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Designing new teams with Cognitive Work Analysis

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Introduction

The expectation in designing new systems, such as military aircraft, is that the new system will offer better ways of working than existing ones. Typically, however, the design effort is heavily biased towards the engineering of the technical component, and little attention is given to the design of the work structure and work processes that are critical for ensuring that the functions and purposes of the new system are properly fulfilled. Consequently, although a system design may look attractive on paper, the potential offered by the new technology may be negated in practice. To avoid this state of affairs, a systematic and pre-emptive analysis of the new ways of working with a new technology is essential (Rasmussen, 1991).

Our focus in this paper is the design of team work for complex new systems. Where a system is populated with several workers who must collaborate and coordinate their activities to achieve system goals, a number of issues emerge regarding the team design that will best carry out the work of the system. Some of the relevant issues include: (1) team size, (2) team structure (eg levels of hierarchy, number of subteams), (3) dedicated roles vs multiskilled workers, and (4) spatial arrangement.

In the following sections, we will discuss why conventional techniques for analysing work requirements are unsuitable for addressing these kinds of issues. We will describe a new approach that we have developed for designing teams, which is based on Cognitive Work Analysis (CWA; Rasmussen, Pejtersen & Goodstein, 1994; Vicente, 1999), and we will show how we have applied this technique to design teams for a new military aircraft called Airborne Early Warning and Control (AEW&C). To conclude, we will examine the strengths and limitations of this approach based on our experience with AEW&C, and briefly discuss key directions for further research.

Standard techniques for designing teams

Standard techniques for designing teams are better suited to existing work systems with workers who can be observed, recorded, or measured in some way (eg Hendrick, 1997; Medsker & Campion, 1997). However, when the design of teams for new systems is based on previous solutions, potentially effective ways of working may be left uncovered. Worse still, previously unproductive ways of working may be inadvertently incorporated into the new design.

Normative techniques that reflect an idealised or optimal way of working are also unsuitable for designing teams for complex new systems. Typically, workers will develop novel ways of using a system as they gain experience with it so it is difficult to develop sound work procedures ahead of the system being put into operation. Normative techniques also tend to result in rigid design solutions that do not provide the necessary flexibility for dealing with unanticipated situations.

A Cognitive Work Analysis-based approach to designing teams

CWA offers a formative approach to team design because it focuses on the fundamental boundary conditions on system safety and performance (Rasmussen et al., 1994; Vicente, 1999). Each of the five analytic techniques that make up CWA identify particular types of boundaries or constraints: (1) the work domain or environment (Work Domain Analysis), (2) activity (Activity Analysis), (3) strategies (Strategies Analysis), (4) socio-organisational structure (Socio-Organisational Analysis), and (5) worker competencies (Worker Competencies Analysis).

By focussing on boundary conditions, rather than on the details of workers' behaviour or physical-system implementation, CWA can be conducted prior to a system being developed and prior to populating it with workers. Furthermore, by focusing on boundary conditions, CWA avoids the kinds of models that reflect previous technical solutions (descriptive models) or models that reflect an idealised optimum (normative).

So far, our approach for designing teams relies on Work Domain Analysis, Activity Analysis, and Socio-Organisational Analysis. In essence, a Temporal Coordination Work Function Analysis, an extension of Rasmussen's Activity Analysis in work domain terms, is used to analyse the activity of a new system in terms of a set of *work functions* or 'problems to solve' (Rasmussen et al., 1994). Then, as part of Socio-Organisational Analysis, the work functions together with a Crew Cognitive Walkthrough procedure are used to model workers' activity as a function of alternative team designs. Finally, by using Work Domain Analysis, alternative team designs can be evaluated against how well they support the functions, priorities and values, and purposes of the system, as well as how effectively the physical resources of the system are employed. In the following sections, we illustrate each of these steps within the context of AEW&C.

Using Cognitive Work Analysis to design AEW&C teams

AEW&C is a next generation AWACS (US Air Force & NATO) and E2C-Hawkeye (US Navy) type of system that is currently being manufactured by Boeing for the Australian Defence Force. When it is operational, AEW&C will be manned by a team of people at the 'back end' of the aircraft who will be responsible for developing a situation picture using sophisticated sensor, intelligence, and communications equipment, and also for coordinating the activities of defence assets in the area. A key concern of the Australian Defence Force is how the work of this team should be structured in order to enhance system performance and safety.

