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AC/243(Panel 8)TP/7

IMPROVING FUNCTION ALLOCATION FOR INTEGRATED SYSTEMS DESIGN

Panel 8 on the Defence Applications of
Human and Bio-Medical Sciences

RSG.14 on Analysis Techniques for
Man-Machine Systems Design

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A Committee drawn from members of P.8/RSG.14 organized a workshop on function allocation on 29-30 November 1994, in Soesterberg, The Netherlands. The purpose of the workshop was to bring together human factors specialists from academia, government, and industry, as well as engineers and project managers, to discuss function allocation. Twenty presentations on function allocation provided the basis for discussions on: the state-of-the-art, needs for research, and promising approaches which could be used by practioners.

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TECHNICAL PROCEEDINGS
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DEFENCE RESEARCH GROUP

PANEL 8 ON THE DEFENCE APPLICATIONS OF HUMAN AND BIO-MEDICAL SCIENCES

Technical Proceedings of the Workshop on Improving Function Allocation for Integrated Systems Design

1. This is the Proceedings of the Workshop on Improving Function Allocation for Integrated Systems Design organized by AC/243(Panel 8/RSG.14) on Analysis Techniques for Man-Machine Systems Design at TNO Human Factors Research Institute, Soesterberg, The Netherlands on 28-30 November 1994.

2. The Executive Summary ("Yellow Paper") has been distributed under reference AC/243-N/426 dated 1 February 1995.

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PREFACE

Typically, decisions about the roles, functions and tasks performed by humans in a system are made implicitly in the design process through the selection or development of equipment and software. While this approach is logical, in that mechanization is usually beneficial (Chapanis, 1970), such decisions can ignore the systematic consideration of the capabilities and limitations of humans and how these affect the performance of the system. Function allocation is "the process of deciding how system functions shall be implemented - by human, by equipment, or by both - and assigning them accordingly" (Beevis, 1992). Function allocation tries to balance attempts to mechanize or automate as many system functions as possible by seeking roles and tasks for humans which make best use of their capabilities but which avoiding human limitations.

Function allocation is one of several iterative stages in the implementation of ergonomics or human factors engineering in the design of human-machine systems (Figure 1). Function allocation provides the basis for subsequent human factors efforts relating to operator task analysis and description, operator performance analysis, display and control selection or design, and crew-station design, development, and evaluation.

The concept of function allocation is usually attributed to the suggestion by Fitts in 1951 that system functions could be assigned by identifying those areas in which man is superior to machine and vice versa (Kantowitz & Sorkin, 1987). By the late-1950s, this approach had been incorporated in a number of human factors engineering guidelines (Javitz, 1956; Starkey, 1959; Van Cott & Altman, 1956). It was soon recognized, however, that functions should not be allocated on the basis of a direct comparison of human and machine capabilities, because machines are built to complement humans not to duplicate them (Fitts, 1962; Jordan, 1963). Since then, several different approaches have been advocated (Singleton, 1974):

- comparative assessment of human and machine performance
- economic cost comparisons of human and machine
- design of tasks to exploit complementary human and machine characteristics
- grading of human tasks to match individual differences
- basing human functions on system functions and supplementing them with machines
- permitting humans to vary their degree of participation in the system through flexible delegation of computer facilities.

Throughout this evolution, opinions have varied widely about the utility of function allocation. It has been described as "one of the first and most important problems in man-machine systems design" (Chapanis, 1965), but one which was not helped by the general statements about human and machine capabilities. Function allocation has also been described as a "fiction" and an "artifact," a "purely" post-hoc, descriptive analysis generating few, if any, particular results" (Fuld, 1993). Kantowitz and Sorkin (1987) noted the following problems in application:

- users consider comparative tables little help in accomplishing function allocation in real systems;
- designers of real systems complain about the lack of allocation algorithms; and
- the final version of a design seldom looks like the function allocation table.

This last observation suggests that the techniques used lack predictive validity.

Despite these problems, many human factors texts continue to illustrate only the earliest approach to function allocation using a tabular comparison of human and machine abilities (US DoD, 1987). Kantowitz and Sorkin (1987) have suggested that designers continue to use tables of relative merit either because they do not find criticisms of the approach convincing, or "because they are not familiar with anything better."

Surveys of applications show a lower level of use of formal comparative function allocations than techniques such as operator task analysis (Beevis, 1987). Kantowitz and Sorkin (1987) suggested that, in practice, straightforward human factors considerations must be 'balanced' against political, financial, managerial, and performance constraints. Meister (1985) suggested that these constraints should be addressed as the first of a five stage approach to function allocation.

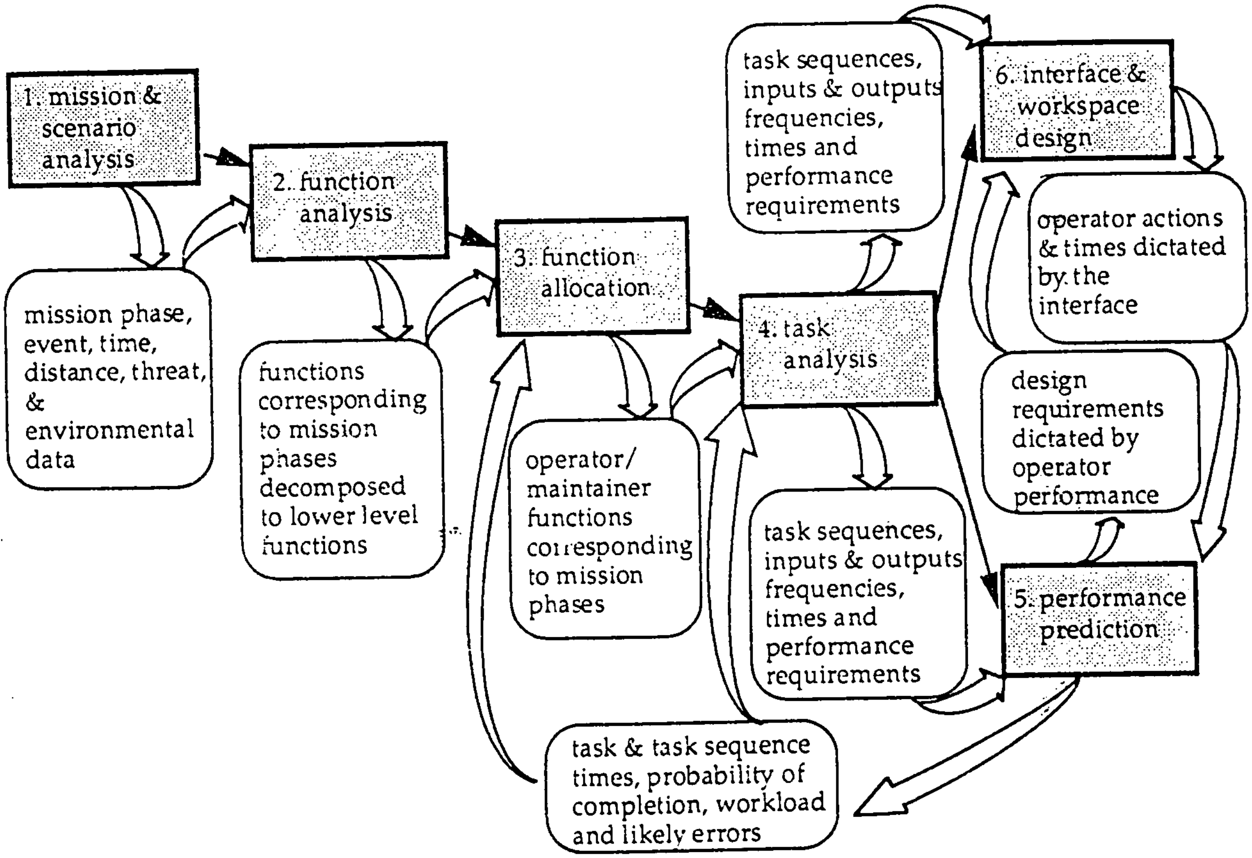

Figure 1: Relationship of function allocation to other human factors engineering activities

As discussed by Sheridan in the Keynote paper in these proceedings, the development of increasingly advanced system hardware and software makes the allocation of functions more complex than a simple dichotomous choice between human and machine. Price (1985) developed an approach in which the capabilities of humans and machines are rated on two orthogonal scales, but function allocation involves many other considerations.

It was with this background that Research Study Group 14 of the NATO Defence Research Group Panel-8 approached function allocation while reviewing the classes of human factors engineering analysis techniques shown in Figure 1 (Beevis, 1992). RSG.14 recognized that function allocation was the weakest of the classes of analysis reviewed: the techniques being recommended had not matured; most techniques used an ordinal level of measurement; few such analyses could be related directly to system performance requirements; and the procedures available for quality control were limited. At the same time RSG.14

recognized that function allocation is an important human factors technology; it integrates system and human requirements and technological opportunities.

The RSG decided to organize a workshop to assess the state of the art of function allocation and the need for research and development. The workshop was organized to bring together experts in human factors applications, systems engineering and project management. The aim of the workshop is to review: the need for function allocation; the maturity of available techniques; and the need for additional research in the area, and to make recommendations to human factors practitioners.

