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Theme: The Future of C2

Track: Decision Making and Cognitive Analysis

Title: Analyzing Decisions and Characterizing Information in C2 Systems

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Abstract
Operators performing C2 functions encounter an ever-increasing amount of information, due to advances in sensors combined with the multiplying effects of Network Centric Warfare. The problem is that information systems are often designed without formal models of how decisions are made or what information is required to make those decisions. In this paper we analyze key decisions in several C2 systems using the methods of Applied Cognitive Work Analysis, and characterize the associated information with respect to three aspects, namely: Dimensionality, Temporality and Uncertainty. The results are used to construct pictures of the information characteristics for decisions within each system, and a composite picture for all three systems. These pictures highlight similarities and differences across systems, and suggest where C2 could be improved by support systems that provide automation and/or visualizations.

1 Introduction

Command and Control (C2) is concerned with accomplishing *functions* like allocating sensors to obtain data and assigning weapons to achieve effects. These functions are *information* processing tasks, commonly referred to as *decisions* (Figure 1).

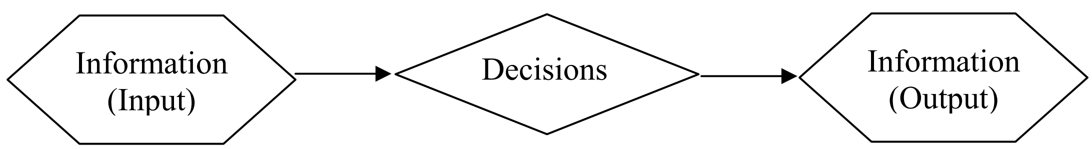

Figure 1: Decision making is information processing.

Operators performing C2 functions, using C2 *systems*, encounter an ever-increasing amount of information due to advances in sensors combined with the multiplying effects of Network Centric Warfare (NCW). The problem is that systems are often designed without formal models of *how* decisions are made or *what* information is required to make those decisions.

In this paper we focus on the information associated with C2 decisions. For breadth, we address three different Air Force systems (functions), namely: Time Critical Targeting Functionality (TCTF); Joint Surveillance Targeting Attack Radar System (JSTARS); and Airborne Warning and Control System (AWACS). For depth, we use the methods of Applied Cognitive Work Analysis (ACWA) to develop Functional Decomposition Diagrams (FDDs) that identify the goals, decisions and information in major functions and sub-functions of each system. We then characterize the *Dimensionality*, *Temporality* and *Uncertainty* of information associated with each decision.

Using a similar triad in their book on NCW, Alberts, Garstka, & Stein (1999) discuss the *relevancy*, *timeliness* and *accuracy* of information. They also define information *superiority* as "... a state that is achieved when a competitive advantage is derived from the ability to exploit a superior information position." Here the key word is *exploit*, which means that C2 systems must provide human decision makers with *useful* information, which depends on the decision making task at hand as well as the cognitive capabilities of the decision maker. In short, information superiority can only be achieved if C2 systems support human beings in dealing with the cognitive challenges of Dimensionality (relevancy), Temporality (timeliness) and Uncertainty (accuracy).

Using this triad to characterize the nature of information associated with C2 decisions, we construct a picture for each system and a composite picture for all three systems. We present these pictures to highlight similarities and differences across systems. We also discuss how our results can be used to improve the design of C2 systems, by suggesting opportunities for automation and/or visualizations.

2 Functional Decompositions

This section presents Functional Decomposition Diagrams (FDDs) that were developed using methods of Applied Cognitive Work Analysis; see Elm, Potter, Gualtieri, Easter, & Roth (2003); also Means, Darling, & Perron (2004). Each C2 system is treated as a collection of functions with three features in each function, namely: *goals*, *information* and *decisions* (Figure 2).

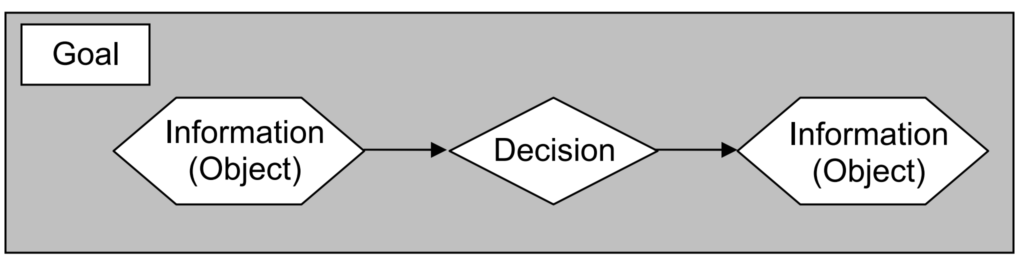

Figure 2: Features and symbols used in Functional Decomposition Diagrams.

The goals in the FDDs are organized hierarchically, and the decisions are numbered sequentially. FDDs were created for three Air Force systems, namely: Time Critical Targeting Functionality (TCTF); Joint Surveillance Targeting Attack Radar System (JSTARS); and Airborne Warning and Control System (AWACS). The resulting FDDs are presented below (Figures 3, 4 and 5), along with a summary discussion of the goals, decisions and information for each basic function (gray box) of each major system.