So far, we have used our CWA-based technique to consider issues of team size, and whether AEW&C crew should have dedicated roles and responsibilities or whether they should be multiskilled. We will describe the AEW&C Work Domain Analysis and the Temporal Coordination Work Function Analysis, and then show how these products were used as part of a Socio-Organisational Analysis, together with a Crew Cognitive Walkthrough, to provide recommendations for an AEW&C team design.

AEW&C Work Domain Analysis

The AEW&C Work Domain Analysis, which was constructed on the basis of various documents and input from subject matter experts, illustrates: (1) the functional purposes or high-level objectives of the AEW&C work domain, (2) the Priorities and Values that are preserved in AEW&C operation, (3) the Purpose-Related Functions that are executed and coordinated on AEW&C missions, (4) the Physical Functionality afforded by the physical devices of the AEW&C platform, and (5) the Physical Devices themselves. Figure 1 shows a sample of functions from each of these layers of the AEW&C abstraction hierarchy.

Some readers may notice that this representation of AEW&C is different from the abstraction hierarchy that was initially used for tender evaluation (source selection) of AEW&C system designs (Naikar & Sanderson, 2000). In the original description, the AEW&C functions tended to be misinterpreted as activity. We have now reworked these functions to emphasise the

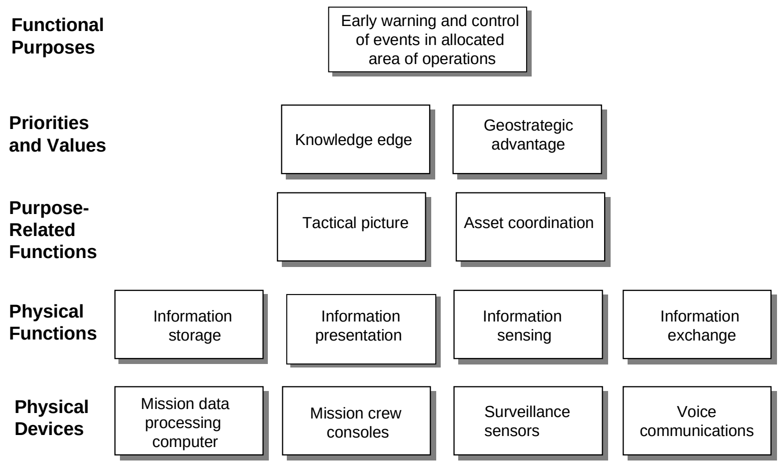

Figure 1: A sample of functions from each layer of the AEW&C abstraction hierarchy.

structural properties of the AEW&C work domain. In addition, several of the functions have been summarised at a higher level of granularity, which has resulted in a more condensed version of the original AEW&C abstraction hierarchy.

AEW&C Temporal Coordination Work Function Analysis

Temporal Coordination Work Function Analysis describes the activity of a system in terms of a set of work functions or 'problems to solve', and shows the temporal coordination constraints acting on the work functions. This representation is a variant of the Temporal Coordination Control Task Analysis framework we presented in another paper (Sanderson & Naikar, 2000). In the present work, we wished to concentrate on the 'problems' that would preoccupy crew members rather than the control tasks that are necessary for solving problems.

In Figure 2, we show the AEW&C work functions against a backdrop of mission phases. The work functions are placed in the phase of mission with which they are most typically associated, although the temporal boundaries (dashed lines) illustrate that the work functions can also occur at other times. In a separate document we have described each work function in terms of the 'problem' that it presents to workers. For example, for the work function 'manage crew', the problem is 'to distribute tasks, assets, and other resources among crew members in order to support the aims of the mission under changing environmental and tactical conditions'.

Socio-Organisational Analysis

For this phase of analysis, we developed a Crew Cognitive Walkthrough technique to explore the feasibility of alternative crewing arrangements for AEW&C. This technique is an extension of the Cognitive Walkthrough procedure (Lewis, Polson, Wharton & Rieman, 1990) in that it focuses on the processes of group interaction and communication just as much as on individual cognitive factors. The advantage of this technique is that it can be used to elicit information about crew work functions and communication needs for systems that are yet to exist in their physical state.

