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Collaborative, academic-industry research approach for advancing Systems Engineering

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Abstract

In contrast to many technology-based research programmes on which industry and academia may collaborate, a programme in systems engineering – a discipline which is practitioner-focused – requires a different approach to enabling exploitation of research outputs. Those outputs tend to be process, approach and methodological in nature rather than specifically tools and technologies. The NECTISE research programme is a multi-year, industrially-led research activity focused on developing the systems of systems (SoS) techniques required for Network Enabled Capability. The research consortium includes ten UK universities working in a multi- and cross-disciplinary manner to create more agile approaches to SoS Engineering. This paper will report the integration approaches taken in this research programme and the ways in which exploitation of the research may be achieved and demonstrated.*

NECTISE is composed of four topic groups investigating Systems Architectures, Through Life Systems Management, Decision Support, and Control and Monitoring, together with a number of cross-cutting themes. It has been driven by industry-derived requirements, and the industry-academic interface is enabled by the transformation of the requirements into a set of research questions. The formulation of such questions will be discussed.

*A major integrating activity is a set of four demonstrations that take place at regular intervals through the five-year programme. The TTCP** GUIDEx*** was found to be a helpful framework in which to integrate the various component researches for demonstration. The use of scenarios as a means of experimentation and demonstration is long-established; in NECTISE, a scenario approach is taken that embraces not only the military field of operation in which NEC is realised, but also the acquisition and support enterprise that delivers capability components to the military. In this paper, the development of the scenario, its use as a demonstration vehicle, and its role in integration across the research programme will be described, together with an assessment of the extent to which such an approach may aid exploitation of research outputs.*

Systems approaches have been both the focus of this research programme and the mechanisms through which it is being delivered. We shall assert that a systems approach can be a significant enabler of effective industry-academic collaborative research and we shall identify the important learning that has taken place in NECTISE in this regard.

** Network Enabled Capability Through Innovative Systems Engineering*

*** The Technical Cooperation Program*

**** Guide for Understanding and Implementing Defense Experimentation (GUIDEx)*

Keywords – NEC, Systems of systems research, exploitation, industry-academic collaboration

1 Introduction

In contrast to many technology-based research programmes on which industry and academia may collaborate, a programme in systems engineering – a discipline which is practitioner-focused – requires a different approach to enabling exploitation of research outputs. Those outputs tend to be process, approach and methodological in nature rather than specifically tools and technologies, though these may supplement them.

This paper examines how systems engineering research is carried out, from the perspectives of definition of the problem through to validating or demonstrating the outputs. To exemplify this approach, and the conclusions drawn, reference will be made to a multi-partner research project sponsored jointly by BAE Systems and the UK Engineering and Physical Research Council (EPSRC) known as

NECTISE¹ The project commenced in November 2005, and is scheduled to complete in April 2009. Ten UK universities and five Business Units (Divisions) of BAE systems have collaborated in the work. Although the bulk of the work was carried out by the academic community, the close and continued inputs and interactions with the industrial sponsor team proved to be key elements in setting the direction and extracting value from the research.

We begin by considering the nature of systems engineering research; the need for it to be rooted in real industrial practice and the implications this has for its exploitation. We then describe the consortium-based research in Network Enabled Capability (NEC) and the systems of systems (SoS) research agenda. We have taken a systems approach to research in systems and this approach is outlined together with its implications for the industry-academic collaboration. Through these discussions we

¹ Network Enabled Capability Through Innovative Systems Engineering

draw towards conclusions that highlight the need for industry to have – as part of their research exploitation programme – a change management plan that will implement the new systems engineering knowledge. The importance of education as a primary exploitation mechanism will be emphasised.

