inform and re-assess the decisions made in the other stages of the process.

An Italian study used Systems Engineering modelling approaches to assess the optimum maintenance model for each of the pumps on an offshore platform. Rather than just using reliability data, they also interviewed the responsible offshore personnel about what approaches were really followed, and why. This subjective data was also built into their model, which accurately identified which pumps should be subjected to planned, predictive, monitored or reactive maintenance schemes.

Integrate

Integration as a stage spans all aspects of the design, from physical interfaces, to functional interfaces, to the human interfaces of manufacture, test and commissioning processes. Integration relies on good communication between all relevant stakeholders, and can be characterised by:

- Frequent project updates for all project members
- Reliability design options
- Failure Mode, Effect and Criticality Analyses (FMECA)
- Functional integration workshops
- Reliability, Availability, Maintainability (RAM) analyses
- And so on

In essence, the integration stage is the mechanism by which feedback is generated to inform all other stages.

Launch the System

As with the other stages of Systems Engineering, launching the system occurs iteratively and provides feedback to inform and develop the other stages.

Launching the system takes many forms that are commonly practised as part of the engineering design process. This can include 'iron birds', or physical integration rigs for the testing of dynamic parts or software, test rigs for the assessment of individual sub-systems, up to full system testing. All these system assessments inform the design process, and allow for a product to enter final testing and assurance at a higher point on the reliability growth curve, which increases stakeholder satisfaction and customer confidence.

Within this stage, the desirable requirement weightings that have been identified through modelling practices can be confirmed and accepted, or modified and retrialled.

Assess Performance

Assessing performance occurs at all stages, with confidence growing throughout the design process. From each of the modelling, integrating and launching stages, large amounts of new data are being produced that can inform many aspects of the review of the system. Robust data management is essential to allow for system performance, inter-system communication, suitability for production, and human factors reviews. Further to this, predictive reviews of decommissioning and maintenance can be conducted through the appropriate use of existing material.

Again, the key to this stage is the clear communication of performance results to all relevant stakeholders, so that informed decisions on design progression can be made.

Re-evaluate/Redesign

The information generated in all previous stages can, and in many examples of design projects within the oil & gas industry does, contribute to the redesign and re-evaluation of systems. This process happens reactively to account for emerging information and developing requirements. The earlier that lessons learned from existing or previous projects, modelling results or test data can be incorporated into a design, the more likely it becomes that a sufficiently high-quality project can be delivered within time and cost constraints.

EXAMPLES OF SYSTEMS ENGINEERING APPLICATIONS

A true systems engineering approach is used so rarely in the oil & gas industry that good examples are hard to find. However, some examples are given in the following sections, where elements of the approach have been applied. First, we look at non-oil-&-gas examples.

THE HUBBLE SPACE TELESCOPE

NASA has always been regarded as the source of all good Systems Engineering practice, yet it was a failure of Systems Engineering practice that led to a small mistake early in the project, that could have been fixed for $1,000, being missed and ultimately requiring repair in space at an estimated cost of $1bn. This example is so extreme that it is now regularly used for Systems Engineering education programmes.

Essentially, a poor initial organisational structure and inadequate customer knowledge led to a small mistake in one of the original requirements being propagated through to a flaw in the mirror support design. NASA has published five key learnings from this programme, many of which will sound familiar to anyone involved in an offshore engineering project:

- Stakeholder Requirements Definition. Not only were there weaknesses in the requirements, the mechanism for getting requirements from the customer was poor.
- Planning: The use of multiple contractors at different stages led to confusion and even competition between entities that were supposed to be collaborating. Poor planning of project stages and responsibilities was the issue.
- Systems Integration: A complex programme was made more so when it was decided to use the shuttle as a launch platform. Even so, the problems of integration were under-estimated.
- Life Cycle Models: To quote the NASA report, 'Life Cycle Support planning and execution must be integral from day one, including concept and design phases', and in fact this element was extremely well executed, with the unplanned repair mission, although expensive, completely successful.
- Risk Management: NASA relied heavily on a prime contractor, who in turn relied on other key contractors. This delegated the ownership of risk, and the risk management, oversight and quality assurance procedures through the supply chain were inadequate. These lapses led to the launch of Hubble with an undetected flaw in the mirror.