In essence, the Crew Cognitive Walkthrough involves: (1) scenario design, (2) knowledge elicitation, and (3) representation and analysis. For AEW&C, the first step (scenario design) involved working with two Australian Defence Force personnel to develop air defence scenarios that covered the kind of activity that would be seen routinely on an AEW&C mission as well as periods of high workload activity. The subject matter experts had a good understanding of what is to be achieved by AEW&C as they had been involved in writing the Concept of Operations for this platform. The scenarios were divided into general 'epochs' during which a coherent set of

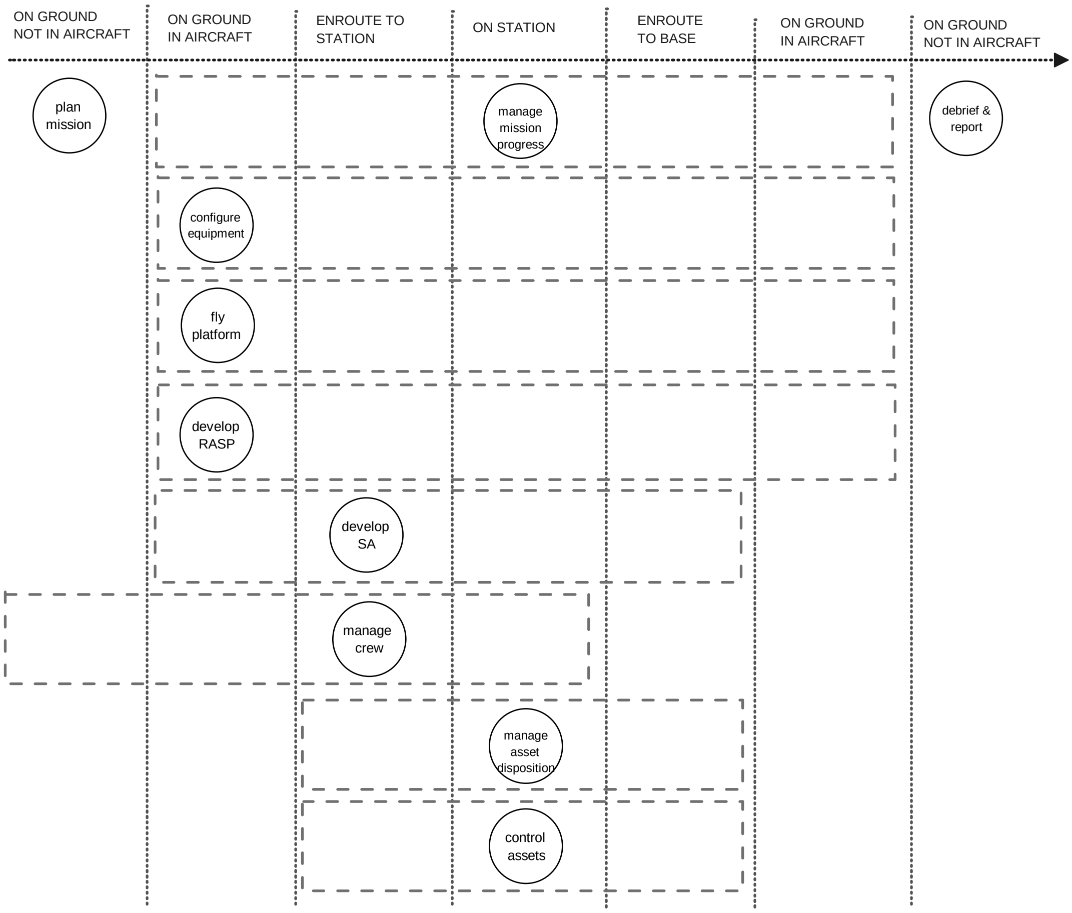

Figure 2: The AEW&C Temporal Coordination Work Function Analysis

mission events and units of activity occurred (eg strike package enters no fly zone, hostile firing of friendly ships).

In the second step (knowledge elicitation), the subject matter experts described the activity of each crew member for every epoch in a scenario, assuming a particular team design. The questions that were posed to the subject matter experts included: the preoccupations of the crew members at each epoch, how work allocations would be negotiated and implemented, and the criteria used for work allocation. We kept a record of crew tasking – in terms of work functions – on a whiteboard, and we also took notes to supplement the record on the whiteboard. Where there was a reallocation of work functions among crew members, the communication and coordination requirements associated with this change were also noted.