2 The nature of Systems Engineering research

Stevens et. al. [1] assert that ‘systems engineering is about creating effective solutions to problems, and managing the technical complexity of the resulting developments.’ To do this, systems engineers translate their customers’ goals into appropriate requirements for a system and, through a process of creativity, integration, verification, validation and development or production in some form, change existing systems or create new ones to meet those goals. Systems engineering concerns the means through which the development or management of systems is achieved in the most effective manner. Effective can be understood, in general, to mean less cost and/or less risk and/or less time. It is true to say, then, that systems engineering is concerned with the way that problems are tackled, i.e. the means of arriving at a solution. The ‘means’ can be many and varied, but a successful approach will be one which provides a systematic way either of decomposing the problem or the requirement, or of investigating the implications and limitations of a potential solution. An understanding of interfaces and of those elements of a problem or a design which can be decoupled, is also key to success.

Systems engineering is concerned with structuring complex problems to make them tractable and ensuring that the behaviours of the systems are understood and predictable. As such, research in systems engineering aims to create methods for visualising and structuring problems, for aiding creation and testing of potential solutions, and for managing the implementation of the best solution.. Thus, the outputs of systems engineering research are techniques, approaches, processes and some tools that support the engineer in the task of generating solutions, along with an understanding of the scope and limitations of any such outputs.

For the purposes of this paper we shall assume these solutions are in the domain of engineering. This is different from much (though not all) research in the technology domain, in which the research outputs may impact the solution in terms of the technology that is eventually used. In the case of systems engineering, research impacts not only the final solution, but also the route to its achievement. Its value must be measured over appropriate timescales, or life cycles.

An organisation embarking on systems engineering research should say to itself: “the outcome of this activity will be a change to the way that we operate; we will be changing the processes we use, or the tools that we use, or the whole way that we approach the problem.” This is an important point. The outcome of systems engineering research should not be business as usual!

The nature of the research outputs necessarily influences the research methodology that is appropriate for systems engineering and the means of exploitation. For a

programme that involves academic research in support of business activities, such as NECTISE, there must be significant interaction between the industrial engineering community and the research team. Systems engineering is a practitioner activity, and so the research must be conducted in the context of real engineering problems and exploited either through skills development or through artefacts that enhance the engineer’s toolkit. In general, the latter will also require a skills development programme.

Figure 1 shows a notional approach to systems engineering research. A real problem (or set of problems) must be expressed as a generic problem type (or class) so that the research outputs have general applicability when complete. It is the job of the systems engineer, not the researcher, to tailor processes to real problems. Those outputs may be delivered as new tools, processes, templates, training or education. They may be deployed within the engineering community directly, or may be tested by that same community to understand how things might be different. The latter is a necessary approach, in some cases, to reduce the risks associated with implementation, though the practicalities of carrying it out are essentially the same as in the case of direct deployment. In both cases, measurement of the new process etc., will be needed to establish that a beneficial change has taken place, or will take place.

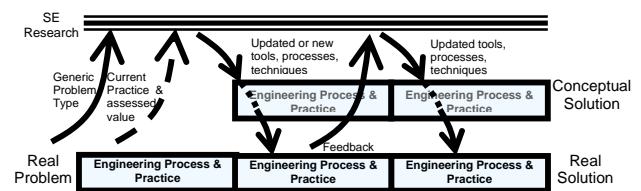


Figure 1: Notional researcher practitioner community interaction in systems engineering research

Tools and, to a large extent, templates, can be exploited directly by being fitted into existing processes in a traditional sense.

Changes to process will generally be a major undertaking. Processes rarely exist in isolation, so that a change to one will have implications for other company processes. The benefits of such changes may be very significant, but their achievement will require the research exploitation team to have put in place a change management programme in order to realise those benefits.

It is worth noting that some tools may require engineers to take new approaches in order for them to be effective; i.e. some change to process may be inevitable.

It is important to distinguish between training and education. In the case of the former, this will often be related to changes to process or the implementation of new tools. Exploitation through education, however, is applicable where the problem must be conceived in a new way, i.e. it is not only necessary for the engineer to employ a different solution approach, but to change the way that he or she thinks about the problem. The importance of this point has been well articulated at the Dstl Skills

Symposium [2] and follow-up meeting at the SEIC, which emphasised the competitive advantages, the need to deal better with unintended consequences, and the complex challenges of sustainability and globalisation [3] as drivers for up-skilling the workforce in systems engineering.