Time Critical Targeting Functionality (TCTF)

Time Critical Targeting Functionality (TCTF) is a C2 system designed to identify emerging enemy ground targets and allocate assets to destroy the targets. TCTF operators work within the Air Operations Center (AOC), which is a ground-based command center combining the planning and operational phases of the air battle plan. TCTF allows operators to conduct Intelligence Preparation of the Battlespace (IPB), locate enemy tracks, develop tracks into targets (Target Development (TD)) and assign optimal assets to targets (Weapon Target Pairing (WTP)); see http://www.zeltech.com.

Here we consider both the TD and WTP components of TCTF and focus on the decisions, which are represented as diamonds in the FDD (Figure 3). Each diamond is numbered [T1, T2, T3, etc.] and discussed in the text below.

The TCT process begins when operators receive sensor returns as ground radar hits (Ground Moving Target Indicator (GMTI)). These are analyzed and compared to background intelligence and other sensors in order to aggregate the returns and form tracks [T1]. Once a track is created, operators develop the initial target ID [T2] based on radar returns, Intel, available imagery and video. If a track is determined to be a potential hostile target, it is "nominated" as an emerging target [T3].

During the TD process, operators attempt to obtain additional Intel that will help refine the target location and ID. Here operators must consider the current and required levels of positional accuracy, ID accuracy and temporal accuracy – where the required levels are dictated by the Commander's Guidance and Rules of Engagement (ROEs) [T4]. Operators then determine the required sensor coverage to achieve the desired accuracy [T5].

Once operators have enough information on the target, as described above, the target is declared a "validated" target [T6]. If operators determine that the target has an extremely limited window of vulnerability or opportunity, and that its destruction is critical to ensure successful completion of the campaign objectives, then it is declared a "TCT" [T7].

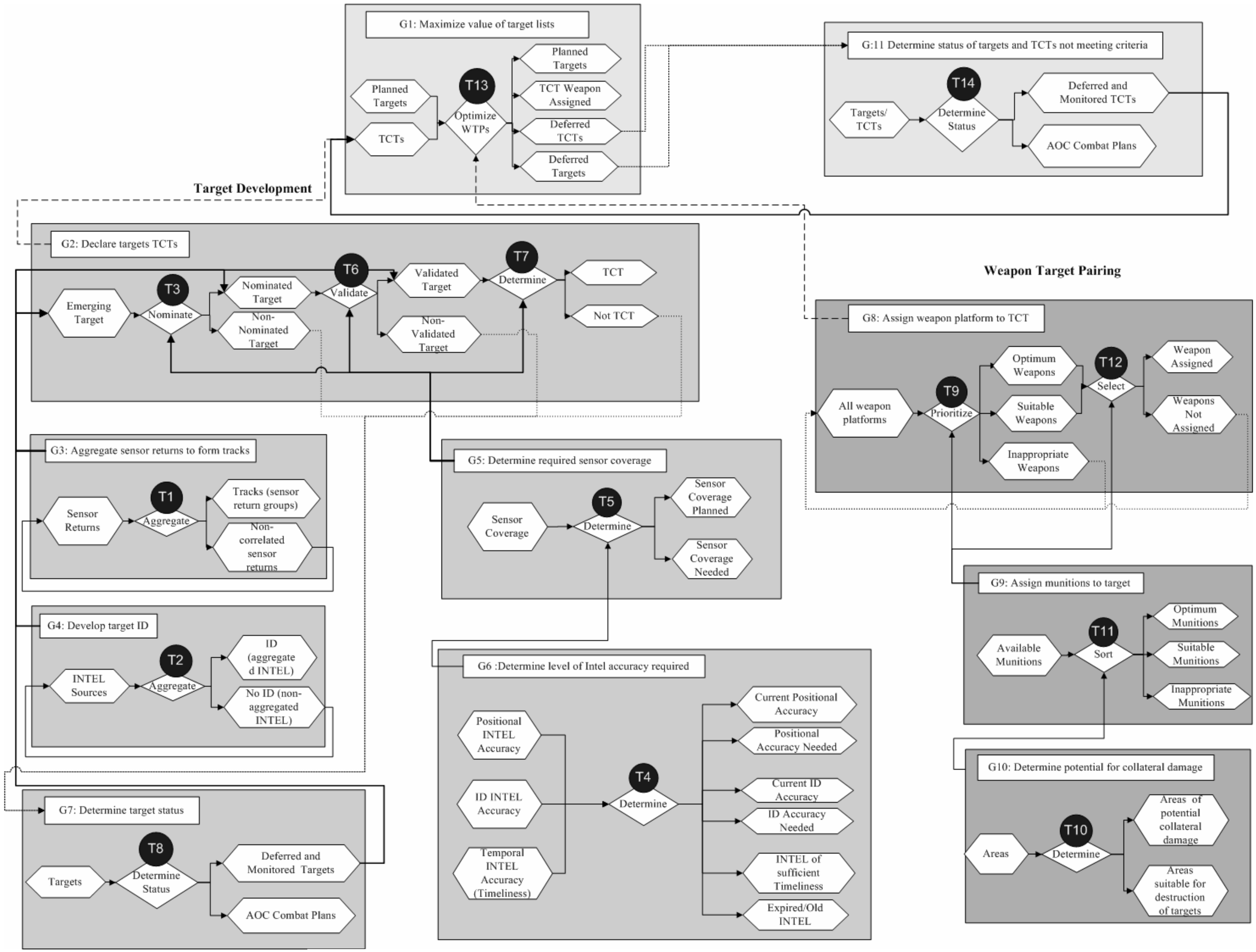

Figure 3: FDD for Time Critical Targeting Functionality (TCTF).