These five lessons follow the mirror issue from its generation as an error in requirements capture, through the planning, integration and risk management activities that failed to spot it. Only the good work in life cycle modelling, which created a design that could be repaired, saved the programme.

Oil & gas platforms are not in space and so it is easier to remedy errors made in design. However, this apparent ease shouldn't mask the cost, in terms of either capital or lost production, of making fundamental errors.

THE STANDARD KOREA LIGHT TRANSIT SYSTEM

A more positive example of systems engineering comes from Korea, where local and central governments collaborated to design a standard light transit system that could be deployed in any municipality that wanted it, without bespoke designs.

Four key areas of requirements were identified: safety, reliability, function and performance. Requirements were identified for each area for each life cycle stage – concept, design, initial operation and so forth. Reliability was seen as particularly important and much work went into the Reliability, Availability and Maintainability (RAM) analysis. Otherwise there was a desire to minimise human interfaces, leading to driverless operation, and for a completely digital signalling system.

Four parts of the design were also identified: trains, signalling, electrical & mechanical systems, and civil engineering infrastructure. A fifth domain that overlapped all of these was Systems Engineering.

By following a strict Systems Engineering approach, the final system could be successfully deployed at a number of locations. As with Hubble it wasn't perfect (the requirements capture process was found not to be rigorous enough), but an often- understated advantage of following a Systems Engineering approach is that it simplifies the identification of lessons learnt.

ROYAL AIR FORCE C130J HERCULES AIRCRAFT

The project harks back to the early 1990s, when the existing Royal Air Force C130K was being considered for replacement. In broad terms, the operational requirements were very well understood in terms of role definitions, theatres of operation, range, payload etc. However, the older C130K was approaching the end of its life, with substantial support costs (OPEX) to maintain operational capability and availability. Therefore, given the advance in aerospace technologies since the original design and engineering, there was significant opportunity to improve the life cycle costs of a replacement system.

At the time of the project kick-off, it was recognised that military expenditure was growing in real terms, against tightly constrained budgets. This was brought into sharp focus following the end of the Cold War with the so-called ‘peace dividend’ where the perceived threat to Western Europe had waned, so opportunities for reducing defence expenditure were taken. Consequently, to maintain an effective military capability, the defence budget had to be used on maximising capability with less resource.

Primary areas of focus on defence equipment programmes, including the C130K replacement, were to improve operational capability with strong emphasis on reliability and maintainability, which would have beneficial effects on:

- Operational availability
- Smaller support infrastructure requirements
- Reduced support personnel
- Reduced spares inventory
- Reduced contractual support

With Systems Engineering very much embedded in the aerospace and military project cultures, integrated project teams were established within the Ministry of Defence to address all aspects of the requirements. As a result, the use of Integrated Logistics Support (ILS), which is a catch-all to include all support elements (including engineering and maintenance) rather than merely resupply, with Logistics Support Analysis (LSA) as the toolkit used to define the support. These were derived from US military standards Mil-Std-1388-1A, 2A and 2B, which were used as the tools to identify and manage the programme support requirements for optimising life cycle costs.
This was implemented before potential C130K replacement options had been identified, let alone a platform selection being made. Therefore, it is a prime example of early integration of all aspects of the aircraft life. As a result, long-term operations and support requirements were very well defined, specified and balanced before formal platform selection. This was seen through the procurement cycle into full operation. The results have borne out the key points identified above.