New ways of thinking about the problem are certainly needed for Network Enabled Capability (NEC), which is the subject of the NECTISE programme, and entirely new approaches must supplement traditional systems engineering to address the NEC challenge [4]. Exploitation comes not only through 'end of research' products (that might include courses etc.), but through the researcher and the engineer travelling a road of discovery in terms of developing the applicable systems engineering practice. Thus, the principles of action research [5] are applicable in terms of the need for research-subject engagement if the purpose is to achieve specific exploitation of the research. However, the outcomes are generally pertinent across a range of applications and so the researcher should endeavour to generalise his or her results so that they may benefit many different projects.

Two approaches to research are considered: the positivist approach (generally deductive and quantitative, i.e. scientific) and the phenomenological approach, which is concerned with the way people experience and understand social phenomena [6]. The researcher in systems engineering cannot be confined to a single approach. Some aspects are concerned with hard systems to which a positivist approach is appropriate. But the system need not be exclusively hard; indeed, in general it is not, and for Systems of Systems it is very often the case that the systems involved will concern both hard and soft system matters. Culture, behaviours and competencies will all play a role in systems of systems problems. A phenomenological approach will, therefore, be required for some aspects of research. It is perfectly reasonable to combine both approaches within the same piece of research [6], but the researcher must pay great attention to the choice of research approach and the manner in which positivism and phenomenology are combined. It is stating the obvious to observe that such research requires a team approach, with a team composed of researchers not only from different disciplines, but also with experience in the range of research approaches that must be applied.

Given the commercial nature of systems engineering as a core competence, exploitation of research outputs will generally require the confidence in managers to be built up prior to making changes to processes (for example). The value of systems engineering has been difficult to quantify [7], even though managers intuitively understand the value and there is empirical evidence to support this intuition in a general sense [8]. So the researcher is faced with the difficulty of reliably predicting the value of the systems engineering research outputs. M'Pherson and Davies [9] have expressed the intellectual capital of systems engineering as the value within praxis and related this to the system lifecycle (generic) to derive a set of intangible and tangible assets that must be managed effectively by a systems organisation. Based on these, they have developed a tool that calculates the relative importance (value) of 21

different systems engineering competences with respect to specific projects. In principle, the value of research outputs could be related through this framework to the competences that it enhances and, thus, an estimate of the value could be derived. Nevertheless, the nature of systems engineering as a life cycle based discipline makes it a complex task to estimate in advance what the value will be, and it is still a difficult task to calculate retrospectively what value has been achieved (because there is no longer a baseline with which to make comparison). A plausible and potentially effective means of assessing value is through a 'Demonstration' of systems research outputs, perhaps by comparing the as-is process with a conjectured process based on the research outputs. This can also be a way of persuading investors that changing to a new approach or process is of manageable risk and sufficient benefit financially to be worthwhile.

3 The NECTISE consortium

The NECTISE consortium grew out of recognition of the need for research to support the systems engineering needs of industry in its contribution to the MoD's NEC aspirations. NEC concerns the geographical distribution of sensors, weapons, support services, and decision makers together with appropriate changes in command and control to achieve higher tempo operations and agility in terms of military operational decision making. The implications of NEC for the defence systems development community are huge and the research programme is founded on the question: *are you ready for NEC?* This question can be applied across the range of stakeholders from the military commanders in the field through the defence systems development community to the subcontractors and SMEs in the overall supply chain. NECTISE must accommodate all those viewpoints, but its outputs target the engineers in industry who must respond to the challenges of NEC. The outputs can be viewed, then, as the approaches, techniques, tools and processes that enable the industrial stakeholder to be ready for NEC through improved systems engineering practices.

