Bringing Human Tasks into the Mainstream of Ship Design and Operation: Developing a Toolset to Integrate Task Analyses with Systems Engineering.

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Abstract - **Human Factors practitioners have long advocated that information on people and their tasks should be collected and used to inform design and operation. Task Analysis methods and tools have a strong track record but are typically regarded as specialist techniques rather than basic engineering. They also tend to focus on single or small groups of users.**

However, the domain of ship design and operation often requires that we take into account large numbers of crew. Ships are also highly complex in engineering terms. The size of the enterprise means that straightforward ways are needed of collating the relationships between people and the systems and equipments which they either use themselves or which impact upon their work or occupation of the ship. This challenge is too great to be managed by a small specialist Human Factors resource: it must be addressed by Systems Engineering processes as a whole.

BAE Systems' Advanced Technology Centre is developing a tool, based on Hierarchical Task Analysis, which supports a functional decomposition of a ship. This provides a linkage between the people who perform tasks and the equipment they use. The tool is designed to be integrated within the Systems Engineering Environments used by ship development programmes, with cross-referencing against other Systems Engineering products such as the Product Breakdown Structure and Operating Scenarios.

Initial development is focused on generating ships' complement sizes and making manpower/equipment tradeoffs: manpower optimisation is a pressing concern for customers in ship design and operation. The design philosophy is to keep the tool 'open' so that it can collect different types of human data and to support varied levels of detail throughout the ship's lifecycle.

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INTRODUCTION

One of the challenges facing Human Factors Practitioners in influencing ship design and operation is the size and complexity of both the products and their originating and operating organisations.

Ships comprise many systems, sub-systems and equipments, typically developed by interrelated engineering teams. The multitude of technical components may present Human Factors issues to a greater or lesser extent, depending on how they affect the safety, performance or workload of the crew. It can be difficult for Human Factors practitioners to identify which part of the design team they must influence to address the most important issues. (Carr, 2007).

There is also a 'Human Component' to be considered. The crew is not a given and its 'design' is not a matter of chance; the considerations of how many people are needed to operate and maintain, how they can be trained, how to provide them with sustainable career paths, etc. are all topics which fall somewhat within the remit of Human Factors.

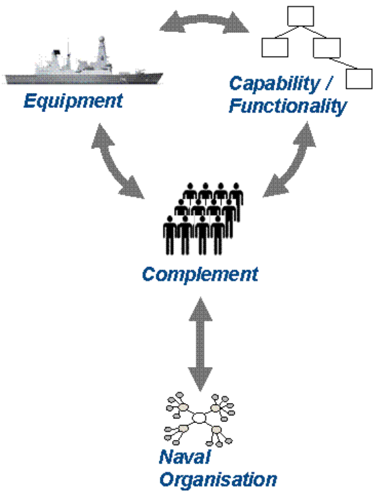

Figure 1: There are complex, dynamic tradeoffs between People and Equipment elements.

To add a further level of complexity, a ship's technical design and its crew design are clearly interdependent (See Figure 1). For example: if a ship requires a large number of operators, this can be reduced through automation; if maintenance load at sea is high, this can be reduced by more reliable equipment (or by changing maintenance policy: e.g. more maintenance can be carried out alongside; spares carried to allow simpler repair-by-replacement). However, in ship development programmes, crew size and systems design are not static: there are often complex, dynamic trade-offs to be made. Often it is not obvious how an individual equipment attributes cost to the crew.

Human Factors resources are comparatively scarce when weighed against the large ship development programmes. A different approach is needed to share the load. The guilty secret of Human Factors is that those supporting it do not necessarily require initiation into the *arcana* of the human sciences. Often Human Factors is concerned with promoting and supporting an attitude of mind to do with awareness of – and recording of – human tasks and how these are influenced by equipment. This attitude is formalised in a range of techniques called 'Task Analysis.' Human Factors practitioners can make life easier for themselves if they can pass their attitude of mind on to others. This will require us to develop Task Analysis techniques which integrate well with the methods and tools used by engineers.