SYSTEMS ENGINEERING IN CONCEPT SELECTION – MULTI-CRITERIA DECISION ANALYSIS (MCDA)

MCDA is a family of mathematical techniques for assessing the best option in situations where:

- There are many potential solutions
- There are many competing criteria to consider
- The criteria are measured in different units, or even qualitatively

Because of this flexibility it has a great range of applicability, ranging from very specific equipment selection decisions to matters of national policy. The value of the method for Systems Engineering, illustrated in these examples, is the ability to incorporate spatial, capital cost data and temporal, operational cost data within the same optimisation framework.

Offshore Platform Decommissioning

MCDA techniques are often used where the criteria are entirely qualitative and where the views of experts diverge. Such situations often occur when environmental considerations are important, such as the placement of wind farms, civic amenity sites or power generation facilities. The example given here is from offshore oil platform decommissioning.

Californian law was changed in 2010 to no longer insist on the complete removal of redundant offshore installations, but to allow for other options to be considered. The change came about following complaints from fisherman that biodiversity had dropped after the removal of a platform, although the finding and the change of law were not without opposition. This study considered what options might be suitable for Platform Grace, a mid-sized structure commissioned in 1979.

The authors chose to use the simplest of MCDA methodologies, considering only environmental factors and relying on qualitative data generated by a panel of experts acting independently. The process followed the following steps:

- Firstly, they generated a list of criteria against which to assess each option. There were five criteria: environmental, financial, socio-economic, health & safety and other, where the 'other' category included factors such as fishing rights.
- Each criterion was then divided into sub-criteria, with the 'environmental' category being the most densely populated.
- The expert panel then independently ranked the importance of each criterion. An overall ranking was established by taking the median rank score.
- Each option was then ranked against each criterion. The median score for each criterion was calculated, and any scores equal to or below that level set to zero. Any scores above that level were set to one.
- Sensitivity analysis was conducted to test the robustness of the conclusions.
- Overall, the only option to score one against all 14 of the environmental criteria was the 'leave in place' solution (although two other options failed on only one, minor, criterion).

This extremely simple approach makes no use of any mathematical assessment other than calculating median scores, and the weightings for each criterion assessed at the start are not used explicitly as part of the assessment. However, during the process, opposite positions were taken on some issues by members of the panel, yet each member's opinion was weighted equally to yield a consistent solution.

Figure 5: Ranking of criteria for offshore decommissioning[4]

	Ranks				Standardised Ranks				Median Value	Weighted List
Criteria	Expert 1	Expert 2	Expert 3	Expert 4	Expert 1	Expert 2	Expert 3	Expert 4		
Energy use	2	1	8	5	0.17	0.08	0.89	1.00	0.53	6
Gas emission	1	2	8	5	0.08	0.17	0.89	1.00	0.53	6
Contamination	6	10	1	3	0.50	0.83	0.11	0.60	0.55	7
Production of exploitable biomass	4	5	2	1	0.33	0.42	0.22	0.20	0.28	1
Provision of reef habitat	7	1	4	1	0.58	0.08	0.44	0.20	0.32	2
Enhancement of diversity	8	3	5	2	0.67	0.25	0.56	0.40	0.48	5
Protection from trawling	3	7	4	1	0.25	0.58	0.44	0.20	0.35	3
Spread of invasive species	9	6	1	3	0.75	0.50	0.11	0.60	0.55	7
Loss of the developed community	5	4	6	1	0.42	0.33	0.67	0.20	0.38	4
Facilitation of disease	9	11	5	4	0.75	0.92	0.56	0.80	0.78	9
Alteration of trophic webs	9	8	5	2	0.75	0.67	0.56	0.40	0.61	8
Alteration of hydrodynamic regimes	10	11	7	5	0.83	0.92	0.78	1.00	0.88	11
Habitat damage from scattering of debris	11	9	9	5	0.92	0.75	1.00	1.00	0.96	12
Smothering of soft-bottomed communities	12	12	3	3	1.00	1.00	0.33	0.60	0.80	10