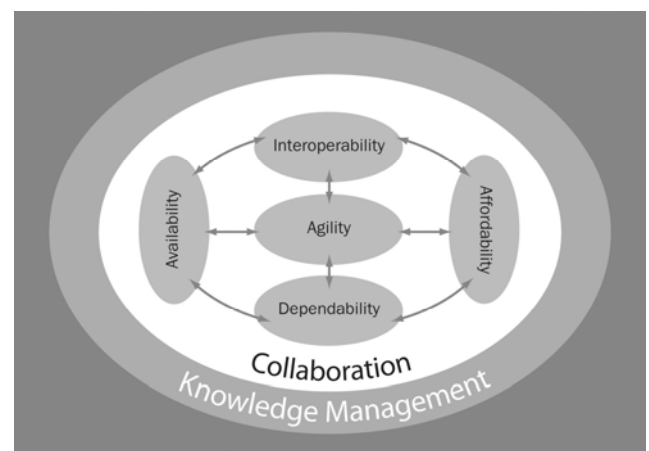


Figure 2: The NECTISE NEC-readiness themes

Figure 2 shows the NEC-readiness themes developed in the NECTISE work. These interrelated themes are the areas that must be improved through better systems engineering. Agility is at the heart of the diagram as the objective of NEC; to achieve this, interoperability, availability, affordability, and dependability must also be addressed within the deployed systems. All the themes are aided by collaboration and knowledge management and, as time goes on, these themes will completely underpin the systems engineering processes associated with managing NEC-ready systems through life.

NECTISE, then, concerns research into agile systems of systems: what they are, how they are developed, how they are measured, etc., where agility must be achieved in the NEC development community (responding to rapidly changing threats) and the military community.

The programme itself has four topic groups:

- Through-Life Systems Management – concerned with the systems engineering processes for capability-based acquisition [10, 11] and covering partnership relationship, whole life cost prediction, qualification of systems of systems, and systems life cycles.
- Decision Support – concerned with information management for decision makers in the NEC development community (largely integrated defence supply chain). This topic includes change prediction, capability component repository and collaborative mechanisms.
- Systems Architectures – focused on systems oriented architectures (SOA) for NEC and consideration of the architecture frameworks (particularly MODAF) and how they must be supplemented for NEC work in industry
- Control and Monitoring – focused on the creation of health monitoring, prognostic and reconfiguration algorithms for systems of systems problems. The main area of application so far has been the use of autonomous vehicles within the NEC environment.

In addition there are a number of cross-cutting themes, such as human factors and the readiness themes presented above. It will be easily appreciated that the diversity represented above in the individual topic groups' technical targets will correspond to a similar diversity in terms of research approaches and methodologies. Indeed, within NECTISE the research activities have ranged from unstructured interviews with stakeholders through to the mathematical modelling and algorithms associated with autonomous systems. DeLaurentis and Calaway [12] have noted the heterogeneity of the elements of systems of systems; the diversity of the systems considered within the NECTISE research is not surprising, but that it should be necessarily reflected as a diverse set of research activities may be less obvious. However, the notion behind large programmes, such as NECTISE, is that by bringing together a full range of expertise in the system of interest, more integrated outputs will result, capable of a greater overall impact on industrial process.

4 A systems approach to research

The INCOSE [12] competency framework suggests three basic themes for measurement of systems skills. These are: Systems Thinking, Holistic Lifecycle View, Systems Engineering Management. These cover, respectively, the underpinning concepts and systems skills; system lifecycle; and planning, monitoring and control of the processes. These themes are also applicable to research in systems engineering. The definition of the problem and the inventiveness and innovation associated with developing and applying systems engineering is described by the Systems Thinking theme. The Holistic lifecycle view provides an applicable set of processes for the conduct of good research, although there are some difficulties (mainly associated with inhibiting inventiveness) concerning the early part of the process - requirements management especially – that are inappropriate to a research endeavour. Finally, the third theme of Systems Engineering Management has direct applicability on such a programme as NECTISE, and this will be a crucial part of effectively integrating and displaying work within that programme.

A formal requirements process [14] might be anticipated to provide a firm basis from which to develop joint industry-academic research. However, our experience has been that the formal derivation of requirements is not particularly conducive to adventurous, industry-targeted research. In fact, the academic-industry research interface is much better served by the development of key research questions. In the case of NECTISE this was achieved by taking business requirements and then developing an initial set of questions that could be expanded within the academic environment. From the outset, NECTISE adopted a spiral model [15] for the development of the research programme.