During the TD process, a target may not fit into one of the three classes of "nominated", "validated" or "TCT" [T8]. In this case, operators must either continue to monitor the target or else send the target information to the AOC Combat Plans cell where it is incorporated into the future battle plan.

Once declared a TCT, operators assign a weapon platform to destroy the target. This is a complex decision for which an operator must first prioritize weapon platforms to determine which assets are optimal, which assets are suitable and which assets do not need to be considered for further analysis [T9]. Determinations are then made using available information on current location, speed, munitions, enemy vulnerabilities, etc. Based on the potential for collateral damage [T10], as well as other factors such as target vulnerabilities and probability of destruction, the operator selects munitions to destroy the target [T11]. An optimal weapon platform is then selected from a pool of suitable weapon platforms considering factors such as ROEs, the priority of the proposed asset's original target, the priority of the TCT and various probabilities (arrival, target acquisition, kill, etc.) [T12].

After operators have developed the target and paired the weapon to the target, higher level decision makers must optimize the weapon-target pairs for both planned (ATO) and dynamic (TCT) targets [T13] by evaluating the probabilities and priorities for all weapon-target pairs. If a target is not paired with a weapon, decision makers must determine the status of the target [T14] and decide whether to continue monitoring the target or forward the target to AOC Combat Plans cell for targeting in another battle plan.

Joint Surveillance Targeting Attack Radar System (JSTARS)

The E-8C Joint Surveillance Target Attack Radar System (JSTARS) is an airborne battle management and C2 platform. This system conducts ground surveillance, enabling commanders to develop an understanding of the enemy situation in order to support attack operations and targeting. From a standoff position, the aircraft – a modified Boeing 707/300 series commercial aircraft – detects, locates, classifies, tracks and targets hostile ground movements, communicating real-time information through secure data links with U.S. Air Force and U.S. Army command posts; see www.iss.northropgrumman.com.