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CHAPTER 0

EXECUTIVE SUMMARY

0.1 SUMMARY OF THE WORKSHOP

In 1992, NATO AC/243 Panel 8/RSG.14 completed a review of human engineering analysis techniques Beevis, 1992). In concluding its work, the RSG recommended that a workshop be organized to review the topic of function allocation, which was the weakest of the techniques reviewed. Function allocation is "the process of deciding how system functions shall be implemented - by human, by equipment, or by both - and assigning them accordingly" Presentations on function allocation were solicited from the nations which participated in RSG.14, and a workshop was organized and held on the 29 and 30 of November 1994. Twenty presentations made by human factors specialists from academia, government and industry, by engineers and by project managers reviewed the state of the art in function allocation. Those presentations provided the basis for workshop discussions on areas where further research is required, and on promising approaches to function allocation which can be used by practitioners.

0.1.1 Background

As weapon systems become more sophisticated and pressure to reduce military manpower increases there is a risk that the unique skills and abilities of humans may not be exploited as effectively as they could be, thus degrading the potential performance of a system. At the same time there are growing concerns about the operation of highly automated systems by humans and about their ability to respond appropriately in stressful, time-critical situations. Human engineering is the specialty within the project systems engineering effort that is aimed at the integration of the human with hardware and software sub-systems through analysis, simulation, test and design (Beevis, 1992). Function allocation is an essential step in human engineering (see Figure 0.1) and is required, for example, by NATO STANAG 3994AI (Application of Human Engineering to Advanced Aircraft Systems) and by NATO AC/141 (IEG/6) SG/8 Allied Naval Engineering Publication (ANEP) 20 (Human Factors/Ergonomics in the Development and Acquisition of Ships and Ship Systems).

Function allocation decisions define the roles, functions, and tasks performed by human operators and maintainers. Thus, function allocation is linked to issues of automation and manpower reduction, as well as to questions about human responsibility for the safe and effective operation of a system. For these reasons some human factors specialists argue that function allocation is the most important step in human engineering. Reviewing function allocation techniques, AC/243 Panel 8/RSG.14 concluded that: those available were limited; those recommended in the human factors literature had not matured; most techniques used an ordinal level of measurement; few such analyses could be related directly to system performance requirements; and the procedures available for quality control were limited. It was for these reasons that the RSG recommended that a workshop on function allocation should be organized.

The presentations made at the workshop lead to discussions of applications, of techniques for function allocation ; and of issues in function allocation. Examples of applications which were reviewed included aircraft, ships, land vehicles, and command and control systems. Some applications of automation which were reviewed permit flexible re-allocation of functions depending on the operator's tasks or mission events. A video presentation of an aircraft control system designed to permit flexible allocation of function between pilot and aircraft demonstrated clearly the potential for systems.

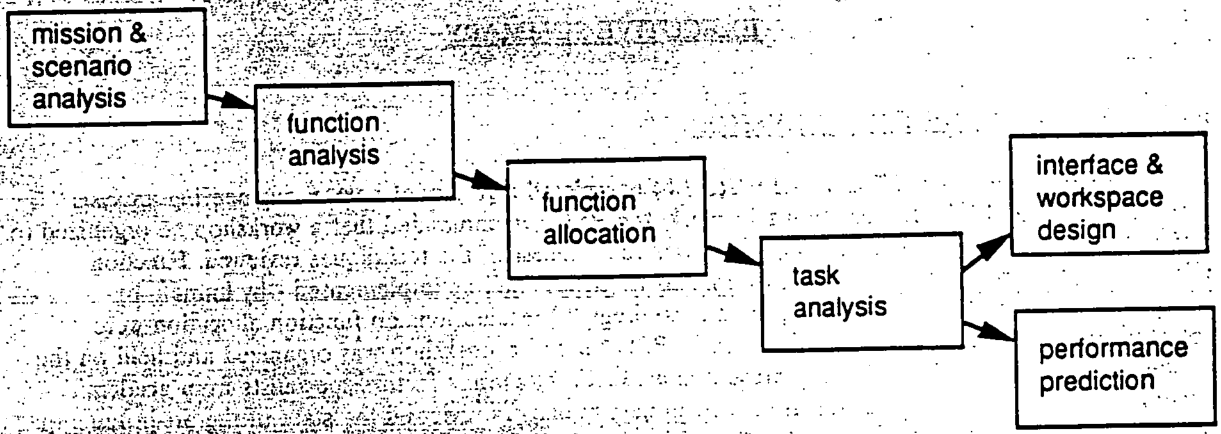

Figure 0.1: The sequence of human engineering analyses

Reviewing the techniques available it was agreed that function allocation is essentially a creative process associated with the design of a system. As such, function allocation does not lend itself to automation, although computer-based tools can facilitate the process. Function allocation techniques which were reviewed included a simple dichotomous choice between human and machine, a two-stage allocation process, iterative modification of function allocations, and reverse engineering of operator tasks.In general, it appeared that users of the techniques compensate for the predictive weakness of available function allocation techniques by concentrating on verifying the implications of the allocation decisions for system performance or operator workload. Methods used for this include computer simuations of operator workload-or-human-in-the-loop simulations, or trials using rapid prototypes or functional mock-ups to predict human or system performance.

It was recognized that many issues affect function allocation including rank, experience, and training parameters, costs, and commercial, legal and cultural constraints. Other issues which were raised with respect to function allocation included: the need to define clearly terms such as function and task when dealing with other engineering specialties; how to set about function allocation; the need to recognize that the allocation of functions between operators can change during a mission, and that 'static' allocations of function do not work well.

One of the major issues raised in the discussions was the question of the role of humans in advanced systems. Should the human monitor the system, given that humans are poor monitors? Should the system monitor the human, and if so, what roles should humans play and what are their responsibilities? Are humans included in systems just to deal with those functions which engineers cannot automate? How should humans and machines work together collaboratively? There are ethical issues associated with these questions which are particularly important in the design of weapon systems. Human failures, such as recent well-publicized incidents where friendly forces or non-combatants have been attacked, can be attributed and are considered the responsibility of the command chain. To whom should the failure of a highly automated sysem be attributed, when that system is designed to modify its behaviour on the basis of experience and the specific situation being played out? This question deserves more attention from all those responsible for the development and procurement of advanced weapon systems.

0.2 MAIN CONCLUSIONS

Based on the discussions outlined above, the workshop drew the following conclusions:

- It was agreed that function allocation is the key process for solving problems associated with human error, system unreliability, and human -machine mismatch, because it seeks to integrate and balance functional requirements specifications with human possibilities and technological opportunities. Function allocation is not an isolated, stand-alone activity, but is one that must be included in the analysis - design - evaluation process.

- The meaning of 'function allocation' differs according to the practitioner: it means different things to the systems engineers with whom human factors engineers must collaborate. The terms 'function' and 'task' also have different meanings depending on the user.

- Function allocation is not an isolated activity, but is intrinsic to an iterative process of analysis - design - evaluation for developing human-machine systems. It must be incorporated in the development process early enough to influence design decisions and to permit iteration.

- No single technique is available which deals with all of the issues involved in assigning functions to humans. Those issues include: effectiveness; reliability; cost; feasible level of automation; personnel selection, training and experience; team effectiveness; and economic, political and cultural constraints.

- Because available allocation techniques are essentially qualitative, function allocation decisions must be validated by predictions of operator workload and system performance, and the allocation decisions revised if necessary. Therefore, within the iterative design process, function allocation requires its own iterative approach to evaluate and refine the decisions made.

- The workshop papers demonstrated that there is an awareness of human factors engineering issues and of current HFE techniques. Judging by the presentations, however, little research activity is devoted currently to human behaviour in systems operation, or to improving HFE techniques.

- Several important research issues relate to function allocation. Chief of these are: research into adaptive function allocation and the role of humans in highly automated weapon systems; research into the validity of methods for testing the implications of function allocation for system performance and operator workload; the development of a taxonomy of function allocation issues which relates factors affecting function allocation to the problem domain and to available function allocation techniques.

0.3 MAJOR RECOMMENDATIONS

Based on the above conclusions, the following recommendations are made to Panel 8 and the DRG:

- No one function allocation technique can be recommended for use by practitioners. Several viable techniques are described in these proceedings, and practitioners should select a particular technique based on the requirements of each specific application.

- To provide more rigorous means of validating function allocation decisions, Panel 8 should support research into the validity of current workload prediction techniques, the relationship of workload to system performance, the use of computer simulations of networks of operator tasks and the validity of extrapolating from such predictions to conclusions about system performance, and the potential of virtual reality simulations for validating design decisions.

- Collaborative work should be directed towards the development of a taxonomy relating factors affecting function allocation to the application domain and to available function allocation techniques. Research into adaptive allocation of function is also recommended.

- Collaborative research should also be undertaken into the role of the human in weapon systems having a high degree of autonomy, and the implications of treating the human being as a system component compared to treating the system as a means of supporting human responsibilities.