Figure 6: Evaluation of decommissioning options[4]

	Options									
Criteria	Leave in place intact	Topple in place	'Top' and leave both sections	Partially remove, transport to shore, re-use	Partially remove, transport to shore, recycle	Partially remove, transport to shore, scrap	Partially remove, relocate to shallow water	Partially remove, relocate to deep water	Completely remove, transport to shore, re-use	Completely remove, transport to shore, recycle
Production of exploitable biomass	1	1	1	0	0	0	1	1	0	0
Provision of reef habitat	1	1	1	0	0	0	1	0	0	0
Protection from trawling	1	1	1	0	0	0	1	0	0	0
Loss of the developed community	1	1	1	0	0	0	1	1	0	0
Enhancement of diversity	1	1	1	0	0	0	1	1	0	0
Energy use	1	1	1	1	1	0	1	0	0	0
Gas emission	1	1	1	1	0	0	1	1	0	0
Contamination	1	1	1	1	0	0	0	0	0	0
Spread of invasive species	1	1	1	0	0	0	1	0	0	0
Alteration of trophic webs	1	1	1	0	0	0	1	0	0	0
Facilitation of disease	1	1	1	0	0	0	1	1	0	0
Smothering of soft-bottomed communities	1	0	0	0	0	0	0	0	1	1
Alteration of hydrodynamic regimes	1	1	1	0	0	0	0	0	1	1
Habitat damage from scattering of debris	1	0	0	1	1	1	0	0	0	0
Total approvals	**14**	**12**	**12**	**4**	**2**	**1**	**10**	**5**	**2**	**2**

OIL PLATFORM PUMP RELIABILITY

This example illustrates how MCDA can be used to select an optimum maintenance strategy, and also combine with other techniques to forecast costs. It presents the decision process followed for the identification of the best maintenance strategy, for a collection of different centrifugal pumps on an oil production facility. Again, the technique relies heavily on expert opinion, but is augmented by hard statistics for failure rates and replacement costs.

There are three fundamental maintenance strategies: corrective, preventative and predictive. The study aims to predict to calculate the best combination of those three for the principal failure modes of ten different pumps. However, they define 'best' as a combination of four different goals, in a fixed order of priority:

- Cost minimisation
- Manpower usage minimisation
- MCDA score maximisation
- Local score maximisation for three criteria (occurrence, severity, detectability)

To allow an MCDA approach to assess four different goals, they have combined it with Goal Programming (GP), a variant of Linear Programming that can cope with multiple objectives. They have then selected the Analytic Hierarchy Process (AHP) as the MCDA methodology, and termed the resulting combination AHP-GP.

AHP is one of the more popular MCDA techniques. It structures the problem as a hierarchy, with the goal at the top, a centre layer formed of the assessment criteria, and a bottom layer of design options. Unlike the simple binary scale used for the environmental example, a numerical scale is used to indicate the strength of preference assigned to one option over another for a given criterion. Weights and preferences are then multiplied, summed and normalised to give a preferred solution.

Goal Programming is an expansion of Linear Programming, which applies a hierarchy of goals. Once the initial goal is satisfied, the options that meet that objective are then re-assessed against the second goal, until all goals are satisfied and a set of possible solutions is found. The combined approach uses AHP to assess options against each goal in turn.

For the example given, weights for each assessment criterion (occurrence, severity, detectability) were determined by interviewing key operational personnel. This did not attempt to determine the values assigned to these criteria, but the value that operational staff would place on each criterion in their normal appreciation of maintenance priorities. Values were taken from operational databases giving frequencies, costs and durations of the three strategies when applied to the failure mode set for each pump.

Mathematically, this is considerably more complex than the offshore decommissioning environmental example, and no more than a brief summary is given here. The outcome of the study was to identify that for the full set of failure modes across all pumps, the preventative and predictive approaches were always better than the corrective, with the predictive methodology being optimal in the majority of cases.