5 Systems of systems research

NECTISE adheres to the Maier [16] characterisation of systems of systems, the key features of which are:

- Managerial and technical independence among the individual systems within the SoS;
- An evolutionary nature;
- A susceptibility to emergent behaviours;
- Geographically dispersed elements.

The last of these indicates that it is information that is transferred between the component systems of the SoS. Interoperability is the defining attribute that distinguishes a SoS from a monolithic system [16] and an understanding thereof must underpin research in SoS. Figure 3 shows a notional system of systems that might be under development. In this example, some systems are the subject of research, while others might already be part of a SoS and are tried and tested legacy for this development. The dashed lines indicate data, information or, possibly, knowledge transfer routes within the SoS. Experimentation that includes many systems arranged and interoperating in such a fashion is very complex. The systems introduced to enable interoperability itself may be the subject of experimentation, which adds another layer of complexity. To model such a SoS requires knowledge not only of the

individual systems, but also the interoperability between them. A number of authors have drawn attention to the concept of levels of interoperability [18, 19, 20]; NCOIC [20] suggest nine levels expressed within the three broad layers of Network Transport, Information Services, and People and Processes. In a general sense, one can appreciate a gradual shift in applicability from a positivist research approach through to a phenomenological approach at the top of the spectrum in which culture, business and political interoperability dominate.

Despite the formidable challenge associated with understanding such SoS and integrating new systems within them, modelling and simulation has made great headway [16, 21]. For the NECTISE programme, however, the challenge is not specifically to design systems that fit within a SoS, but to create, test, validate, and prepare new methods for deployment to assist the systems engineer in the multitude of tasks associated with managing systems of systems. Furthermore, the complexity of the systems involved in defence, and the restrictions on available information for commercial or security reasons, mean that complete simulation – even if it were affordable – is not feasible for university-based research. Nevertheless, the benefits of conducting such research in universities, given the need to exploit it through the development of skills, are substantial.

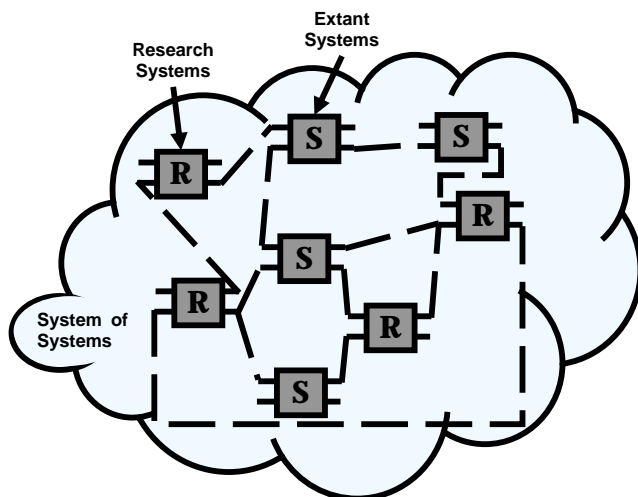


Figure 3: Notional system of systems in which some elements are being researched (under experimentation) and others are part of the extant SoS.

The research in NECTISE concerns the implications of NEC for the defence supply chain; this might be termed the NEC development enterprise that includes stakeholders from UK MoD, industry primes and the other tiers of the supply chain to some extent. As noted in section 3, the NECTISE consortium has tackled four main topic areas so that, in terms of Figure 3, there are four main areas of research that sit within an extensive SoS that contains some other areas of systems research done, or to be done, elsewhere, together with some systems that form part of the existing enterprise, and some parts that are not necessarily visible to the research team, or indeed to other parts of the NEC development enterprise.