The third step (representation and analysis) involved integrating the data from the whiteboard and the analysts' notes into a succinct, high-level representation of how the scenario unfolded (eg Figure 3). The representations, which were created on WinFlow, described: the critical events at each epoch of the scenario (top row); the roles of each of the crew members (first column); the work functions (circles) that the crew members are preoccupied with (cells); the reallocation of work functions and associated communication and coordination requirements (arrows); and the added responsibilities of crew members, given the reduction in team size from 10 to 6 (bold circles).

From these representations, we were able to explore the feasibility of alternative team designs by: (1) summarising patterns of activity and workload of crew members at each epoch of the mission, (2) estimating spare capacity for further work responsibilities, (3) estimating work function performance, and (4) considering the impact on functions in the AEW&C abstraction hierarchy. In the following sections, we describe our analyses of two AEW&C scenarios to

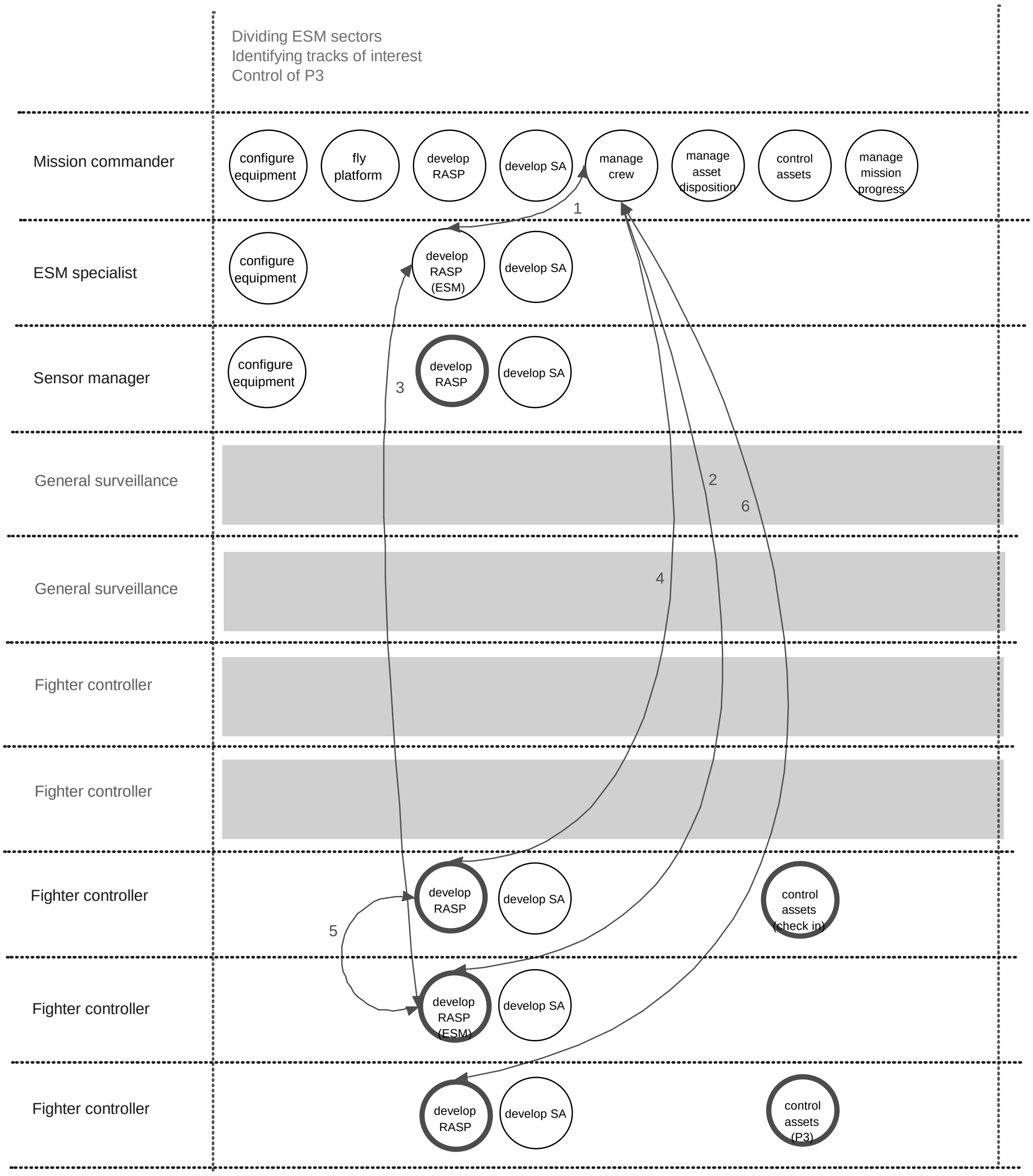

Figure 3: Representation of activity for a 6-crew multiskilled team for one epoch in scenario A. Rows that are blocked out represent individuals who were part of the 10-crew team.

illustrate that these processes can discriminate between different crewing arrangements and lead to recommendations for a potentially effective team design.

Scenario A. Scenario A was a relatively simple scenario that involved focal area surveillance of a country X and 12 major assets comprising the blue force. We modelled crew activity for this scenario as a function of team size (10 vs 6), and assuming that the crew were multiskilled so that work responsibilities could be allocated flexibly across team members in response to local contingencies (Figure 3). Our analysis led to some useful conclusions which are summarised in Table 1.

The 10-crew team had greater spare capacity than the 6-crew team, both for individual members and across the team as a whole. Consequently, in the 6-crew team there were more instances when work had to be reallocated in order to manage workload. As the reallocation of work functions disrupts the performance of those work functions already being performed by the crew, and the crew members in the smaller team are each performing more work functions, a greater number of work functions will be disrupted in the 6-crew condition than in the 10-crew condition. In the 6-crew condition, the mission commander also