This paper describes a tool developed by BAE Systems' Advanced Technology Centre. The tool was ostensibly targeted at warship complement generation and at assisting trade-offs between complement and physical design. Its overall aim is wider: to capture Task Analysis within a programme's Systems Engineering Environment and provide links between the Human View and other views and datasets.

APPROACHES TO COMPLEMENTING

The ability to determine the appropriate crew size and composition of a ship is an important issue for shipbuilders and their customers (Carr, 2010) – one that is frequently emphasised by BAE Systems' Royal Navy and export customers. There are several reasons for this, including:

- The crew is a major component of a ship's through-life costs. There is a desire to reduce cost of ownership. (See Figure 2)
- Many navies are faced with a demographic challenge. There is a shortage of recruits, pay is increasing and there is a desire to put fewer people 'in harm's way'.
- Crew size can be inversely related to systems costs: fewer people means more automation.
- It is important to know crew size and composition reliably and early because they are major drivers for ship size, general arrangement and accommodation requirements.
- Crews are 'long lead items' People have to be recruited, trained and retained in careers while a new class of ship is still in its early development stages.

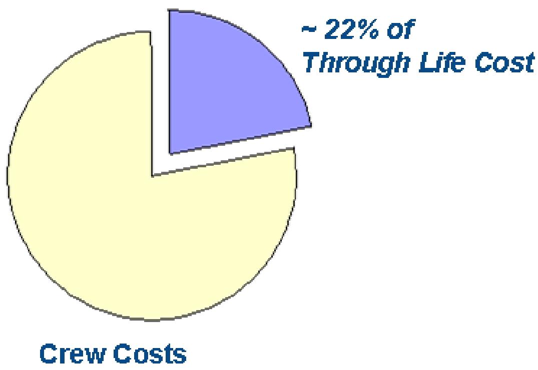

Figure 2: Crew costs are a major component of through life costs (source BAE Systems project data)

Determining crew size and composition is a non-trivial problem. Neither is it a matter of simply specifying a crew for a given technical design. Firstly, there are trade-offs to be considered between manpower and technical costs (see Figure 3). Secondly, there is the consideration, from the point of view of the organisation providing the people for the crew, of whether the jobs demanded will be 'meaningful', e.g.:

- Will they conform to the navy's normal way of doing business?
- Will they require disproportionate amounts of certain types of people from the wider fleet?
- Will sailors be given suitable career paths?
- Will it be possible to recruit and train the people (especially where a new ship requires new skills – such as when the computer-related skills for automated systems replace the mechanical skills for 'mandraulic' systems)?

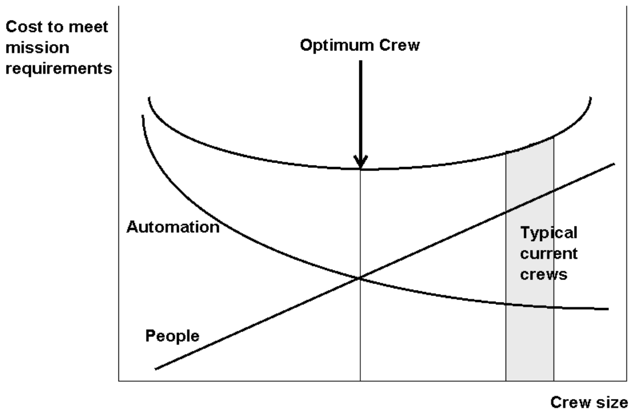

Figure 3: [After Bost, 2005]. For a given capability requirement, there is an optimum cost-effective balance between the crew size and level of automation. Note that capability can also be traded off against people and equipment.

Another reason why suppliers and navies are interested in determining crew size is that they have often got it wrong in the past. They have tried different variants on a theme:

- Specifying a number of bunks, without margin for flexibility. Such ships have found that their crews are often stretched by the varied operational challenges they have to face: they need more crew than they have the bunks for.
- Requiring suppliers to achieve a specified functionality within a tightly specified crew size (with heavy commercial penalties for exceeding it). This removes incentives for innovation aimed at either reducing crew size or enhancing capability.
- Requiring suppliers to specify the crew they believe is feasible, so that the navy can plan for it. This militates against finding the optimum balance.