0.4 MILITARY IMPLICATIONS

The following are the military implications of the workshop:

- Given that manpower is an increasingly limited and expensive resource, and that the human elements have a large influence on the life cycle costs, effectiveness, reliability, and readiness of weapon systems, the allocation of functions between humans and machines is of major concern in the design of advanced weapon systems.

- Viable approaches for function allocation are available and can contribute to the development of advanced systems, provided that they are applied at the correct point in the human engineering process (as specified, for example in STANAG 3994 AI and ANEP 20).

- The development of advanced technology involving decision aids and/or autonomous decision sub-systems poses problems concerning the roles and functions of humans which are not fully understood at this time. The implementation of such technology should be carefully evaluated.

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A historical perspective on allocation of functions between humans and machines is offered. CUrrent taxonomies and paradigms are reviewed. Currently popular topics which impact function allocation are discussed.

CHAPTER 1

ALLOCATING FUNCTIONS AMONG HUMANS AND MACHINES

T.B. Sheridan

1.1 ASSUMPTIONS

First, let us make some assumptions about human-machine function allocation (where *function* is taken here to mean essentially the same thing as *task*: though some people prefer a decomposition of mission into functions, and functions into tasks):

1. Optimum allocation of functions is easy, IF one has well-defined, mathematical equations for behavior of all human and machine functional elements, AND an objective function inclusive of all salient variables is also available in mathematical form. Then all one has to do is find a simultaneous solution of these equations. This is essentially what all formal optimization does. Unhappily these equations are seldom, if ever, available.

2. Human machine systems are getting steadily more complex, referring to military command and control systems, domestic transportation and traffic control systems for air, sea, rail and highway vehicles, hospital systems, business and government information systems, etc. (Complexity, may be defined, for example, by the Kolmogorov (1987) algorithmic information measure, the shortest possible binary string sufficient to describe the parts of a system plus those sufficient to assemble the parts and perform the essential operations of the system.) In addition to this complexity is the fact that human-machine systems are getting steadily more *distributed* , meaning that multiple, isolated agents communicate over noisy, delayed channels to allocate resources held in common (Figure 1.1).

3. There is no commonly accepted allocation methodology (and I'm not going to propose one).

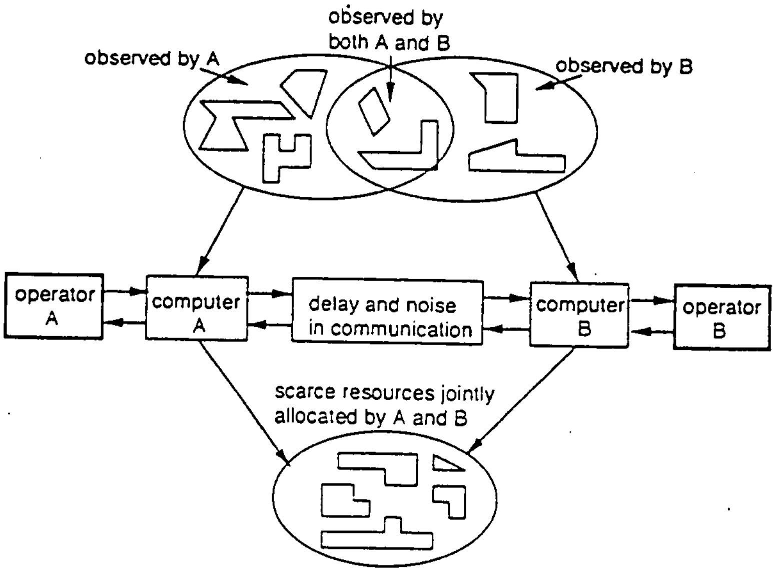


Figure 1.1: Distributed decision making (from Sheridan, 1992)

It is an accepted fact that automation is getting better all the time. However, this means (Kantowitz & Sorkin, 1987) that:

1. The human must become a monitor of automation. However, it is well known that the human is a poor monitor -- unless aided in certain ways which are discussed below.
2. Increased automation means increased training requirements.
3. Newly automated systems have bugs.
4. Failure of automation leads to loss of credibility and trust.
5. Designers tend not to anticipate new problems that automation brings with it (e.g., mode errors and feelings of alienation, both aspects to be discussed below).

1.2 HISTORY: COMPARISONS AND TECHNIQUES

Historically, Fitts (1951) was among the first to suggest criteria for allocating functions among people and machines. My abbreviation of Fitts' List is shown below in Table 1.1.

Table 1.1: Fitts' List

People are better at:
- Detecting small amounts of visual, auditory, or chemical energy
- Perceiving patterns of light or sound
- Improvising and using flexible procedures
- Storing information for long periods of time, and recalling appropriate parts
- Reasoning inductively
- Exercising judgment

Machines are better at:
- Responding quickly to control signals
- Applying great force smoothly and precisely
- Storing information briefly, erasing it completely
- Reasoning deductively
- Doing many complex operations at once

Many others followed Fitts' lead. Meister (1971) suggested a straight forward procedure: (1) write down all the mixes of allocation; (2) write down all the applicable criteria. Following this one could rank order all combinations of allocation mix and criteria (how well each allocation met each criterion), thus determining a rank order score. Alternatively one could weight the relative importance of each criterion, rate each mix on each criterion and multiply by the weight, then add up the scores for each allocation mix. The difficulties in any such direct methods include: hidden assumptions, unanticipated criteria considerations, non-independence of criteria, and nonlinearities in importance functions (invalidating the simple multiplication of weight x rating). Price (1985, 1990) provides more recent reviews of the function allocation problem.

Combining automatic with human functions has seemed the obvious solution. After all, humans and machines seem complementary in what each does best. The cost of combining, of course, is the overhead of communicating between them (in terms of the recoding and the display and control device software and hardware to move information from one to the other).

Analysis of a given job in terms of task and/or functional elements, and their logical and temporal sequences, is amenable to many techniques used by industrial engineers for years. These go by many names, but most fit relatively simply into several categories: (1) operations / flow process diagrams, similar to the now common flow charts of computer software, which show the sequencing of logic or causality and also permit feedback loops; (2) body, hand and eye movement maps, showing what moves where in two (or even three) dimensional space; (3) time lines, that show which human or machine element performs what action at what time, where time is a vertical or horizontal axis (time lines have difficulty with feedback loops); (4) transition frequency / association networks and matrices (Markov models); and (5) dynamic computer simulations which play out these operations in space and time on computer-graphic screens and in some cases even enable the observer to be 'there' through virtual reality.

The Petri net is a relatively new version of (1), now used by manufacturing engineers to simulate which machine is performing which function when. Figure 1.2 shows an example.

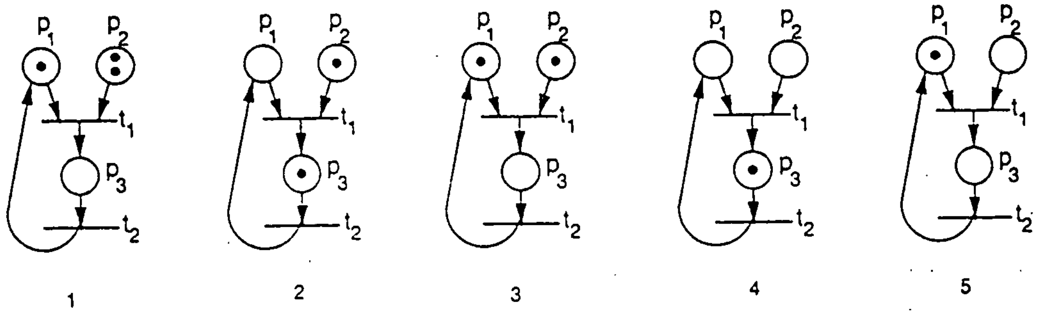


Figure 1.2: Example of how a Petri net works. *Tokens* (dots) t_i at different *places* (circles) p_j signify status of different variables in a system. For example, let tokens at p_1 and p_2 in the first diagram (1, left) signify the availability of a robot and parts to be handled, respectively, and p_3 signify that the robot is in operation. *Transitions* (bars with arrows) are events. For example let t_1 start the robot moving a part, and t_2 end that operation. When every input place to a transition is *marked* (has at least one dot), that transition is *enabled* to fire on a clock cycle, at which time one token is removed from each input place and one token is added to each (possibly many) output place. On the first cycle (1) only t_1 is enabled. At (2) transition t_2 is enabled. At (3) t_1 is again enabled. At (4) t_2 is enabled, and the transition to (5) ends the activity. [After diCesare & Desrochers, 1991.]

Levis et al. (1994) make use of Petri nets to model concurrent execution of tasks by people and machines in teamwork operations, and to evaluate alternative organizational and communication structures. An example is in control of aircraft from leaving the gate though taxi to the point of takeoff, and the reverse, and whether a fixed allocation of terminals and gates to each ground controller is better or worse than a more flexible one which changes with time and tries to balance workload. However, as Levis et al. point out, currently available techniques do not model dynamic transitions from one allocation to another; this is a topic of current research.