NECESSARY COMPETENCIES

Migrating from a conventional staged engineering design approach to a Systems Engineering approach is not a trivial exercise. It requires a fundamental change in approach in both project execution and technical methodology, in which additional competencies are required. This section discusses what those additional competencies are.

COMPETENCY FRAMEWORK

The stages of the Systems Engineering approach show the importance of a workforce that is empowered to see the bigger picture and understand their role and impact within it. In agreement with the Engineering Council's UK-SPEC requirements for the engineering technician, the incorporated engineer and the chartered engineer, the Systems Engineering approach places great importance on technical contribution, accountability and innovation, but also on communication, commercial awareness, the impact of change and good ethical practice.

The UK Engineering Council believes that all these aspects are required to make up a good engineering workforce. It correspondingly follows that the Systems Engineering stages outlined above could be used to aid company employment or progression policies. Questions structured from the stages can provide an understanding of the current competency of an engineer, and areas to be developed.

There is a gradual move towards a Systems Engineering competency structure within the oil & gas industry. INCOSE hosted the inaugural Texas Gulf Coast Chapter Systems Engineering conference in 2017, specifically intended to raise the competency and focus of Systems Engineering within the oil & gas industry. Further to this, University College London's Centre for Systems Engineering provides customised training in Systems Engineering, an opportunity that has already been taken up by major oil & gas operators.

Therefore, it is clear that competency in Systems Engineering is a respected aspect of any engineering practitioner, to meet both the requirements of the Engineering Council for professional recognition, and the future needs of the oil & gas industry.

Looking more broadly, the lack of uptake in the oil & gas industry, especially against a backdrop of continuing cost challenges, should be a cause for concern for industry leaders. With common cries for innovation to help long-term sustainability, it would be an excellent first step to better embrace Systems Engineering as a standardised approach to projects, greenfield and brownfield. Without doubt, that will involve real commitment and effort to change mindsets across the industry, leading a cultural swing away from the legacy approaches being undertaken currently.

ADDITIONAL SKILLS REQUIRED

The adoption of a Systems Engineering approach requires not only additional skills, but also organisational changes, so that the Systems Engineering discipline is the lead discipline in the design process. The specific additional skills are:

- Qualified Systems Engineers. Many universities now provide courses in Systems Engineering for undergraduates, and Masters courses for graduates. These courses provide a detailed understanding of the standards, methods and approaches that are an essential part of the process. Lead project engineers, who are experienced individuals, could benefit from a Masters in Systems Engineering.
- Expertise in optimising OPEX approaches. Selection of the optimum design will largely depend on operational support considerations. The defence sector is highly experienced in this domain, with the Integrated Logistics Support concept covering everything from predicting spares requirements to training course design. Skills such as human factors, training needs analysis and spares optimisation will be required.
- System modelling expertise. Mathematical models of all aspects, from production flows to maintenance procedures, are fundamental to the SE approach. Some system-like models of the physical aspects of an asset, such as process systems and flowlines, already exist, but the integration between them is poor, and the routine modelling of in-service support non-existent. Therefore, a company looking to adopt a systems modelling approach in the oil & gas sector, will have to be prepared to develop its own system and systems dynamics models.

ORGANISATION AND PROCESS

The biggest shift in adoption is in mindset. The entire engineering team must move to considering the entirety of the asset, at every stage of its life, ahead of their individual disciplines. To achieve this, it is necessary for lead members of any team to be primarily Systems Engineers who fully appreciate the concept, Often, a central Systems Engineering team manages the generation and achievement of requirements, and manages the interfaces between different subsystems (note that in an SE approach, even the physical structure of the platform is a subsystem, with its own design, manufacture, maintenance and disposal requirements).