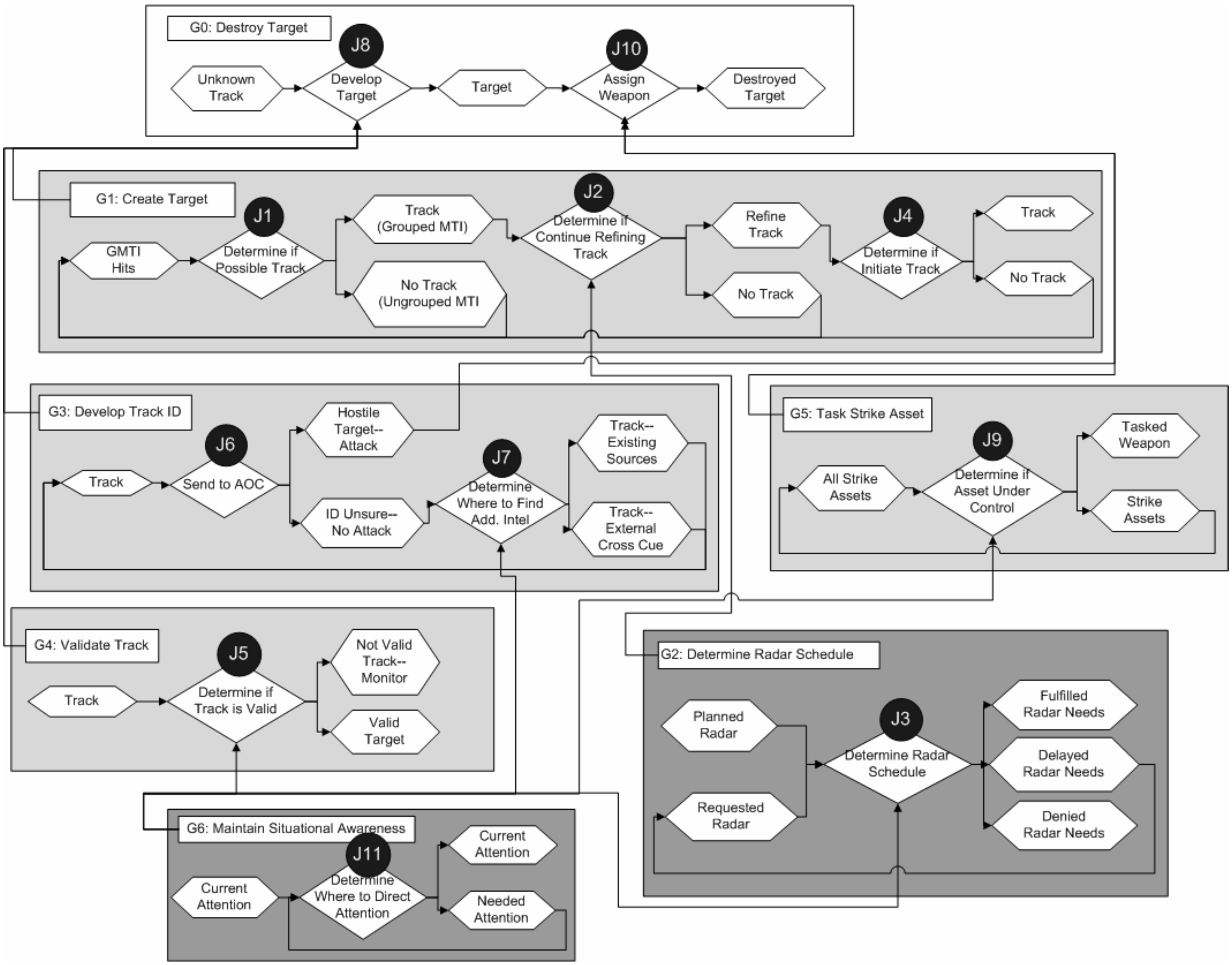

Figure 4: FDD for Joint Surveillance Targeting Attack Radar System (JSTARS).

The JSTARS FDD shown in Figure 4 is based on a task analysis performed by the 2002 Tracker Working Group for the Attack Support Scenario function of the system.

When JSTARS operators receive GMTI hits, they determine if the hits are a possible track of interest [J1]. Because radar hits are received on both civilian and hostile ground vehicles, the operators must make a very preliminary ID estimation for tracks of interest. The operators create a local track and determine if they should continue refining the track [J2]. An operator may create a radar service request to obtain a finer level of detail on the suspected track, and because multiple operators within the aircraft and in the AOC (and external commanders) frequently submit radar requests, other operators must determine the radar schedule [J3]. This is a complex decision where an operator must prioritize the radar requests and create a plan to fulfill or deny requests while anticipating future needs. After operators refine a track based on radar returns, they must determine whether they should initiate the track and send it to the rest of the JSTARS team [J4].

When a track is initiated, a higher level decision maker will compare the known information against high level guidance and existing intelligence to determine if the track is valid [J5]. The track information is sent to the AOC where personnel attempt to determine if the track is indeed hostile [J6]. If the AOC identifies the track as hostile, then the track is paired with a weapon; but if the AOC is unsure then the AOC and JSTARS operators work together to obtain additional Intel [J7]. Information is passed back through the AOC until the track is properly identified. A hostile ID is the final stage in the high level decision to develop the target [J8].

Once a target is developed within the Attack Support Scenario, JSTARS operators select a weapon platform to prosecute the target. To task a strike asset the operator must first determine if the asset is under JSTARS control [J9]. If the desired asset is under control, the operator determines if he should assign the weapon to the target [J10]. Throughout the entire process the operators must constantly attend to GMTI hits and update the status of tracks [J11].

Airborne Warning and Control System (AWACS)

The E-3 Airborne Warning and Control System (AWACS) provides both airborne surveillance and C2 functions for tactical and air defense forces. In its tactical role, the E-3 can detect and track hostile aircraft operating at low altitudes over all terrain, and can identify and control friendly aircraft in the same airspace. In its strategic defense role, the E-3 provides the means to detect, identify, track and intercept airborne threats; see www.boeing.com. AWACS acts as an air traffic control tower in the sky, directing friendly assets toward enemy aircraft while keeping aircraft safely separated.