A recent large-scale application of task analysis was made to every nuclear power plant in the US, mandated by the government following the accident at Three-Mile Island. What was particularly interesting to the writer, who participated in many of these, was the difficulty plant personnel had in considering at each task step what information the operator needed and what process variable(s) had to be controlled by what criteria. Many of the analysts could envision the tasks only in terms of what display and control devices already existed, so the task analysis was conceived in terms of what operators looked at and what they manipulated. The analysts often seemed unable to consider what alternative and potentially better ways there might be to display the required information and control the salient variables, which of course is the basic purpose of task analysis.

1.3 SUPERVISORY CONTROL

What has clearly been happening, ever so quietly (cynics might say insidiously) is that computers have been insinuating themselves into systems: automobiles, medical devices, industrial machinery, home appliances, and of course military systems. In these systems the computers perform data processing for sensing, providing advice (expert systems and decision-aids) and decision-making, in many cases closing control loops through artificial sensors and actuators without any human intervention. This moves the human to a new role of being a supervisor rather a direct or 'inner-loop' controller. As a supervisor he or she operates at a higher-level than in direct manual control, or in an 'outer loop'. The supervisor observes computer-based displays and gets advice in the form of integrated information rather than raw data, and gives instructions (goals, constraints, procedures, suggestions) in high-level (more human) language to a relatively intelligent machine capable of understanding more complex strings of if-then-else instructions and implementing them in the physical world. The use of the 'flight management computer system' in a modern commercial aircraft is a good example, but one can cite other examples in a variety of systems from hospitals to chemical plants to undersea and space robots. Sheridan (1992) provides detailed examples and theoretical discussion of supervisory control.

Figure 1.3 considers systems of various levels of automation performing tasks of various degrees of complexity (entropy or unpredictability), and how some of these are undesirable (e.g., menial labor, in the lower left corner), and some are currently not possible (e.g., ultimate robot, in the upper right corner). The upper left and lower right corners offer satisfactory solutions. Supervisory control is seen as a range of technology-enabled options progressing gradually from lower left to upper right. Several examples are given.

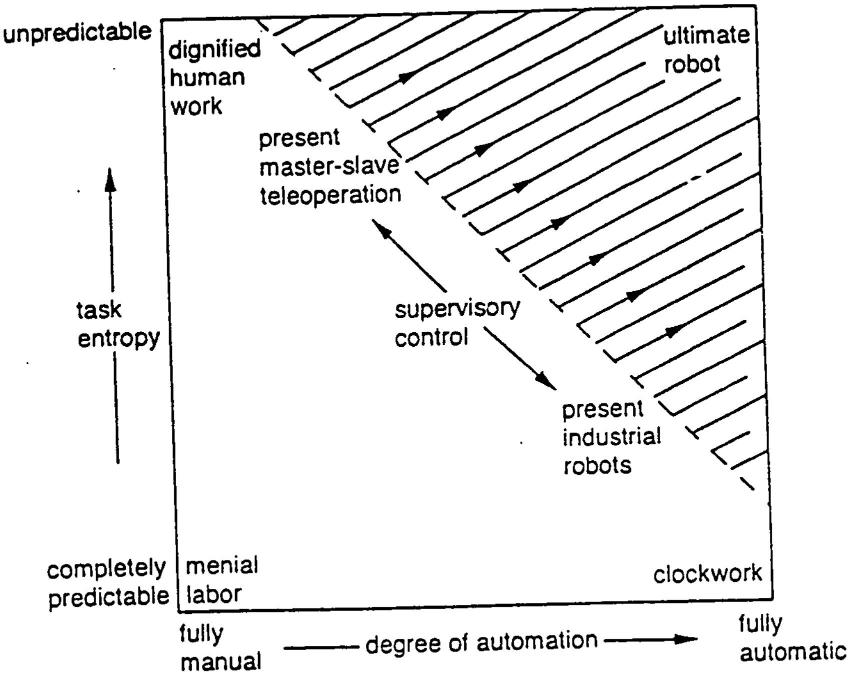


Figure 1.3: Systems of various levels of automation performing tasks of various degrees of complexity entropy or unpredictability (from Sheridan, 1992)

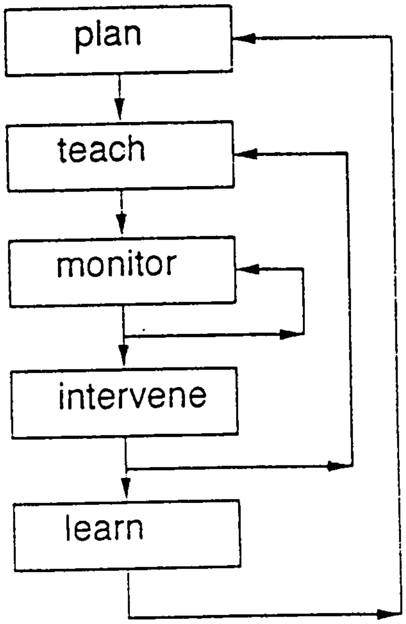


Figure 1.4: Roles of the supervisor

Table 1.2: Detailed breakdown of supervisory roles

SUPERVISORY STEP	ASSOCIATED MENTAL MODEL	ASSOCIATED COMPUTER AID
1. PLAN		
a) understand controlled process	physical variables: transfer relations	physical process training aid
b) satisfice objectives	aspirations: preferences and indifferences	satisficing aid
c) set general strategy	general operating procedures and guidelines	procedures training and optimization aid
2. TEACH		
a) decide and test control actions	decision options: state-procedure-action implications; expected results of control actions	procedures library; action decision aid (in-situ simulation)
b) decide, test, and communicate commands	command language (symbols, syntax, semantics)	aid for editing commands
3. MONITIOR AUTOMATION		
a) acquire, calibrate, and combine measures of process state	state information sources and their relevance	aid for calibration and combination of measures
b) estimate process state from current measure and past control actions	expected results of past actions	estimation aid
c) evaluate process state: detect and diagnose failure or halt	likely modes and causes of failure or halt	detection and diagnosis aid for failure or halt
4. INTERVENE		
a) if failure: execute planned abort	criteria and options for abort	abort execution aid
b) if error benign: act to rectify	criteria for error and options to rectify	error rectification aid
c) if normal end of task: complete	options and criteria for task completion	normal completion execution aid
5. LEARN		
a) record immediate events	immediate memory of salient events	immediate record and memory jogger
b) analyze cumulative experience; update model	cumulative memory of salient events	cumulative record and analysis

The roles (categories of functions) of the supervisor may be considered: (1) planning, usually done off-line, with the aid of the computer and displays in a simulation mode; (2) teaching (programming) the computer with appropriate goals, constraints, procedures and suggestions; (3) putting the system (or parts of the system) into automatic mode when ready and monitoring its operation for abnormalities; (4) intervening in the case of perceived abnormalities to diagnose failures, reprogram to alternate automatic control modes, perform direct manual control, or abort the mission, as appropriate; and (5) learning from experience, so as to improve the planning for future operations. These roles are seen in Figure 1.4 to be nested at three levels, the monitoring taking place in a tight feedback loop, the intervention leading to reprogramming, and the learning resulting in improved planning. Table 1.2 breaks these functions into greater detail.

In 1978 the writer proposed a ten point scale of degrees of computer involvement:

Table 1.3: Scale of degrees of computer aiding

1. The computer offers no assistance, human must do it all.
2. The computer offers a complete set of action alternatives, and
3. narrows the selection down to a few, or
4. suggests one, and
5. executes that suggestion if the human approves, or
6. allows the human a restricted time to veto before automatic execution, or
7. executes automatically, then necessarily informs the human, or
8. informs him after execution only if he asks, or
9. informs him after execution if it, the computer, decides to.
10. The computer decides everything and acts autonomously, ignoring the human.

From considering the scale it is clear that there is little difficulty in moving new systems part way down the scale, but going all the way raises some serious questions.

1.4 CURRENT POPULAR RESEARCH TOPICS WHICH IMPACT FUNCTION ALLOCATION

The following are some popular topics which seem particularly related to human-machine function allocation:

1. *Attention allocation and mental workload*

Mental workload has been a popular topic for more than a decade, but the interest today is largely on the problem of workload transients (Huey & Wickins, 1993). Workload transients occur when automatic or semi-automatic systems go awry, or fail to control unexpected events, and the human monitor or supervisor has a difficult time to diagnose the problem and take proper action. In such cases the workload changes suddenly from very low to very high. Measurement of these transients is particularly difficult, because most physiological and secondary task techniques require sampling over a time period of minutes, and subjective scaling also becomes awkward when things are changing rapidly.

The need is to smooth out the pace by anticipating times of high workload and getting things set up early, for example in getting ready for let-down and approach in landing an aircraft. Pilots call it 'keeping ahead of the airplane'. In emergencies, nuclear power plant operators take actions just to 'buy time' and allow themselves a longer period to perform diagnoses and insure that their response is appropriate.

Tulga simulated and modeled such a situation with a paradigm such as that shown in Figure 1.5, where random blocks (representing tasks) appeared on a computer screen at different distances from a vertical 'deadline' on the right, and moved at constant velocity toward it. The duration of the task was the block's width; its relative importance, the reward per unit time for doing it (by various means such as holding a cursor on it), was the block's height. Tulga found that subjects in this task were objective and even near to optimal in their attention and effort allocation - up to a point of high workload - and then they simply paid attention to what was nearest to the deadline regardless of relative importance.