These issues will never be simple to answer. They may require trade-off and compromise. Different parties will bring their requirements to bear. A starting point for the conversation is to be able to look at the design simultaneously from both a human and technical point of view and to be able to reason about how one affects the other.

HUMAN VIEWS IN SYSTEMS ENGINEERING

Human Factors has potentially been aided by the growth in understanding of Systems Engineering as a discipline. (In the English-speaking world), 'The System' was traditionally taken to refer to elements made of metal, plastic, silicon, etc as distinct to the things made of flesh and blood which would sometime inconveniently interrupt the system's smooth operation.

More recently – especially in the world of software engineering, but also filtering through into hardware - there has been a recognition that the scope for systems description should include the tasks done with it, hence the 'actors' on the system (Carroll, 1990).

In the UK defence community and elsewhere, the importance of the 'non technical' aspects of systems is recognised in the concept of 'Lines of Development' (UK Ministry of Defence, 2005). LoDs are regarded as the building blocks which combine to deliver military capability. The UK's Defence LoDs (DLoDs), sometimes referred to by the mnemonic 'TEPID-OIL', are shown in Figure 4.

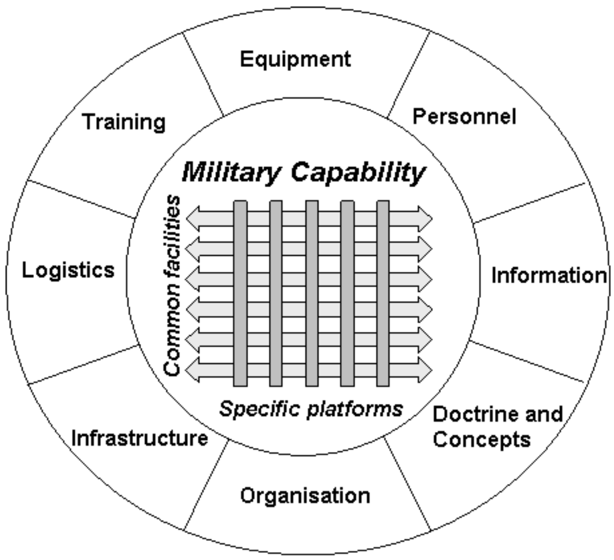

Figure 4: Warship designers need to be aware of how their platform fits in with the Defence Lines of Development (DLoDs) and with other platforms and facilities to deliver overall military capability.

Over the last two decades, the UK Ministry of Defence's (MoD) 'Human Factors Integration' initiative (see the Human Factors Integration Defence Technology Centre website for further information, 2011) has had great success in acknowledging the importance of human issues outwith the scope of the warship itself. The DLoDs concept goes a step further by making explicit that the overall naval system encompasses multiple development streams and that various 'Views' on the system need to be considered.

In a Systems Engineering approach the interrelationship between the system Views is managed within an 'Architectural Framework'. This framework specifies the informational products which combine to describe systems and indicate how these products are linked. Examples include the US Department of Defense's (DoD)

Architectural Framework (DoDAF) (US DoD, 2011) which specifies Views for both the Technical system and Operational Views which include the tasks and activities required to achieve missions. The UK MoD version, MoDAF (UK MoD, 2011), follows DoDAF closely and similarly provides an Operational View.

A weakness of both DoDAF and MoDAF, however, is that they deal with operations/ activities/ tasks in the abstract rather than how they are enacted. In the case of MoDAF, this reflects its emphasis on Network Enabled Capability (NEC) and hence in automated activities rather than manual. However, the UK MoD is working closely with the US Department of Defense, the Canadian Department of National Defence, the Australian Department of Defence, and the Swedish Armed Forces to develop the International Defence Enterprise Architecture Specification (IDEAS) (The IDEAS Group, 2011). The IDEAS Framework, as well as providing for improved interoperability between the contributing partners, defines 'People and Organisations' as a distinct View. This evolution in mindset will, hopefully, make it easier to consider complement and technical design together rather than separately.