has to devote more effort to work reallocation. In addition, in the smaller team, less effort was devoted to developing a satisfactory tactical picture, and individuals were controlling and managing a larger number of assets. These results suggest that it may be harder for the 6-crew team to preserve the AEW&C Priorities and Values of maintaining a knowledge edge and a geostrategic advantage than the 10-crew team.

Table 1: Summary of observations from Crew Cognitive Walkthrough of Scenario A which compared team sizes of 10 and 6, assuming a multiskilled crew.

	10 multiskilled	6 multiskilled
Spare capacity	X	
More instances of work reallocation		X
Reallocation disrupts performance of more work functions		X
Mission commander devoting more effort to work reallocation		X
Less effort devoted to Develop RASP		X
Individuals controlling and managing more assets		X

Scenario B. Scenario B was an 8 hour mission that involved focal area surveillance of a No Fly Zone of Country X and broad area surveillance of a maritime region. There were 48 major assets in the blue force and more hostile activity compared to scenario A. We modelled crew activity for this scenario as a function of team size (10 vs 6) and whether the crew were multiskilled or had dedicated roles and responsibilities. The main observations from these analyses are summarised in Table 2.

Table 2: Summary of observations from Crew Cognitive Walkthrough of Scenario B which compared team sizes of 10 and 6, and dedicated vs multiskilled crew.

	10 dedicated	10 multi-skilled	6 dedicated	6 multi-skilled
MCo has heavy monitoring and reporting responsibilities	X	X	X	X
MCo has added responsibility for work reallocation		X		X
No reallocation of work despite multiskilled crew		X		X
Even distribution of workload across crew		X		X
Less effort devoted to Develop RASP				X
Individuals controlling and managing more assets			X	

In all conditions, the mission commander (MCo) was heavily tasked with monitoring crew and reporting to external authorities. Moreover, in the multiskilled conditions, the mission commander had the added responsibility of monitoring and making decisions about work reallocation. Interestingly, in the multiskilled conditions, there were no actual instances of work reallocation. This was because in the smaller team all crew were already working hard on important work functions whereas in the larger team there was so much spare capacity that work functions did not have to be shuffled among crew members. Overall, however, workload was more evenly distributed amongst the multiskilled crew than the dedicated crew.