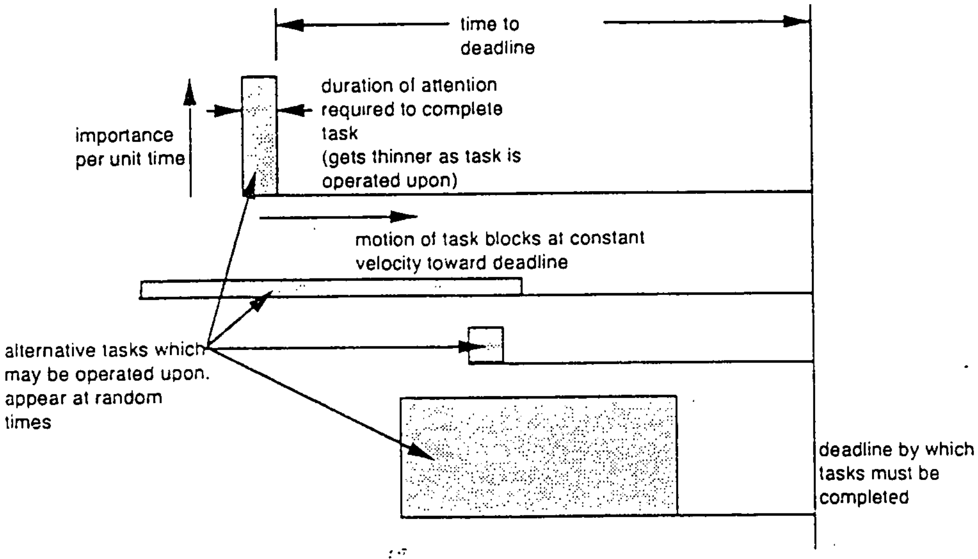


Figure 1.5: Temporal allocation of attention among tasks (Tulga experiment)

A related problem of particular interest is the 'nesting' of stimulus and required response, where first notice of a required action, say A is shortly followed by notice of required action B, where the deadline for B comes sooner than that for A. If the operator is not sufficiently reminded of A, the result is often that B is taken care of, but A is forgotten. Such nesting can sometimes be several layers deep, with disastrous results.

2. *Situation awareness*

There is currently great interest in 'situation awareness', the ability of the operator to keep track of many things at once, to integrate them, and to diagnose when events are turning abnormal or threatening. It is a problem exacerbated by automation, though possibly a problem that can be helped by computers - in the form of 'expert systems', decision aids, and reminders - to direct the operator's attention while monitoring. Failure to remain situationally aware has resulted many kinds of errors, most salient among them mode errors, where operators forget what mode some automatic system his been placed into. In a well-known Airbus accident near Strasbourg, the pilot interpreted numbers on the computer display to mean one thing when they meant something entirely different; the pilot had forgotten which mode he had set the aircraft into.

Experience in any type of human task results in behavior which becomes automatic, and which does not require as much conscious deliberation as during initial learning. One might conclude that this gives the operator more time to scan and be aware of the surrounding situation, but by the same token such 'downloading' of tasks elements and lowered self-consciousness can result in situational unawareness.

3. *Humans and computers keeping running models of each other*

Mental models have been a popular topic in cognitive psychology for a decade, the term mental model usually meaning some mental representation of objects in the external world associated with a task which can be 'run' dynamically to predict what will happen if current conditions are extrapolated, or what would happen if certain hypothetical changes took place. There have been complaints that while hardware, e.g., the trajectory of an observed vehicle, is relatively transparent, the future action of a computer is not - the computer is a black box, and not transparent. For this reason some have suggested the importance of having the computer inform its human operators what it understands and what it therefore intends to do.

While the need for human communication with and modelling of the computer seems obvious, the need for the computer to have some representation or model of the human seems less obvious. However, were the computer able unobtrusively to find out and keep track of the operator's intentions, preferences, training, stress, and physical limitations, especially in times of absence or illness, it might be able to make more intelligent decisions, much as would a human colleague. Figure 1.6 suggests the notion of human and computer keeping running models of one other.

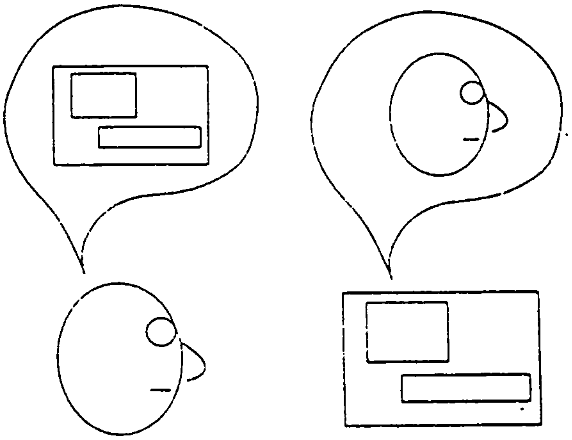


Figure 1.6: People and machines having models of each other

4. *Alienation from computers and automation*

Computers make problems for human operators not only functionally but in other ways as well, particularly when introduced abruptly and where the operator has little say in how and why the change occurred. Problems include: isolation from social contact, worry about employment, loss of skill and the associated dignity, intimidation of 'big brother watching', feeling of ignorance and helplessness, reduced trust in the situation, and reduced sense of responsibility - all of which clearly diminish the ability to function. Any of these factors, particularly loss of trust, can reduce the operator's willingness to make use of computer-based sensing, advising and automation modes which rationally could be to great advantage (Moray & Lee, 1990).

5. *Canonical theories of management applied to teams*

Allocating functions among the members of a team is a form of management (whether hidden in the system design or not) and so it is important to be aware of the various theories of management. An earlier view, variously referred to as 'scientific management' or 'theory X', was attributed to F.L. Taylor. Now definitely out of favor by industrial engineers, it considered the human to be a machine, and sought to define and measure performance quantitatively. Of course that is precisely what the human-machine systems approach seeks to do, but perhaps with some better appreciation of the humanistic character of the worker or operator.

Another theory, attributed to A. Maslow and F. Hertzberg and called 'theory Y', begins from the assumption that any worker works for personal rewards and satisfaction, and that good management amounts to enabling and empowering workers, and motivating them to develop individual initiative and potential. A scientific function allocation has a somewhat more difficult time with this perspective, and may merely regard it as unrelated or irrelevant, possibly leading to job allocations which seem rationally correct but are not satisfying and rewarding to the workers, with unhappy results.

The more recently popular 'theory Z', attributed to W. Ouchi and E. Deming, calls for development of consensus - including function allocation and reallocation - through shared goals and values, quality circles, and 'total quality management'. This approach militates against designing rigid systems by *a priori* function allocation, and favors allowing sufficient flexibility that allocation can always be refined by continued operator participation in problem solving and process improvement.

6. Human-machine system architectures

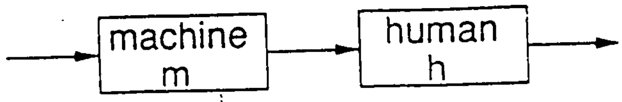
In consideration of all of the above factors, the system engineer must return to the problem of architecture for the human machine system, the question of how all the elements fit together and perform, and the implications of different function allocations on system performance.

Here, finally, we must decide whether, and for which functions, human and machine cooperate by 'trading', where human acts and then machine acts, back and forth, or by 'sharing'. In the latter the human and machine work in parallel, either redundantly doing the same job and later having these results compared as a check, or each does part of the job and the pieces are brought together in hopes that they will fit. The reliability analyst sees these alternatives in terms of whether the elements, be they human or machine, operate in series or in parallel, and what the reliability implications are (Figure 1.7). Perhaps the simplest notion is that various intelligent (human or computer-based automatic) agents are given freedom to perform their assigned functions as they will, and only when their behaviors conflict does the supervisor step in, inhibit one (or more as necessary) and enable the others to go ahead. This approach, called by Brooks (1986) a 'subsumption architecture' was shown by him to work for simple robots, but it broke down for systems faced with more sophisticated problems.

Ultimately the function analyst must face the question of which has authority under what circumstances, human or machine. It is comforting for us to assert that the human always has final authority, but at the same time we readily submit to getting into elevators and pushing their buttons, thus turning authority over to those machines, or spending the night in high rise hotels, trusting completely to the premise that strong winds won't blow them over. Figure 1.8 suggests some categories of programmed ultimate authority as a function of level of abnormality.