In practical terms, the way development programmes work with different system Views is as informational products within Systems Design Environments (SDEs). While sharing a common referent - 'The Design' - different design disciplines may produce and maintain products (i.e. Views) appropriate to their domain - e.g. requirements models for Requirements Engineers; Product Breakdown Structures for (physical) systems developers; cost models for accountants. SDEs act as a repository for these and, crucially, provide traceability so that changes in one are reflected in changes to the others. Such tools include Rational System Architect (IBM, 2011).

If complementing data is included within the SDE, this starts to provide a mechanism for linking people and technical design and for examining trade-offs between the two. However, something is still missing. Because the complement and technical design have not previously been 'joined up', there has tended to be a gap in the process of deriving one from the other.

What is needed within Systems Engineering are views which indicate how people and equipment combine to achieve operational goals. In Human Factors terminology, this is known as *'Task Analysis'*.

TASK ANALYSIS AND SYSTEMS ENGINEERING

Task Analysis is the name given to a broad set of approaches for describing how work is organised to meet various goals. There are various techniques extant (e.g. Kirwan & Ainsworth, 1992; Stanton 2005), although few if any are formalised or have an official imprimatur.

Task Analysis tends to be regarded – by Human Factors practioners and their customers – as a specialist Human Factors technique. This is unfortunate. System developers are well used to the idea of taking a system's functional requirements (in Task Analysis terminology, 'Goals') and decomposing them into sub-functions. They are also used to identifying which parts of their Product Breakdown Structure satisfy which subfunctions.

This is extremely similar to Hierarchical Task Analysis (HTA) (e.g. Shepherd, 2001) – although experience suggests that when talking to Engineers it can be useful to refer to it as 'Functional Decomposition.' The only new idea from Human Factors is that the sub-functions (or 'Tasks') should also record the human activity needed to perform them (and, in the case of a warship with a large complement with competing demands, when those demands occur).

A Task Analysis model within a Systems Design Environment, then, provides a convenient, unified view which links:

- Requirements (which determine system goals/functions)
- Equipment (linked to the Product Breakdown Structure)
- People (specified as part of the complement. Conventionally, this has not been regarded as part of the design per se and in the past it has been mandated by customers. However, responsibility is now frequently shared with customers who typically require suppliers to specify complement, in various standard formats).

For the purposes of defining the complement, recording information against the Task Analysis allows the following:

- Overall crew requirements can be collated across tasks, taking note that different tasks may be performed at different times in a ship's operating scenario. (This is a non-trivial task: attention must be given to efficient personnel use; to proper combination of tasks into meaningful roles; etc.)

- The common view of people, equipment and capability provides a vehicle for discussing trade-offs between the three (e.g. Does changing an equipment affect overall complement size; if fewer people are available, will it affect capability; etc.)

BAE SYSTEMS' *flexiCRU* TOOL

The BAE Systems Advanced Technology Centre has developed the ***flexiCRU*** tool (Figure 5) to promote the concept of using Hierarchical Task Analysis both to give a sound basis for complementing and to promote complement/equipment trade-offs.

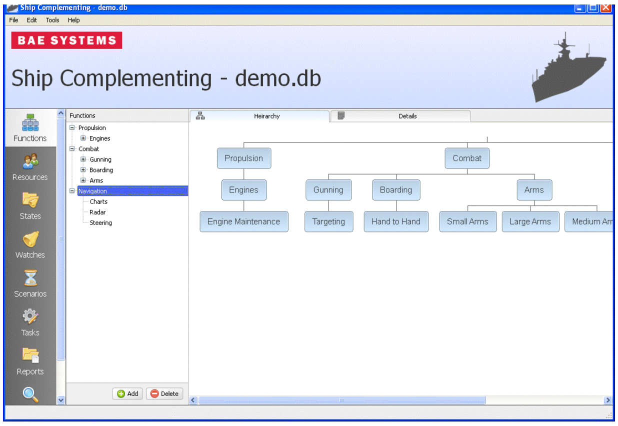

Figure 5: BAE Systems' *flexiCRU* tool uses Hierarchical Task Analysis to give a sound basis to complementing and to promote tradeoffs between people, equipment and requirements.