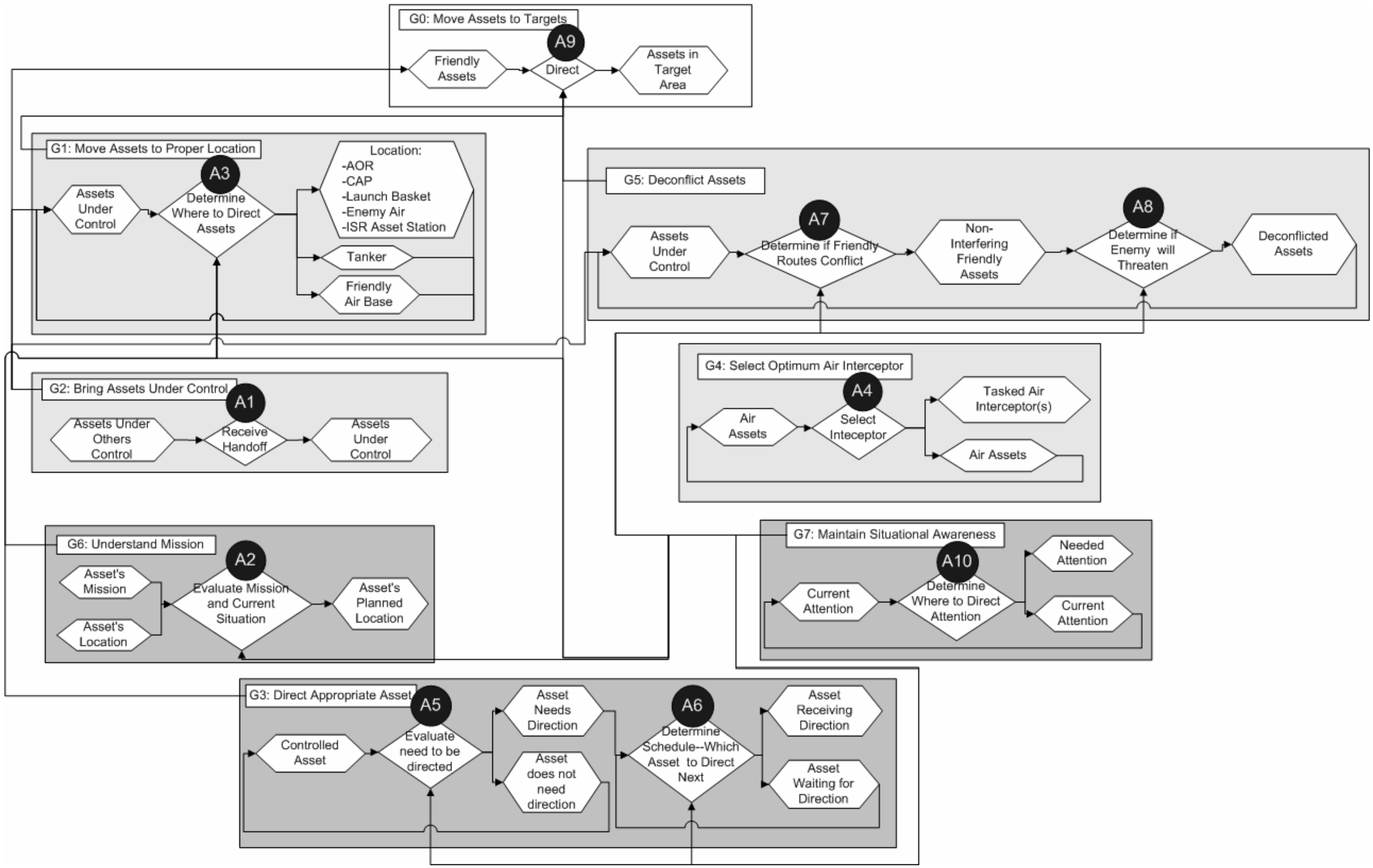

Figure 5: FDD for Airborne Warning and Control System (AWACS).

The AWACS FDD in Figure 5 is based on a task analysis performed for the Air Force Research Laboratory; see Fahey, Rowe, Dunlap, & deBoom (2001); along with information documented by Snook (2002). AWACS crews consist of surveillance personnel and Weapons Director (WD) teams, where WD teams are usually organized in one of two ways. A geographical organization, which occurs less often, divides the airspace into different areas or lanes. A functional organization divides the responsibility based on aircraft tasking; for example different team members control airborne tankers, aircraft traveling to/from the Area of Responsibility (AOR) and aircraft within the AOR. Here our analysis focuses on functionally organized WDs.

A WD's tasks begin when he receives a handoff from another WD or external control authority such as a tower [A1]. Once under his control, he must direct the asset according to the ATO [A2], for example: enroute to the AOR or areas within the AOR such as a Combat Air Patrol (CAP), or to a weapons release point or an intelligence platform orbit [A3]. Many of these areas will be preplanned, except for when a dynamic battlespace event, such as an enemy air intercept, requires a change to the plan. The WD must also react to dynamic situations such as scheduling of in-flight refueling and redirection of AWACS itself as dictated by the ground situation. One of the most dynamic and complex rerouting decisions is to select the optimal air interceptor(s) to investigate, identify or destroy hostile aircraft [A4]. This decision requires a trade-off analysis to determine which interceptors have the highest probability of successfully destroying the target with the least impact on current missions.

WDs must constantly monitor the assets under their control and evaluate the need for direction [A5]. The WD must build a mental schedule to determine which asset to direct next and which assets to place in a mental queue [A6].

While WDs are directing aircraft to the desired location, they must also consider potential impediments, such as whether the friendly routes will conflict at some point in the future [A7]. This decision requires mental simulation (Klein, 1998) on the part of the operator to play out the remainder of the friendly assets' routes and determine if any adjustments are needed. The WDs must also determine if enemy aircraft will threaten friendly assets' missions or other friendly forces, in addition to determining if enemy ground threats such as Surface to Air Missiles (SAMs) will threaten friendly assets [A8]. Complicating this decision, some SAM sites are known (previously planned in routing) but some are unknown and can pop-up at any time.

With the considerations discussed above, the operator successfully completes the process of directing assets to their targets [A9]. Throughout the entire process the operators must constantly attend to assets, missions and threats [A10].

3 Cross-System Comparisons

The FDDs developed above provide flowchart descriptions of various decisions and associated information in three C2 functions (systems). To gain more insight and to facilitate comparisons, we reviewed the information associated with each decision and assigned a rating (High or Low) to each of the following three aspects of the information: *Dimensionality*, *Temporality* and *Uncertainty*.

Dimensionality refers to the *size* of information that must be processed, including the number of inputs and the number of outcomes that the decision maker must consider. Temporality refers to a *change* in information that must be processed, including the need for making future predictions from current information. Uncertainty refers to the *fuzz* in information that must be processed, including ambiguities and probabilities that the decision maker must consider.