P(x) = P(x fails)

Series

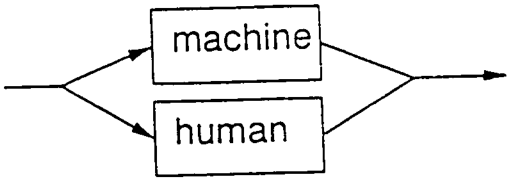


P(series combination succeeds) =
P(both m and h succeed) =

[1- P(m)]•[1- P(h)] if h failure independent of m,

[1- P(m)]•[1- P(h lm succeeds)] if h failure dependent on m

Parallel

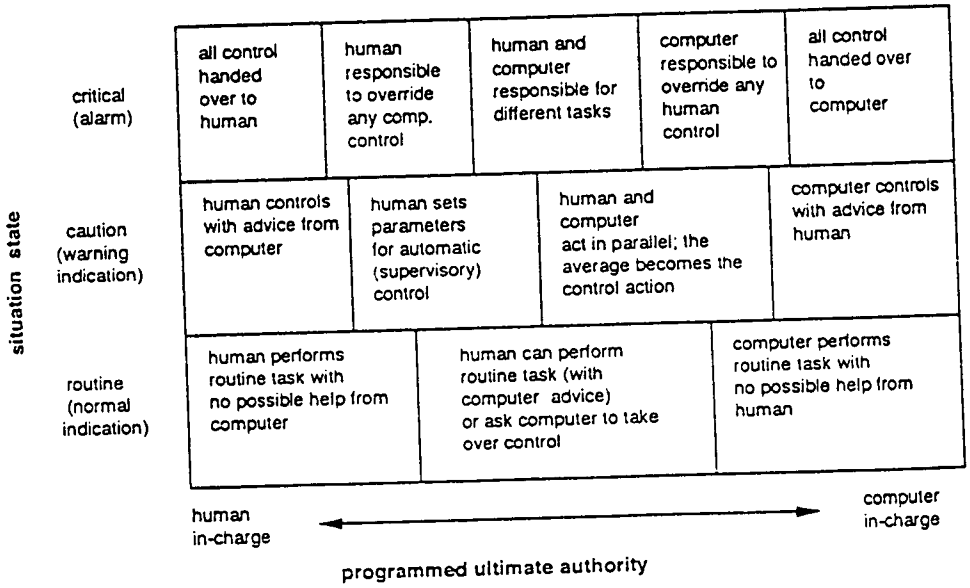


P(parallel combination succeeds) =
P(either or both m or h succeed) =
1 - P(both m and h fail) =

1 - P(m)•P(h) if h failure independent of m,

1 - P(m)•P(h lm fails) if h failure dependent on m

Figure 1.7: Reliability of functional elements in series and in parallel



critical (alarm)	all control handed over to human	human responsible to override any comp. control	human and computer responsible for different tasks	computer responsible to override any human control	all control handed over to computer
caution (warning indication)	human controls with advice from computer	human sets parameters for automatic (supervisory) control	human and computer act in parallel; the average becomes the control action	computer controls with advice from human	
routine (normal indication)	human performs routine task with no possible help from computer	human can perform routine task (with computer advice) or ask computer to take over control	computer performs routine task with no possible help from human		

Figure 1.8: Alternate allocations of authority among human and computer for different levels of criticality

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CHAPTER 2

WHY FUNCTION ALLOCATION AND WHY NOW?

J.R. Bost and F.R. Oberman

2.1 INTRODUCTION

Function allocation is the analytical process by which functions are logically assigned to be performed by personnel and/or machines. Function allocation is the first systems engineering process which addresses functions in terms of personnel. A comprehensive and measurable function allocation process is now needed to ensure optimum use of advanced automation technology and the role of human in future systems.

Criteria for formal function allocation was initially developed by Paul Fitts at Ohio State University in 1951. Table 2.1 shows an example of the original Fitts' List which compares the *capabilities* of human and machine. Dr. Fitts' view was that, by applying these criteria, an optimum allocation of functions between humans and machines could be achieved.

Table 2.1: Orginal Fitts' list (from Beevis, 1992; after Price, 1985)

Humans appear to surpass present-day machines with respect to the following:

1. Ability to detect small amounts of visual or acoustic energy
2. Ability to perceive patterns of light or sound
3. Ability to improvise and use flexible procedures
4. Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time
5. Ability to exercise judgment

Present day machines appear to surpass humans with respect to the following:

1. Ability to respond quickly to control signals, and to apply great force smoothly and precisely
2. Ability to perform repetitive, routine tasks
3. Ability to store information briefly and then to erase it completely
4. Ability to reason deductively, including computational ability
5. Ability to handle complex operations, i.e. to do many different things at once

These human-machine allocations provide the baseline for downstream efforts relating to control/display task requirements, workplace configuration requirements, workload requirements, and work station design and development. In addition, function allocation dictates crew workload and the role of human, thereby significantly defining manpower, training, and procedure requirements (Bost, 1986).

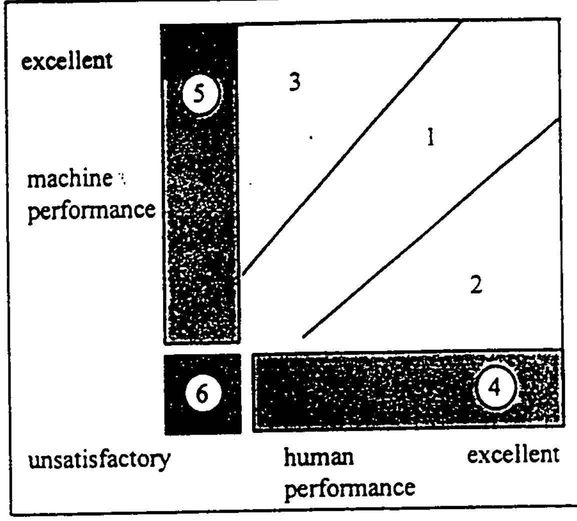
A common form of the Fitts' List used by the US Department of Defense (1987) is shown in Table 2.2. This format again emphasized direct comparison of *capabilities* which were then applied sequentially against defined system functions. Other versions of Fitts' Lists not only compare the *capabilities* of humans and machines but also the *limitations* of humans and machines.

Table 2.2: Common form of Fitts' list (US Department of Defense, 1987)

MAN EXCELS IN	MACHINES EXCEL IN
Detection of certain forms of very low energy levels	Monitoring (both human and machines)
Sensitivity to an extremely wide variety of stimuli	Performing routine, repetitive, or very precise operations
Perceiving patterns and making generalizations about them	Responding very quickly to control signals
Ability to store large amounts of information for long periods, and recalling relevant facts at appropriate moments	Storing and recalling large amounts of information in short time periods
Ability to exercise judgment where events cannot be completely predicted	Performing complex and rapid computation with high accuracy
Improving and adopting flexible procedures	Sensitivity to stimuli beyond the range of human sensitivity (infrared, radio waves, etc.)
Ability to react to unexpected low-probability events	Doing many different things at one time
Applying originality in solving problems: i.e., alternative solutions	Exerting large amounts of force smoothly and precisely
Ability to profit from experience and alter course of action	Insensitivity to extraneous factors
Ability to perform fine manipulation, especially where misalignment appears unexpectedly	Ability to repeat operations very rapidly continuously, and precisely the same way over a long period
Ability to continue to perform when overloaded	Operating in environments which are hostile to human or beyond human tolerance
Ability to reason inductively	Deductive processes

2.1.1 Issues and Alternatives

Problems with 1) sequential dichotomous applications (or the sequential selection of human or machine based on single capabilities or limitations) of Fitts' Lists 2) making human OR machine assessments, 3) the qualitative nature of assignments, and 4) the factoring in of political, managerial, financial, and performance constraints have seen evolutionary improvements in the development of function allocation criteria. The problem of sequential dichotomous application has been addressed by Price (1985) who proposed six different categories/regions of human-machine performance as shown in Figure 2.1.



The approach recognizes six different cases of human and machine capability.

- In region 1 there is little difference in the relative capability of human and machine, and function allocation decisions can be made on the basis of criteria other than relative performance.
- In area 2, human performance exceeds machine performance.
- In area 3, machine performance exceeds human.
- In area 4, machine performance is so poor that the functions should definitely be allocated to humans.
- In area 5, humans performance is so poor that the functions should be allocated to machine.
- In area 6, the functions are performed unacceptably by both human and machine, arguing for a different design approach.

Figure 2.1: Criteria for allocating functions to human or machine (from Beevis, 1992; after Price, 1985)

The problem of human OR computer allocation has been addressed, and criteria established (Sheridan, Vamos, & Aida, 1983). These options are:

(1) Offer no assistance to the operator.
(2) Offer a complete set of alternatives to the operator, AND
(3) Narrow the set of alternatives to a restricted set, OR
(4) Suggest one of the alternatives, AND
(5) Execute the suggestion if the human approves, OR
(6) Allow the human to veto the suggestion before automatic execution, OR
(7) Inform the human after execution, OR
(8) Inform the human after execution, if asked, OR
(9) Inform the human after execution, if the hardware and software decides to.
(10) The hardware and/or software decides everything without communication to the human.

In addition, Malone (1992) addressed this issue by restating the allocation process to define the role of human in *using* the system. This approach could be extended to define the role of human in the *design* of the system. The qualitative nature of assignments and the need for more sophisticated criteria have been addressed by Beevis (1992) and by Sheridan (1994).