The Advanced Technology Centre has various customers in the maritime domain for whom complementing is a pressing concern. However, they each have different needs, e.g:

- To determine the outline costs, for competitive tenders, for a platform with a roughly specified crew size (e.g. X officers and Y ratings)
- To confirm that a ship at a detailed stage of design will be operable with a specified complement.
- To determine the complement requirement for a ship at an early stage of design, and to track this as the design matures.
- To investigate the impact of different design variants on complement requirements.
- To support programme cost savings by identifying means of optimising/reducing complement.

Accordingly, ***flexiCRU*** has been designed to fulfil three key requirements:

- **Flexibility** to handle different datasets at different levels of detail, depending on a programme's objectives and its stage in the development lifecycle.
- **Transparency** to give clear explanations of how complements are derived and clear indications of the impact of changes to functional requirements, equipment and complement on one another.
- **Interoperability** to make use of existing data products and support links between complement and other data and to be manageable within a Systems Design Environment.

flexiCRU is targeted at an environment in which the complementing in general, and the links between people, equipment and capability in particular, have not been well supported to date. This has been recognised by potential customers who see the need for a tool and who are supporting its development.

The intention is that ***flexiCRU*** should not simply be a 'hand crank' model that takes in data and spits out a complement: it should enhance the complementing process by bringing it into the mainstream. Its aspiration is to promote complementing as an issue by fitting neatly into the overall development process and its supporting Systems Design Environment.

The basic principle of ***flexiCRU*** is that it:

- Collates the demands for personnel imposed over time due to different types of activity (e.g. watchkeeping; equipment operation; maintenance; peripatetic demands such as administration, husbandry, etc.)
- Determines the minimum size of crew to meet those demands, taking into account constraints on people's availability (e.g. watch patterns; maximum weekly capacity) and the suitable combinations of tasks that can be carried out by individual roles at different times.
- Where possible, reschedules demands to times when personnel are available, to achieve an efficient spread of demand resourced by an optimised complement.

Data linked to *flexiCRU*

The inputs to ***flexiCRU*** are linked to data products which are found within Systems Design Environments (or should be: where they are absent, it is hoped that ***flexiCRU*** will provide a spur to good Systems Engineering practice, to the programme's wider benefit). They include:

- A **Functional Decomposition** of the ship, to the level of detail where it is possible to identify the People and Equipment associated with individual sub-functions (i.e. 'Tasks'). The starting point for this is analysis of requirements documentation, and Tasks are traceable to the requirements they satisfy. In some programmes there will already be such a decomposition – it is useful to various engineering functions besides complementing. The intention is that ***flexiCRU*** should either provide or import a common, project-wide Functional Decomposition (or 'Task Analysis')

- A **Scenario**, generally provided as part of requirements documentation, which defines what activities are carried out, and when, over the course of a mission. These are generally described in terms of 'Operating States' which define which positions must be manned (e.g. numbers of people required on the bridge when leaving harbour) and when certain tasks may or may not be done (e.g. maintenance is carried out in Peacetime Cruising but not while at Action). States may be overlaid by 'Evolutions' which impose additional demands and may inhibit other tasks. ***flexiCRU*** provides facilities to capture Scenarios and annotate tasks to indicate which are done when. In future work it is intended to expand the timeline to include activities alongside, specifically to examine the options of moving the 'at sea' maintenance burden to alongside periods when it can be supported by contractors – an example of the goal of interoperability, this time with models from the Integrated Logistcs Support (ILS) domain.

- A specification of the **Equipment** associated with tasks. Equipment can impose demands on the crew by its operation or maintenance (although not all tasks are directly related to equipment – and some equipments require no operation or maintenance). The sources for equipment data are:

    - The Product Breakdown Structure (PBS) which describes the ship's systems, subsystems, and components.

    - Integrated Logistics Support (ILS) data which describes maintenance effort (frequency, schedule, duration, people/skill required.) and whether maintenance is Planned, Failure-based or Condition/Use-based.

  The importance of equipment data within ***flexiCRU*** is partly due to its Task demands – but more crucially because ***flexiCRU*** provides traceability of the interrelationship between technical and complement design, i.e:

    - To identify implications of the impact of technical design for complement.

    - To suggest design solutions which might resolve complement issues (e.g. provide automation; adopt a different maintenance philosophy).