The strategy adopted by the NECTISE team in support of validation of the work and its exploitability has been to construct a set of composite demonstrations. Using an overarching scenario, the individual work packages have been demonstrated (as experiments or straightforward demonstrations of current status) within particular vignettes. The vignettes themselves have been linked together to tell the overall story of the scenario in such a way as to cover the multiple timescales at which certain systems engineering practices will be relevant. The links from certain activities (for instance a fundamental architecture) conceived and developed at the capability planning stage through to the realisation in an instantiation of systems used in a military operation, are important for the purposes of understanding the systems lifecycle aspects. Through this, the relationship of systems of systems engineering to ‘traditional’ systems engineering of monolithic systems can be understood [4]. This is important if the research is to be exploited within the general industrial systems engineering community.

A formal approach has been taken by NECTISE to the development of the scenario and the incorporation of individual research areas within it. The TTCP GuideX [22] has been used, but tailored to suit the purposes of the programme. This guide to defence experimentation defines the documentation and a set of activities to ensure consistency and completeness of the demonstration. This proved to be an invaluable approach for the NECTISE consortium, because the research covered a wide range of systems-related topics, performed by twelve separate university research groups, with a primary customer base drawn from across the BAE Systems businesses in land, sea, air, and network systems. [23]

Such an approach, as described above, begs the obvious question regarding the degree to which reliable experimentation and/or demonstration can take place when the systems under consideration are not integrated in precisely the way that they would be if such experimental systems were actually built. In terms of research, it is not usually the task to build the completed SoS under consideration, but rather to develop the fundamental understanding of the types of systems involved and the nature of their integration. NECTISE was conceived as an integrated project, but the meaning of integration in this context bears examination. For some aspects of the research it is vital that different research contributions are *actually* integrated in order to realise a useful output. For other parts, however, it is sufficient to understand the implications of integration without actually carrying out the integration itself (Figure 4). Indeed, there are circumstances in which it is not the integration that is of primary importance, but the knowledge of how to manage the integration when it must really be done. The emergent properties of the SoS are likely to be influenced by the context or environment (that can be considered as a part of the overall system). In this case, it is important to understand the implications of integration so that good judgement can then be made once the environment is known.

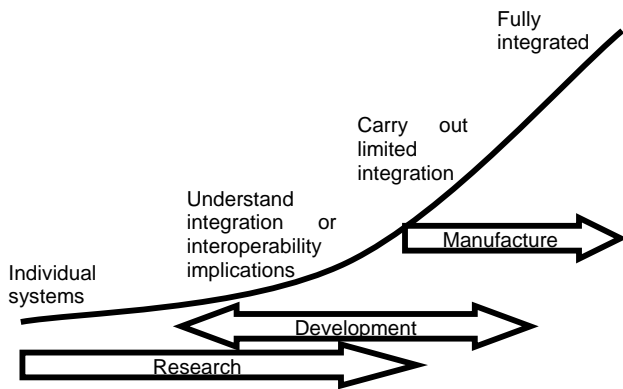


Figure 4: Integration as part of the research activity

6 Exploitation

As an integrating discipline, systems engineering is by nature a means of exploiting the research endeavours associated with lower level systems. Similarly, the exploitation of systems engineering research requires integration, this time into the existing industrial practice. The research activities in NECTISE are concerned with describing systems (architectures), managing systems (through life systems management), supporting the enterprise design and systems decision makers (decision support), and providing the algorithmic techniques for systems management in the deployed environment (control and monitoring). Exploitation of the research outputs takes place in a variety of forms.

The control and monitoring algorithms represent new approaches applicable to SoS; in a sense the research has lifted health management, prognostics, and reconfiguration above the systems level to the SoS level. Exploitation of the methods is achieved through standard reports and software and for the techniques exploitation is through specialist training. Delivery of software has, therefore, been accompanied by a specific training module for end users.

Decision support incorporates consideration of change prediction for systems, and an information management system that allows retrieval of required information from any (format-neutral) source using a single search engine, within a management system known as Virtual Integrated Platform for Decision Support (VIP-DS) [24]. This tool is designed to support distributed decision makers, and for the purposes of the NECTISE work those decision makers are distributed not only geographically, but also across different (many) organisations. Work on collaborative environments would enable the tool to be tailored (automatically) to suit the type of collaboration that pertains to the particular project in which the tool is being deployed at the time. Exploitation will be through delivery of the prototype tool but, more particularly, through exercising it during development on real programmes. Thus, there is a strong training element associated with its exploitation.