In some views these three aspects might be seen as highly overlapping. For example, Temporality can be seen as contributing to Uncertainty, and Uncertainty can be seen as contributing to Dimensionality. However, we use the terms in a non-overlapping sense and treat the three as relatively independent aspects of information.

We then construct a 3-D cube with an axis for each aspect. And, using the binary (High or Low) distinction noted above, we plot the number of decisions of each type (for each of the eight possible types) on the corners of the cube.

The ratings for each decision, which are necessarily subjective, are based on judgments provided by a subject matter expert (although he consulted with other subject matter experts). Nevertheless, the ratings provide some measure of the similarities and differences between different decisions, and this was our aim in the study. The ratings are provided in Appendix A. The basis for each rating is currently being documented in a more detailed report.

The combined results for all three C2 systems are shown in Figure 6. The individual results for each C2 system are shown in Figures 7 and 8.

Referring to Figure 6, roughly one-third of the decisions (11/35) were rated High on all three axes. In our framework, these would be considered the most complex C2 decisions. Also referring to Figure 6, roughly one-quarter of the decisions (8/35) were rated Low on all three axes. In our framework, these would be considered the least complex C2 decisions.

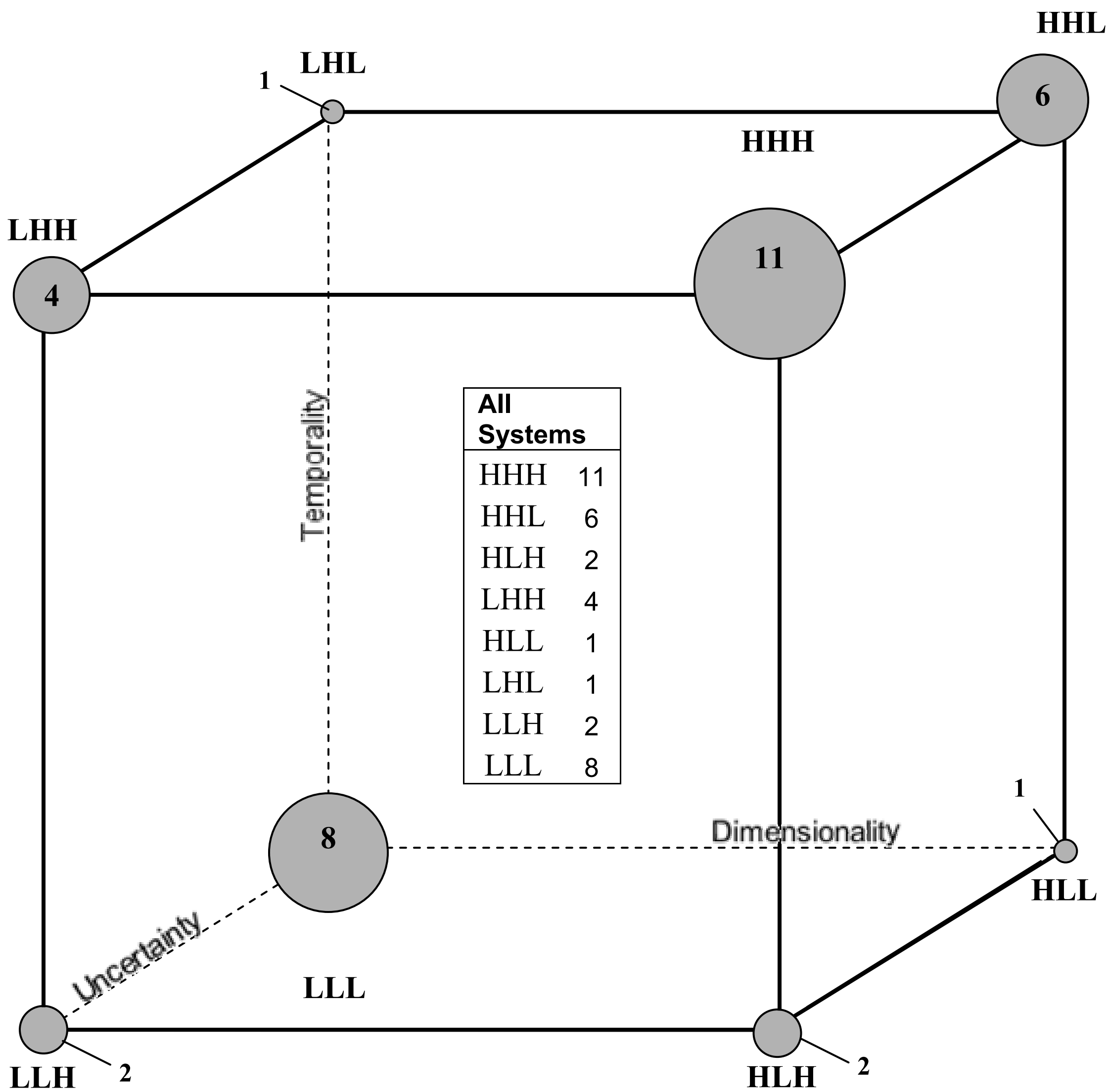

Figure 6: Decision types (totals for three C2 systems).