- A specification of the types of **People Resources** available to resource Tasks. Note that these may or may not be whole people but amount to 'Skills' – e.g. maintaining equipment X requires a Marine Engineering skill Y – and it is only through later collation that the tool associates the demand with, e.g. a Marine Engineering Artificer. Different ship programmes require skills to be specified in different ways, depending on what sort of output collation they need (e.g. Officers vs Ratings; Ranks and Rates grouped by department; etc.) and ***flexiCRU*** is designed to give flexibility in how skills are specified – theoretically one could specify any human attribute (eye colour, musical taste…). In real-world naval complementing cases, the relationships between skills and how this governs the way tasks are resourced is complex. ***flexiCRU*** allows People Resources to be modelled in a way which is consistent with different ways that demands might be specified and which allows flexibility in the way they are scheduled and resourced, e.g.:

    - A Lieutenant Commander is identifiable as an officer

    - A Chief Petty Officer Marine Engineering Artificer is identified as a skilled, rating, Petty Officer, in the Marine Engineering Department

    - A task that can be done by a Marine Engineering Artificer may, if one isn't available, be done by a Chief Petty Officer Marine Engineering Artificer.

- There is a hierarchy from Captain down through the ranks and ratings: a Leading Hand might stand in for an Able Bodied Seaman but not, usually, an officer.

The way skills combine to provide an organisationally viable complement – e.g. whether it is sustainable to have a captain who is also the chef – is outwith the scope of ***flexiCRU***. However, it remains cognisant of the issue. While the specification or 'Role Task Groups' – i.e. specifications of the skills and activities which the navy will provide in individual crew members - is a separate design activity, ***flexiCRU*** is explicitly designed to import Role Task Groups into People Resources. There is a feedback loop to the extent that outputs may show that Role Task Groups over-constrain resource allocation and task scheduling.

flexiCRU modelling and output

flexiCRU works by a process of 'Constraint-Based Modelling'. It proceeds by taking the most heavily constrained tasks (e.g. tasks that have least freedom for rescheduling; tasks with heaviest resource demands) and uses them to progressively build up the minimum size of complement needed to resource them. For any task it looks at the possibility of allocating it to a resource that has already been created. If the resources exist but are in use, it looks at the possibility of rescheduling the task until the resource becomes available.

This process is carried out in accordance with a set of 'Rules.' Led by the requirement of flexibility, ***flexiCRU*** has been implemented so that its rules are extensible (the tool includes a scripting interface) to handle various data and data formats, including any unspecified at present.

The tractability of the rules also contributes to meeting the transparency requirement. It is important for users to have confidence in ***flexiCRU***'s outputs, and visibility of the rules gives them an understanding of how the input data has been handled.

Another aid to transparency is that ***flexiCRU*** indicates what input data has been used to derive its outputs. The principal output is a Gantt-like timeline which shows tasks scheduled across the scenario. For each task there is a link to the People Resources, Equipment and other data which define it. This is an aid to reasoning about any anomalies observed *(e.g:'I've specified that this task requires two people when really it could be done by one')* or options for redesign *('These tasks cause complement to peak – maybe they could be automated')*

Additional views of the output data which can be used to inform tradeoffs between complement, technical design, maintenance policy and requirements are:

- Collations of complement by rank, department and operating state. Programmes require these in various standardised formats (for the Royal Navy, e.g. Watch and Station Bills; Unit Establishment Lists)
- Graphs of complement use over time, filtered by department, skill, individual, etc.
- Time slices of the tasks carried out within a specified period.

Complementing is not a routine, mechanical process. It is intended that these output views – and others which may be added as required – will support the conversations needed to make the trade-offs that will yield an optimised crew.