The TISM Topic Group work has a variety of outputs that are exploited as follows. Work on partnerships for NEC,

which is based very largely on studies of IPTs², is exploited through application of derived techniques in workshops. These can be regarded as direct deployment of the techniques within current programmes [e.g. 25]. Whole life cost prediction [26] will be exploited through delivery of a software tool and appropriate training to support its use. Qualification of SoS is a major challenge that is of immediate and direct relevance to the realisation of NEC benefits. The modular approach adopted [27] will be exploited through the generation of use cases and templates. Finally, work on lifecycle management will be exploited through new architecting techniques and direct modification of the systems engineering processes.

The architectures work has focused on the two areas of architecture frameworks and their uses and service oriented architecture as a means for managing NEC [28]. Exploitation is through development of templates and models; an important exploitation mechanism is training and education.

In all cases, exploitation through skills development is a major thrust of the exploitation plan. This is achieved through the development of courses and the updating of existing courses, through the direct training of engineers and through workshops that enable the end user to experience the outputs as developed research examples.

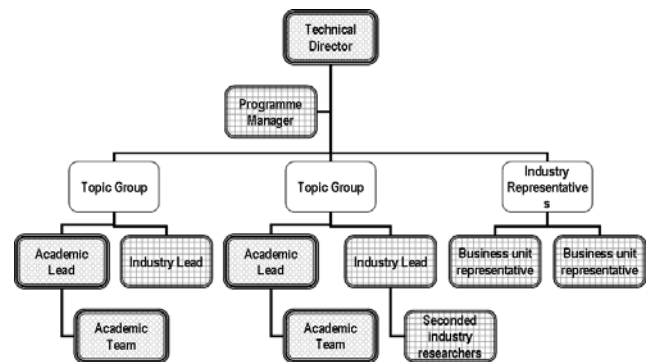


Figure 5: Basic structure of NECTISE, showing only the main role types and split between industry and academia

7 Industry-Academic Collaborative Research in Systems Engineering

To achieve the impact promised from the research described above, the relationship between the university researchers and the industry-based end users is critical. First, appropriate management structures are needed to ensure that the systems challenges are properly articulated and that the research outputs are tailored for exploitation by industry. Figure 5 shows the basic roles in NECTISE; there is an academic and industry equivalent for each leadership role. Note that all participating business units (which are the business streams within BAE Systems) have a representative on the management group to influence the

² Integrated Project Teams – created by MoD and usually including industry, responsible for delivering defence projects

research agenda and manage the exploitation routes back into their individual businesses.

Second, the translation of business requirements into research questions proved an important, but difficult task. The derivation of appropriate research questions that would lead to exploitation was achieved by starting with a set of business requirements and then conducting a series of workshops in which the academics and the industry representatives negotiated and agreed the questions. The reporting processes within NECTISE require the questions and related business requirements to be identified against each deliverable.

Third, all the business units generated an exploitation plan. At the start of the programme these plans were, generally, at a high level, but as the programme matured, so the exploitation plans became more detailed.

Systems engineering is a fast moving discipline, and there are two important implications of this. The first is that deployment of new techniques into practice takes place fairly rapidly. The second is that the researchers on the programme have needed to be flexible in their approach. This has been especially true for NEC research as this concept has undergone rapid development in the UK over the last 5-6 years; contrast [29] with [30].

The demonstrations are an important means through which the research is conveyed – particularly to people whose contact with the programme is less frequent – and through which the exploitation challenges and opportunities are understood. They are also a means through which the research team can discover the industry needs, through feedback from participants. In addition to the TTCP GUIDEx process for developing the demonstrations, design reviews have been carried out, chaired and managed by the industry sponsor. Thus the demonstrations have been reviewed against the stated needs of the industry customer prior to taking place. This has proved very valuable in determining the questions of highest priority to the industry sponsor.