Referring to Figures 7 and 8, TCTF has many decisions with High Dimensionality (and High Temporality and High Uncertainty). JSTARS has many decisions with High Uncertainty. AWACS has many decisions with High Temporality (and High Dimensionality). This shows that different C2 functions (systems), which address different C2 problems, pose somewhat different decision challenges in terms of their associated information characteristics.

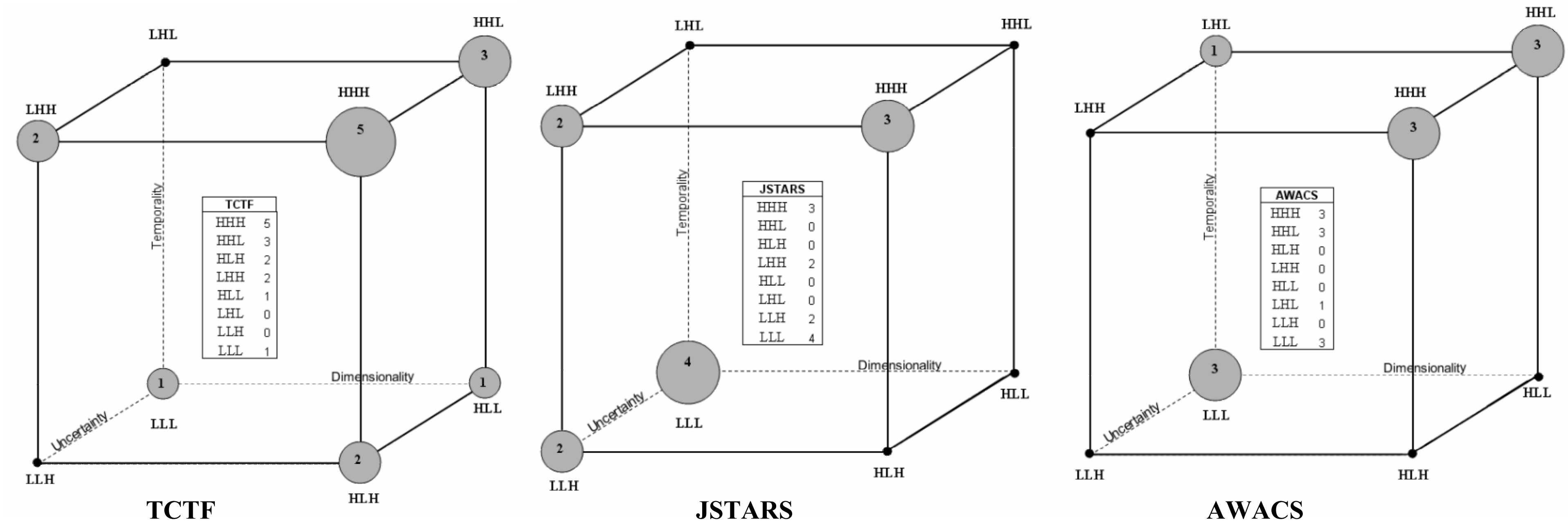

Figure 7: Decision types (totals for each C2 system).

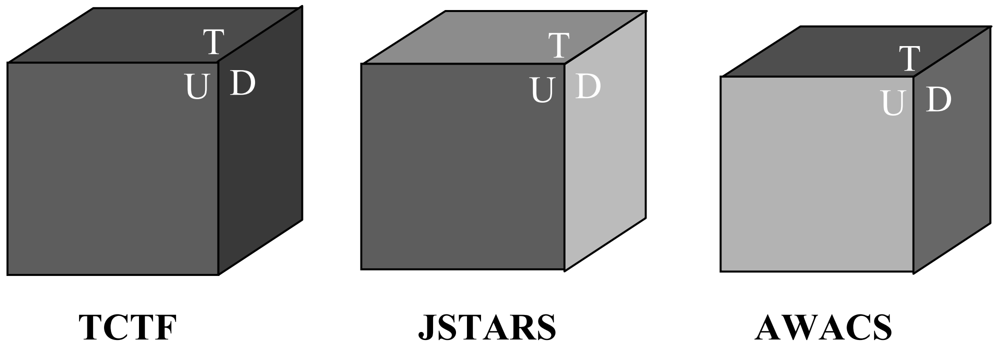

Figure 8: Darkness shows fraction of decisions rated High for Dimensionality (D), Temporality (T) and Uncertainty (U). Cube size represents number of decisions (total).

4 Applications

Our approach is useful because it illustrates (Figures 3, 4 and 5) how the three *features* of goals, information and decisions are related in C2 systems. The approach is also useful because it focuses on conceptual *functions* and not the physical hardware or software of *systems*. This is important because the need for more integrated C2 in NCW may require major changes to future systems (see Tirpak, 2002) in order to accomplish C2 functions.

Our results are useful because they illustrate (Figures 6, 7 and 8) how the three *aspects* of Dimensionality, Temporality and Uncertainty give rise to different sorts of decisions involving different sorts of information in different C2 function/systems. In particular, our results highlight which decisions are the most complex (HHH) and which decisions are the least complex (LLL) – and suggest where future efforts to improve C2 systems might best be directed.