Kantowitz and Sorkin (1987) developed a balanced approach to deal with political and managerial, as well as performance constraints. Meister (1985) has also developed a 5 stage balanced approach, as shown in Figure 2.2.

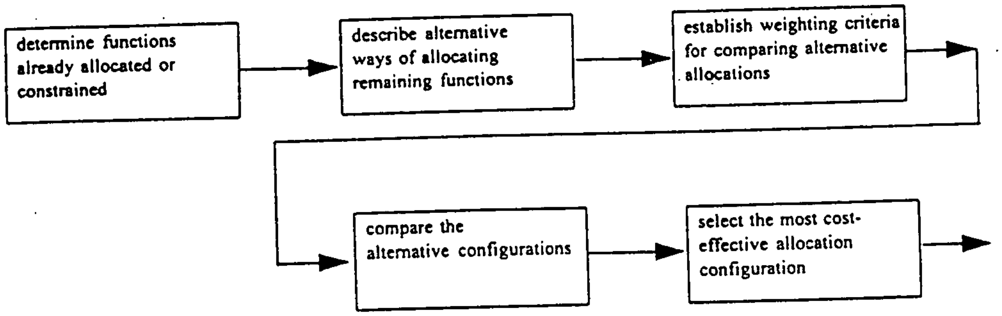


Figure 2.2: Five stage approach to function allocation (from Beevis, 1992; after Meister, 1985)

Another view of function allocation is in the approaches of R.W. Bailey (1982). Bailey categorizes three approaches to function allocation: 1) a comparison of the relative capabilities of humans and machines; 2) the automation of as many functions as technology permits with only the leftover functions being assigned to the human operator; and, 3) the use of economic allocation methods to emphasize cost constraints as a basis for the allocation.

The future of function allocation probably will be oriented towards a synthesis of the balanced approach and Bailey's three approaches, and in fact there can be synergistic benefits generated by these multiple objective approaches. The best alternative from a traditional comparison standpoint may also produce the best economic benefits. One way of approaching an optimal method of ensuring that function allocation is performed in a logical manner and produces the best economic benefit (long term and short term benefits should be determined separately) is to do a sequential function allocation study; first performing a traditional study, then performing an economic study comparing drivers and benefits via a decision/sensitivity analysis process.

2.2 COST BENEFITS

The explosion of information is leading toward more functions allocated to automation. The automation of functions will produce two major cost benefit incentives - the reduction of direct manpower and manpower support costs and the potential reduction of human error. There are enormous savings which can be achieved potentially in the area of manpower reduction. Within the US Navy (and dependent on the class of ships involved) manpower costs are up to 50% of life cycle costs. Bost (1994) believes that cultural changes in the way we design, acquire, and operate ships will be needed to bring about revolutionary reduction in ship manpower. More logical, cost effective function allocation tools are required to engineer the reduced manning savings. A key factor in this process is the recognition of the importance of the enormous cost of keeping manpower aboard the ship and in upgrading system automation and reliability in order to keep pace with and use advanced technology. Manpower costs in the US Navy also have a ship acquisition cost component, in that every person aboard a ship has an associated supportability component of 3-5 tons of ship displacement.

Another significant cost reduction factor in automating functions is in the reduction of human error since over 50% of mishaps are now classified as being due to human error.

2.3 DEGREE OF TRUST IN AUTOMATION

One of the key cultural changes which will have to take place to secure the manpower and accident reduction benefits associated with automation is for policies, procedures, doctrine, and perceptions to change with respect to trusting in automation. A first step is to produce automated equipment of sufficient reliability necessary to engender trust by the user. One discussion session at the First Automation Technology and Human Performance Conference produced the interesting analogy that in "Star Trek - The Next Generation" the android "DATA" is both perceived and treated as *a member of the crew.* That type of perceptual change must occur with respect to automated verses manual functions, i.e., there must be enough trust in the built-in reliability and performance of the automatic system to allow it to perform ship operations and missions. This will have profound and significant changes on doctrine and procedures, on the role of man, and on the redefinition of responsibility.

On the other hand, human must not become so complacent in using automation that normal monitoring does not take place. The recent Aeroflot Airbus crash where the pilot, who was found in the passenger compartment, left his son (who managed to disengage the autopilot) in the cockpit, is an example of poor judgment engendered by complacency with respect to the automatic pilot.

An answer is that the general situation should determine the degree of automation, e.g., chemical process control already has high degrees of automation. Yet in cases that are not time dependent, the human will still play the major role of decision maker/monitor.

2.4 AUTOMATION TODAY

One of the reasons that automation is able to provide these cost benefits is the current and near future state-of-the-art in this technology. Automation has advanced a long way since Fitts' initial concept was developed - a PC is now more powerful and faster than a main frame in 1951. Not only has the technology changed to allow implementing reduced manning concepts which were only espoused in the 1950s and 1960s but a new generation of computer-literate personnel will very shortly be available to implement the decisions and actions of the future. They will think in terms of the computer to accomplish these ends.

Not only has automation technology enhanced the speed and the performance of functions, it has also provided the same benefits to the development of human factors tools, including function allocation tools. Some papers presented by the US at this workshop will specifically deal with function allocation tools which make use of automated function allocation developed with respect to total system design and with respect to system re-engineering (Malone, 1992; Swartz, 1994). The capability to perform automated function allocation can now enable this human system engineering process to be performed and the results of the analyses to be used within the time constraints of design phases. Moreover when function allocation is performed in the conceptual phases of acquisition, data storage by electronic means, such as CD-ROM, allows the iterative updating of information to proceed in a cost effective, timely manner.

2.4.1 Future Research Questions

There are questions which come with the opportunities which will be available in implementing the function allocation methodologies of the future. Among the most important questions are:

(a) Should the review of earlier Fitts' Lists be undertaken to ensure that new technology has not altered the original comparisons?

(b) What is the role of human to be in future systems? Is human only to be a system monitor and let machines/automation perform most functions? If so how and by what criteria does human override computer operations?

(c) How does human decide when there is an automation malfunction? How will we ensure that systems will give human adequate time to both perceive a malfunction and to be able to initiate corrective action?

(d) If human is in control, should the decision as to when to go to automatic be standardized in doctrine or left open for individual action? What should be provided in the way of decision aids? Should we ever let the system be involuntarily taken over by automation? What would be the criteria for automation taking control? Should the operator be notified when automation has taken control?

(e) Function allocation will become more dependent on expert (opinion) systems in the future - what studies are now taking place with respect to validation and evaluation of results? What criteria have been established to determine the value of proposed function allocation tools? Have return on investment considerations been factored into current tool development?

(f) There are cultural differences in how automation is currently applied (R. Tefler, 1994). The European A320/340 AIRBUS, is flown with different degrees of manual and automatic control dependent on the countries/airlines operating it. Are cultural differences and diversity useful or should the degree of automation and when to use it be controlled or standardized?

(g) How should the problem of keeping controllers/decision makers proficient in manual (backup) operations be handled?

(h) Should automatic systems take over in periods of high workload from a human operator? (This assumes workload sensors will be required.) When should control be transferred back? Should this be a human decision or performed automatically? Should dynamic task automation (Hilburn, et. al., 1994) be considered?

(i) What status information should be displayed and how should it be displayed? Should it be under human control or should some status information be automatically displayed? If automatic, what should be displayed and when should it be displayed?

(j) In some new display systems new cognitive skills and cognitive pathways are required. What is being done to ensure that overall human-machine operational processing is improved with respect to accuracy and time?

(k) How do we evaluate alternatives? What criteria should be used? Can these criteria be further used to generate deterministic and/or probabilistic performance parameters? Can we now evaluate overall reliability of the human-machine system by using decision analysis and sensitivity analyses?

2.5 SYSTEM ENGINEERING CONCERNS

Although universities include human factors as an essential component of system engineering and include function allocation as a fundamental analytical process, this view of function allocation has *not* been incorporated in recent proposed revisions to the US military standard on System Engineering (MIL-STD-499B). There seems to be confusion between the analytical processes of requirements allocation and function allocation, i.e., requirements allocation which matches requirements against functions versus function allocation which matches functions against human-machine capabilities and limitations. This has resulted in no attention being given to human-machine comparisons. Human-machine analysis needs to be reiterated in this primary system engineering document.

2.5.1 Final Paradigm - Situational Management

There has been much discussion of Situational Awareness with respect to decision making and control. What is really needed is to suggest managing decision making and control with respect to two variables - available time and problem complexity. Moreover problem solving should not only involve human and computer, it should also involve *humans* and *computers* which gives the added benefit of group participation in complex problem solving that has been documented since the 1960s (Oberman, 1964) and is a recurrent theme in aircraft and commercial ship management today (Foushee, 1988). A general view of Situational Decision Management (SDM) is presented by the authors in Table 2.3. Figure 2.3 presents a situational assessment example in a diagrammatic format. This management model emphasizes the ultimate decision making, humans *and* computers, to be used when appropriate and still considers the paramount constraint of time as an overriding factor. In this model, time is the first decision point. If time is short, then the decison should be made the pre-programmed computer. If an intermediate time, the problem is broken down into simple or complex situation. The manager makes the decision directly if a simple situation. If complex, the group discussions the solution, and then a decision is made.