In both of the 10-crew conditions, there was sufficient effort devoted to all work functions. In the 6-crew conditions, there was less effort devoted to develop RASP when the crew were multiskilled than when the crew were dedicated. This was due to the urgency associated with controlling and managing a large number of assets, and flexible allocation in a multiskilled crew to meet this demand. However, the workload for controlling and managing assets was more evenly distributed across multiskilled than dedicated crew. Thus, in the 6-crew conditions, the dedicated crew were more likely to find it harder to facilitate asset coordination and maintain a geostrategic advantage, whereas the multiskilled crew were more likely to find it harder to develop a tactical picture and maintain a knowledge edge.

Recommendations for AEW&C team design

In this section we will discuss two main issues which have significantly influenced our concept of a potential AEW&C team design. First, we have observed that multiskilling offers the flexibility for dealing with a dynamic environment because the effort that is directed to particular work functions can be matched to demand, and workload can be distributed more evenly across crew members. However, in a complex scenario with a small crew, it may be difficult to take advantage of multiskilling if the workload of all crew members is high and all work functions require significant effort. Multiskilling may also be of little benefit in a large crew where there is so much spare capacity that there is little need for work reallocation. Thus, to realise the benefits of multiskilling an appropriate team size must be in place.

Second, regardless of team size and whether the crew are multiskilled or dedicated, the mission commander is kept very busy with monitoring crew and liaising with external authorities. These house-keeping responsibilities distract him from and reduce the amount of time he can devote to his primary responsibility of understanding the emerging situation and making effective decisions. Thus, a better team design may be to introduce a deputy mission commander to take up the roles of supervisor and coordinator. This person would be responsible for monitoring crew, coordinating their efforts, and liasing with external agencies. All significant decision-making responsibilities, however, would belong to the mission commander.

On the basis of these and other observations, we have proposed a new team design for AEW&C. This design does not reflect a final solution in any sense but simply incorporates our observations from previous analyses into a structure that can be evaluated in further analyses. Figure 4 shows that this team design uses 7 people, and involves a Mission Commander supported by a Deputy Mission Commander. In this arrangement, the role of Deputy Mission Commander is a flexible one that is implemented in complex missions where the Mission Commander needs to be buffered from the dangers of micromanagement. On missions or segments of missions, when this buffer is not required, the crew member in this role can drop back into general surveillance or fighter controller responsibilities. Figure 4 also shows that although the crew are multiskilled, each crew member will be given primary and secondary responsibilities (eg SM/GS) to ensure that, across the team, adequate effort is always directed to key work functions. This team structure is intended to be highly flexible.

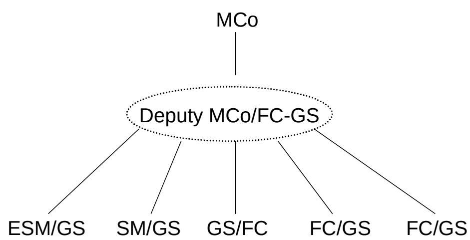

Figure 4: Potential AEW&C team design where MCo = Mission Commander, Deputy MCo = Deputy Mission Commander, FC = Fighter Controller, GS = General Surveillance, and ESM = Electronic Support Measures specialist.

Conclusion

In this paper, we have shown that a CWA-based approach to team design is useful for examining concepts surrounding team size, and multiskilled vs dedicated crew. We have used this technique to generate a new team design for AEW&C that subject matter experts think is highly promising. Further research will involve evaluating this team design as well as using a CWA-based technique to examine other crew configuration issues such as subteam structures. This work, which can be conducted in the absence of a physical work system, will help the Australian

Defence Force make effective use of new systems right from the start, rather than working out how to use these systems in an evolutionary fashion.

Further work will involve modifying the Crew Cognitive Walkthrough technique so that it is more representative of real world contingencies and the 'fog of war'; for example, by requiring subject matter experts to play out a scenario against an unpredictable, intelligent enemy (Elliott, Crawford, Solodilova, Sanderson, & Naikar et al., 2000). We also face the challenge of empirical validation of our CWA-based approach to team design. While this too is part of our future research program, the reality is that the operationalisation of many new systems, like AEW&C, will proceed in the absence of these data. For such projects, we believe that it is reasonable to assume that a systematic approach, such as the one we have proposed here, where the work requirements of a system drive team design will offer better results than basing team design on intuition or informal analysis.

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