Complementing and beyond

So far ***flexiCRU***'s development has focussed on a customer's immediate complementing concerns. Beyond complementing, there are many other areas where an approach grounded in Hierarchical Task Analysis could bring benefits:

- Provision of training facilities depends on the ability to identify training needs specific to equipment and missions. Training Needs Analysis (TNA) requires a hierarchical task analysis linked to people and equipment. It would be sensible to share that analysis used for complementing. BAE Systems Advanced Technology Centre has developed the TACTIC tool for TNA. Future work on ***flexiCRU*** will address compatibility with TACTIC.
- Because Human Factors resources are limited, they need to be focussed on the areas of design most critical for effectiveness. Task Analysis indicates which human tasks support critical requirements. Human Factors Risk Registers are used to list the associated parts of the ship for which Human Factors input is most important, and to track the resolution of Human Factors concerns. ***flexiCRU***'s Task Analysis can provide a reference point.
- The linkage between technical design and functional requirements has conventionally

been weak. Work by BAE Systems Surface Ships on 'Systems of Systems' has explored the benefits of aligning Product Breakdown Structures with functional views. ***flexiCRU***'s HTA would provide a convenient vehicle. The intention is to find ways of capturing ***flexiCRU*** models within programmes' Systems Design Environments where they would be common data products, linked to other data.

- Integrated Logistics Support modelling addresses the most cost effective strategies for maintenance (e.g. Planned vs Condition Based vs Failure Based; At sea vs Alongside; Own ship vs Supported; etc.). Maintenance policy has implications for crew size, and vice versa. An intention will be to establish links between ***flexiCRU*** and ILS models.
- Crew size and composition have cost implications and there will be a relationship between ***flexiCRU*** and cost models. It is a non-obvious question as to whether complements should be optimised on cost, number of people (e.g. a more expensive crew but with fewer people in harm's way) or crew composition (e.g. minimising use of the scarcest types of skilled people; ensuring a balanced complement). ***flexiCRU***'s open approach to writing resource allocation and scheduling will allow for different types of optimisation.
- In ***flexiCRU***, any information can be recorded against tasks. An intriguing idea would be to add task location. This would allow a link between ***flexiCRU***'s HTA and the ship's General Arrangement or CAD model. The exciting analyses this would allow include:
    - Personnel traffic flow modelling (for sizing passageways, etc)
    - Evacuation and escape modelling.
    - Human vulnerability and survivability modelling. (e.g. if a missile hits *here* and *this* compartment is damaged and *these* people are killed or injured…can the ship still fight and survive?)

Admittedly the preceding is a 'wish list' for the future: the current focus is on the customers' urgent complementing problems. However, ***flexiCRU*** has been designed specifically with a longer term vision in mind. Its development philosophy is based on Openness and Extensibility. Once the initial step of building Task Analysis into the Systems Engineering process is achieved the subsidiary benefits ought to be easier to achieve.

CONCLUSION: TASK ANALYSIS AS THE 'COMMON PICTURE'.

To use an analogy from physics, balancing complement – and design – and capability – and logistics – and so on is a 'Three Body Problem'. They are hard to get right when all are interdependent on one another – and it can be hard even to see what the interdependencies are.

Systems engineers already know this and have achieved successes in software-related projects. 'Traditional Engineering' has remained more conservative. Part of the problem *may* be that, to the uninitiated, the world of Systems Engineering looks distant and abstract: you can't hammer an Entity Relationship Diagram in the same way as you can a sheet of steel.

Human Factors practitioners have had the answer for years: Hierarchical Task Analysis is easy to do and easy to understand. But we haven't completely succeeded in pulling it into the mainstream. Perhaps the answer is to place it in the middle of a Systems Design Environment where everyone will trip over it.

That would be doing everyone a favour because HTA - or Functional Modelling if one prefers: we shouldn't be proprietorial about it - is useful for reasons other than Human Factors and complementing. It provides a convenient, common viewpoint which links various parts of the design. The aspiration should be to maintain a Functional Model which evolves over the development cycle, reflects changes in various aspects and indicates their implications for other aspects.

BAE Systems' Advanced Technology Centre's ***flexiCRU*** is a step towards this. Partly, it's a tool for warship complementing – and that's why it's being funded. Complementing is a key issue for ship design. It also has a wider vision of using the same Task Analysis that is needed for complementing for other purposes. It aims to integrate with Systems Design Environments. Not only will this give easy access to the data needed for complementing, but it will add value to other disciplines. They will gladly support complementing and other Human Factors activities if they can see that they are getting something out of it in return.

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