The process must also evolve so that it follows the Systems Engineering process, of setting requirements for each stage, doing the necessary work, and then checking that the requirements have been met. Requirements must be tiered down to the various subsystems, so that a maintenance requirement on a water injection system leads to subsystems' maintenance requirements on pumps, valves, instrumentation and so on.

COST OF IMPLEMENTATION

The adoption of additional skills, and the introduction of additional stages in the design process, would appear to add cost. However, it should be noted that Systems Engineering has been so widely adopted in other industries because it has been found to reduce cost both through reductions in errors and rework, and through the generation of better designs.

NEXT STEPS

CURRENT SYSTEMS ENGINEERING PRACTICE

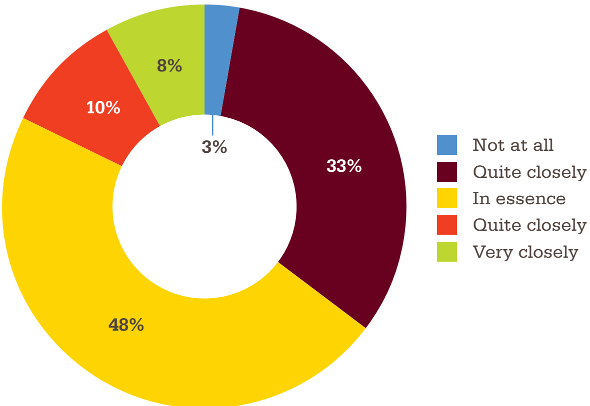
This section considers where Systems Engineering currently stands in the oil & gas industry, and what is required to advance the discipline further.

Figure 7 (from the industry survey described earlier) shows that there is not a close adherence to a Systems Engineering approach in the oil & gas industry, and as other elements of the study revealed a poor understanding of what constituted Systems Engineering, the actual levels of compliance with the concept are probably even lower. The second part of the figure shows that only 43% of respondents were able to claim that projects were frequently delivered on time. It does not necessarily follow that as delivery is poor when Systems Engineering concepts are not followed, then it will improve when they are, but that is the experience of other industries.

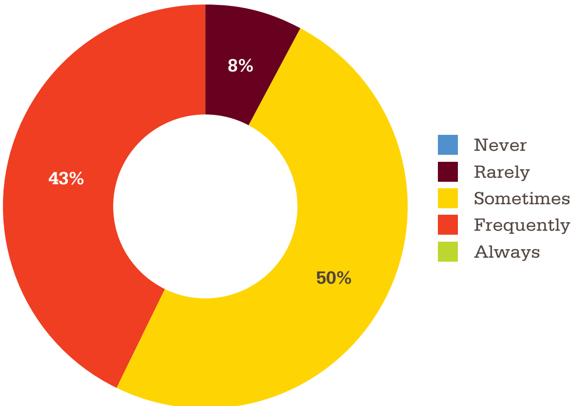
There is a general lack of understanding of what constitutes a Systems Engineering approach, and confusion about the terminology. Therefore, an important first step will be raising the understanding of the topic in the oil & gas industry.

Figure 7: Comparison of current levels of Systems Engineering practice to stakeholder satisfaction

How closely to a Systems Engineering approach is the average project run within your workplace?



How often is a project delivered within time, within cost and to the correct level of quality?



IMPROVING UNDERSTANDING

There are currently a number of support materials specifically for the oil & gas industry that are under preparation. INCOSE's oil & gas working group are producing a series of case studies to provide an insight into good Systems Engineering practice, along with a requirements development coaching tool, and support for the assessment of individuals within the oil & gas industry against Systems Engineering competencies.

The industry is seeing an increase in activity to support those who desire to further their understanding and application of Systems Engineering.

Looking ahead, collaboration between different industry bodies could prove to be vital in promoting Systems Engineering. For example, co-operation between the Institution of Mechanical Engineers and INCOSE would be a good step to promote the discipline. However, if bodies such as the Institution of Engineering and Technology, the Society of Petroleum Engineers and the Society for Underwater Technology also collaborated, the catchment is much larger, with potential acceleration of adoption. Furthermore, involving bodies such as Oil & Gas UK, and perhaps the Oil and Gas Authority, to promote Systems Engineering may provide further publicity and impetus.