For example, the least complex decisions (LLL) offer opportunities for *automation* by systems. This is because the relatively low size (Dimensionality), low change (Temporality) and low fuzz (Uncertainty) in the associated information constrains the *context* in which these decisions must be made – and this makes the decisions more straightforward for computer solutions.

Similarly, the most complex decisions (HHH) offer opportunities for *visualizations* by systems to help humans. These decisions are and will continue to be made by humans, simply because the relatively large size, large change and large fuzz make it difficult to anticipate the *context* in which the decisions must be made – and this makes it difficult to automate. In these cases, the major function of information systems is to support human decision makers in overcoming their cognitive limitations. And this can often be done via graphic displays that exploit the perceptual powers of human vision.

As examples of how complex decisions can be aided by advanced visualizations, Burns (2004) has developed prototype designs for support systems in problems of Bayesian Inference (for Target Development) and Weapon Target Pairing (for Time Critical Targeting). According to our ratings here, the latter (WTP in TCT) is a decision [T13] in Figure 3 that is rated High on all three aspects: Dimensionality, Temporality and Uncertainty. The proposed support systems use *dynamic diagrams* to help users deal with the complexities of the WTP decision <u>and</u> to help users deal with solutions offered by an automated WTP algorithm. Here the tradeoff is this: The pairing problem is hard to solve manually by humans because it is HHH; but it is also hard to solve automatically by a system because the system may not have the right context (models and data) such that its algorithm may be getting the right answer to the wrong problem.

The advantage of dynamic diagrams, as proposed by Burns (2004), is that they picture the basic structure of the problem in a graphic format (Tufte, 2001) that allows users to better manage the complexities of Dimensionality, Temporality and Uncertainty. The basic approach is to identify the *conceptual* features of the problem structure that are important to its solution, and represent them with *graphical* features in a system display.

For WTP, the basic structure of the problem is an asset-target matrix. As such, the *dynamic diagrams* display bar graphs of net gains and contributing factors for various pairing options – in a color-coded matrix that allows drill-down and roll-up to help users manage the High Dimensionality of the pairing problem. The dynamic diagrams also include animated illustrations of the targets' Windows-of-Vulnerability and assets' Windows-of-Availability, in the same matrix format to help users manage the High Temporality of the pairing problem. Finally, the dynamic diagrams assist users in developing manual solutions by showing which options are eliminated as individual pairing choices are made, in the same matrix format as automated solutions are presented. Different solutions (manual versus automatic) are rolled-up in a summary display that compares the results of sensitivity studies (manual versus automatic) to help users manage the High Uncertainty of the pairing problem.

As described above, these dynamic diagrams offer both a general approach to designing visualizations and a specific application to the C2 problem of WTP in TCT. Here we suggest that a similar approach can be applied to other C2 decisions, especially the HHH decisions highlighted in this study, which are the most challenging (according to our ratings) and hence the most in need of advanced support system designs.

5 Conclusion

C2 decision making situations can range from less complex to more complex, depending on the nature of the underlying information and the challenge of the decision making task itself. In this paper we analyzed decisions in three C2 functions/systems and characterized the Dimensionality, Temporality and Uncertainty of the associated information. Our results highlight the least complex decisions, which we suggest are areas of opportunity for increasing automation. Our results also highlight the most complex decisions, which we suggest are areas of opportunities for improving visualizations – to help human decision maker deal with the complexities of High Dimensionality, High Temporality and High Uncertainty.

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Appendix A: Decision Ratings

TCTF	Decision	D	T	U
T1	Aggregate sensor returns to form tracks	H	H	H
T2	Aggregate Intel to form target ID	H	H	H
T3	Nominate emerging target	L	H	H
T4	Determine level of additional Intel required	L	H	H
T5	Determine required sensor coverage	H	H	L
T6	Validate target	H	L	L
T7	Determine if target is TCT	L	L	L
T8	Determine target status if doesn't fit categories	H	H	L
T9	Prioritize weapon platforms	H	H	H
T10	Determine potential for collateral damage	H	L	H
T11	Prioritize munitions	H	L	H
T12	Select from weapon platform choices	H	H	H
T13	Optimize WTPs	H	H	H
T14	Determine status of deferred targets	H	H	L
JSTARS	**Decision**	**D**	**T**	**U**
J1	Determine if possible track	H	H	H
J2	Determine if continue refining track	L	L	H
J3	Determine radar schedule	H	H	H
J4	Determine if initiate track	L	H	H
J5	Determine if track is valid	L	L	H
J6	Send to AOC	L	L	L
J7	Determine where to find additional Intel	L	H	H
J8	Develop Target	L	L	L
J9	Determine if asset is under team control	L	L	L
J10	Assign assets to targets	L	L	L
J11	Determine where to direct attention	H	H	H
AWACS	**Decision**	**D**	**T**	**U**
A1	Receive handoff	L	L	L
A2	Evaluate mission and current situation	L	L	L
A3	Determine where to direct asset	H	H	L
A4	Select interceptor to divert	H	H	H
A5	Evaluate need for asset to be directed	L	H	L
A6	Determine direction schedule	H	H	L
A7	Determine if friendly routes conflict	H	H	L
A8	Determine if enemy will threaten	H	H	H
A9	Determine where to direct attention	H	H	H
A10	Direct assets to target	L	L	L