As noted above, many of the outputs are exploitable through learning. Participation in workshops, demonstrations, etc. by members of the industry team is an essential part of achieving a successful research programme in systems engineering.

Inevitably, personal relationships are critical to the success of the endeavour and it is notable that the close working relationships indicated in Figure 5 have resulted both in strong friendships and shared planning, managing, and delivery of the research outputs. This integration of the academic and industry team leaders is an essential element of systems engineering research. The mechanisms that have led to this integration have been stability of personnel, diligent joint review of both plans and outputs, programme metrics that require contributions from both sides, and frequent meetings that cover both project management and academic/technical matters. Although it may seem obvious, it is important to state that frank, open exchanges are an imperative to a successful programme such as NECTISE.

Another important ingredient for success is the relationship between the participating university groups. The original selection of partner university groups ensured that each one had a non-overlapping role with others. The nature of systems engineering research means that collaborative working is a necessary part of delivery and there are very few activities in NECTISE that do not require interaction with another part of the programme. However, integration across a multi-disciplinary programme is a significant challenge. Researchers with an in-depth knowledge of their own specialism cannot necessarily understand the precise relationships to work elsewhere in the programme that does not fall within their own area of specialisation. This challenges the individuals involved and those responsible, ultimately, for an appropriate level of integration within the programme. The integrated demonstrations are, again, a key enabler in this respect. In fact, it is not so much the demonstrations themselves (as discrete events) that assists programme integration, but the preparation for them in which all researchers must understand the contribution of their own work within the overall demonstration scenario and also the interactions with other work in the programme. Frequent demonstration development and planning meetings, which includes rehearsals and specific identification of links between work packages, led finally to a broad appreciation of the systems of systems problem and the contribution of individual work packages to that problem right across the research team.

8 Conclusions

In this paper, the nature of systems engineering research has been considered, based on our experience of conducting a large academic programme collaboratively with industry. Our focus has been on the characteristics of the research endeavour that maximise the likelihood of successful exploitation of the academic outputs by industry. It is concluded that the nature of the outputs means that industry should prepare a change management programme to fully utilise the research and that many of the outputs will provide educational materials. Academia is well placed to enable exploitation through various forms of training and education. For the research topic of NEC, it is concluded that exploitation must be significantly through up-skilling in systems.

It was noted that systems of systems research will often include both positivist and phenomenological research approaches and that a multi-disciplinary team, that includes skills in these approaches, is required.

A scenario-based demonstration has been found to enable the importance of systems engineering to be appreciated by non-systems stakeholders and provides a useful context in which to understand exploitation opportunities. The manner in which this scenario must be built and verified has not, however, been dealt with in the present paper. Nevertheless, the composite scenario approach has been shown to be advantageous for programmes such as NECTISE, in which the cost, availability of information, and magnitude of the systems of systems pose challenges for the demonstration of university-based research. The

process of developing the demonstration scenario and research contributions to it was a significant enabler of integration within the multi-disciplinary and multi-institution team. Systems learning is a part of the conduct of the research activity; thus, the development of the researchers' systems skills, both as a team and as individuals, is enhanced through the demonstration activity in the programme.

Integration between the industry and academic parts of the team is vital to the delivery of actionable outputs. This was achieved through shared planning, the joint development of research questions based on business requirements, and the preparation of exploitation plans. For NECTISE these were done by five business units and were tailored to meet their specific requirements.

This paper has covered a wide range of matters associated with systems engineering research. These have been derived from our experience of conducting a large multi-institution, multi-disciplinary research programme that is a collaboration between industry and academia. In summary, the three most important conclusions are:

- Systems of systems research required a multi-disciplinary team and specific integration activities; fulfilled in the NECTISE case by planning and delivering an integrated demonstration. It is the experience of the whole research team in managing integration that is vital.
- Industry-academic collaboration in systems engineering research is vital to ensure actionable research outputs, but this requires joint ownership of the whole problem (planning, execution, and exploitation)
- Training and education are a significant part of exploitation to which academia is very well suited, but these also imply the need for a change management plan, alongside the research, as part of the industry exploitation planning

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