BARRIERS TO ADOPTION

There are a number of organisational and cultural barriers that prevent the oil & gas industry from developing systems in the fourth dimension of time, in addition to the three spatial dimensions.

- It is almost impossible to partially adopt a Systems Engineering approach. Adoption must occur at every level of the supply chain and ideally be driven by the operators who are ultimately commissioning the work. During the survey phase, it became clear that engineering companies that were attempting to adopt the systems methodology, were struggling with operator customers who were not. Successful adoption of the approach will require the operators to mandate it from their supply chains, and as the operators ultimately gain the benefit, they have every reason to do so.
- Contract models, especially the widely applied EPC model, have often been cited as a problem. Under pressure from the customers to reduce capital costs and with a responsibility for operational costs that lasts no more than a year or two, EPCs have little incentive to apply a systems methodology.
- Sometimes, the internal organisation at an operator can impose the same cost pressures, by over-emphasising capital cost targets within their project teams. Some operators place personal incentives on their project managers to ensure that operational issues are properly addressed, but this is far from ensuring the full methodology is applied.
- The cost modelling processes used to assess the future performance of a new development, and select which should proceed, are heavily skewed towards capital cost assessment. Net Present Value (NPV) methods discount capital and operational costs against revenue earned, but the operational cost estimates used in such models are very poor. Nor does this initial estimate allow for optimisation of operational costs within the wider design process. As a result, many developments are saddled with sub-optimal design concepts from the outset.

- The ownership of assets changes, and there is little incentive for an operator to develop an asset optimised for a 20-year life when the financial case recommends disposal after ten. A cheaply-built platform may extract the bulk of the recoverable resources before it begins to require major maintenance work, so then it can be sold, but if it's still capable of profitable operation, shouldn't it have been designed for a full life? It could then be sold for a higher price.
- Investment in training will inevitably be required. While more junior engineers may have been exposed to the discipline while at university, more senior engineers and project managers will have to be equipped with the skills to break the cycle. Experience will remain essential in the industry to deliver good projects, but the skills will have to be adjusted to ensure that projects are managed for life cycle benefits, rather than merely initial capital costs.
- Cultural reluctance to change from legacy approaches must also be addressed. This will cover a broad spectrum of challenges including 'we have always done it this way', general reluctance to change or move out of comfort zone, through to perceived constraints by project budgets. Systems may prove easier to change than culture.

CONCLUSIONS

In many regions in the world, the oil & gas industry is experiencing a change in the scale and operation type of oil & gas fields. Driven by new reserves becoming more difficult to locate, to access, to maintain and to decommission, many existing reserves are becoming commercially viable for redevelopment. For both the further development of existing reserves, and the identification and exploitation of new reserves, new and existing technology needs to be developed to be cheaper to operate, or apply to a broader range of opportunities.

A framework for engineering practice that meets the below aspects is required:

- Assistance in the identification of the needs of all stakeholders
- Consideration of the complexity and commercial challenges within the oil & gas industry
- Development of a product against the identified needs
- Integration and assessment of complex system interfaces
- Comparison of performance attributes for review against the identified needs

The Systems Engineering approach meets these criteria.

It facilitates the development of new and existing technology to new, or broader, applications. With clear feedback mechanisms in place, it can lead to a clear understanding of the project technical and commercial trade-off, and agreement by the full range of stakeholders.

The survey shows that many individuals within the oil & gas industry believe that developing the industry's understanding of Systems Engineering is of great potential benefit for delivering high-quality products and services, within budget and time constraints.

Moreover, the competencies required to deliver a project in this manner align with those identified by the Engineering Council, and can provide a framework for good engineering practice.

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