Table 2.3: Situational decision management

DECISION/ACTION AGENT	TIME AVAILABLE	COGNITIVE DIFFICULTY
1. Personnel and Software	Long	Complex
2. Individual Manager and Software	↕	↕
3. Software	Short	Simple

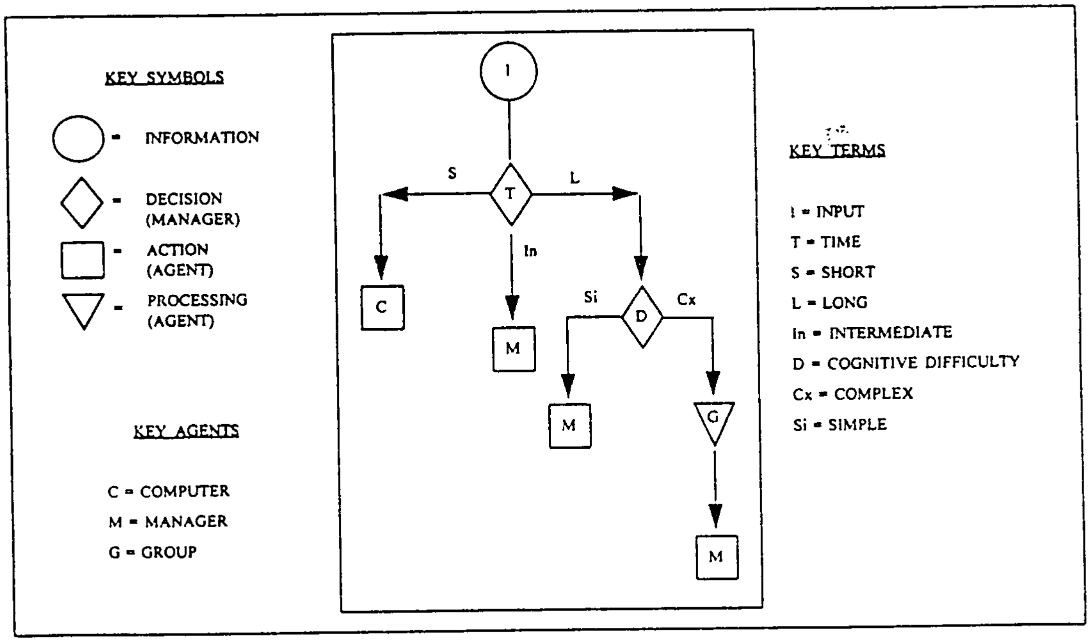


Figure 2.3: Situational assessment decision action diagram

2.6 SUMMARY

2.6.1 Why do Function Allocation?

We need to do function allocation in order to maintain logical and rational control of the human-computer process. We need to do function allocation to ensure that the role of human in future systems is well defined and understood. We need to do function allocation to provide the cost benefits of rational automation processes.

2.6.2 Why Now?

We need to do and improve function allocation now because we are at a technological crossroads engendered by the capabilities of software to reliably take over processes previously performed by humans. We need to do and improve automated function allocation processes now in order to be a part of this automation and information revolution. We need to make sure that function allocation is understood and stated as part of system engineering in key military and commercial standards because system engineering is and will be a major controller of how future automation is performed. Human systems engineering *must* remain a major player in the systems engineering process.

2.7 GLOSSARY

Fitts' List:	compares the capabilities and/or limitations of humans and machines
Automation:	the automatic operation or control of a process, machine, equipment, or system
Function allocation:	the analytical process by which functions are logically assigned to be performed by human and/or machine
Function:	an activity performed by a system (for example, provide electric power) to meet mission objectives
Human Engineering:	a specialized engineering discipline within the area of human factors that applies scientific knowledge of human physiological and psychological capabilities and limitations to the design of hardware to achieve effective Human-machine integration
Human Systems Integration (HSI):	the technical process of integrating the human operator with a materiel system to ensure safe, effective operability and supportability
Human-Machine Systems:	a composite of equipment, related facilities, material, software, and personnel required for an intended operational role
Situation:	is a set of environmental conditions and system states with which the participant is interacting that can be characterized uniquely by a set of information, knowledge and response options
Situational Awareness:	the up-to-the-minute cognizance required to operate or maintain a system

Situational Decision Management (SDM):	the situational assessment and decision process which includes function allocation and management action.
Systems Analysis:	a basic tool for systematically defining the roles of and interactions between the equipment, personnel, communications, and software of one or more systems
Systems Engineering:	a basic tool for systematically defining the equipment, personnel, facilities and procedural data required to meet system objectives

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The paper examines the application of functional allocation to modern defence systems from the perspective of the MANPRINT programme. It is based on the experiences of formulating a practical MANPRINT framework that allows system developers to design for the user in an efficient manner. Functional allocation is found to be applied throughout the development cycle rather than as a clearly identifiable event and methods for controlling and recording the logic of the allocation decisions are proposed. The traditional attribute list approach has been found to be unsuitable for many of our systems, and allocation on the basis of job design and workload predictions appears to be more appropriate. Finally a task database linked to probable user performance metrics is proposed as long term aim.

CHAPTER 3

FUNCTION ALLOCATION AND MANPRINT

M.K. Goom

3.1 INTRODUCTION

This paper examines the application of function allocation to modern defence systems from the perspective of the MANPRINT programme. It is based on the experiences of formulating a practical MANPRINT framework that allows system developers to design for the user in an efficient manner. It seeks to link the allocation process to some of the lessons that have been learned during the development of the MANPRINT programme within the Dynamics Division of British Aerospace.

The workshop is being held because function allocation has been identified as the weakest technology in the process of integrating users into defence systems. This paper attempts to show that in the real world function allocation (and MANPRINT) take place throughout system development. It does not exist as a discrete entity and, because of this pervasive nature, does not attract the attention that it should from system designers. Many of the practical considerations relate to the constraints on time and funding that often accompany the commercial development of a defence system. These constraints cause a focusing of effort on those aspects that can be shown to have a cost benefit, are likely to produce results in the correct time frame, and most importantly can be defined clearly enough to appear in a work breakdown structure (WBS). An additional practical consideration is the problem of obtaining an adequate definition of the end users from the customer.

The traditional Fitts' List approach to Allocation of Function (AoF) taught on many human factors courses is hardly sufficient for complex weapon systems. Ergonomists must recognise these practical difficulties and devise methods that are relevant to modern needs and can be applied throughout the development process. MANPRINT has the same aims as AoF in that it seeks to recognise the characteristics and capabilities of the constituent components of the system. MANPRINT's strength is the concern that it focuses on the detail of the end user. The practical methodology BAe has produced in response to the MANPRINT requirement provides useful indicators for the AoF activity.

The paper does not cover the very interesting and important areas of allocation between teams of individuals and machines (Stammers & Hallam, 1985). In section two the MANPRINT programme is briefly described to identify the contractor's tasks within system development. The section also discusses where the allocation activities occur within the system design life cycle. Section three examines the commercial constraints that apply to projects that may compromise the optimal allocation of functions between hardware, software and the users. The difficulty that many system developers have in separating mission analysis, functional analysis and task analysis is considered in section four. This uncertainty with terminology only increases the problem of applying function allocation. Section five considers the allocation process itself, considers where the weaknesses of the traditional methods occur and describes a possible approach that has resulted from producing a practical MANPRINT implementation. The use of adaptive or dynamic function allocation and some of the benefits and concerns are briefly examined in section six. Section seven contains the author's suggestions for next steps in ways of improving the allocation of functions during practical system development. Finally, section eight draws some conclusions as to why function allocation is difficult to identify in a practical development project and possible ways it could be made more efficient.

3.2 THE MANPRINT PROGRAMME

MANPRINT is an acronym for MANpower and PeRsonnel INTegration. Essentially it is ensuring that the design is optimised for the people who will have to operate, maintain and support the hardware and software portions of the system. MANPRINT or Human Systems Integration or Human Factors Integration Programme or Liveware are about designing for the true end users. For these reasons the allocation of functions and tasks to either human or equipment is at the very core of MANPRINT.

3.2.1 The Historical Reasons for MANPRINT

The US MANPRINT programme came into being during the early eighties. It was born out of a realisation that many of the 'high tech' systems that were being delivered were not producing their designed performance. The development emphasis had been on the technology with the implicit assumption that suitable people could be recruited or trained, which turned out not to be true.

Complex systems were supposedly simplified by the use of automation. Those functions that could easily be automated became the province of the machine with little thought that those remaining did not constitute logical 'jobs' for the users. Indiscriminate automation often masks the underlying structure of the system from the users, causing learning difficulties and poor performance. Allocation of Functions (AoF) had usually been applied but in a mechanistic way, with the allocation being on the basis of isolated tasks.

3.2.2 Who is the User?

The cost of adapting users to the system by means of training is usually far greater than changing hardware and software during the early stages of system development. MANPRINT recognises this via the Target Audience Description (TAD). To ensure usability it is important to understand and quantify those capabilities and characteristics of the user that are going to impact on total system performance.

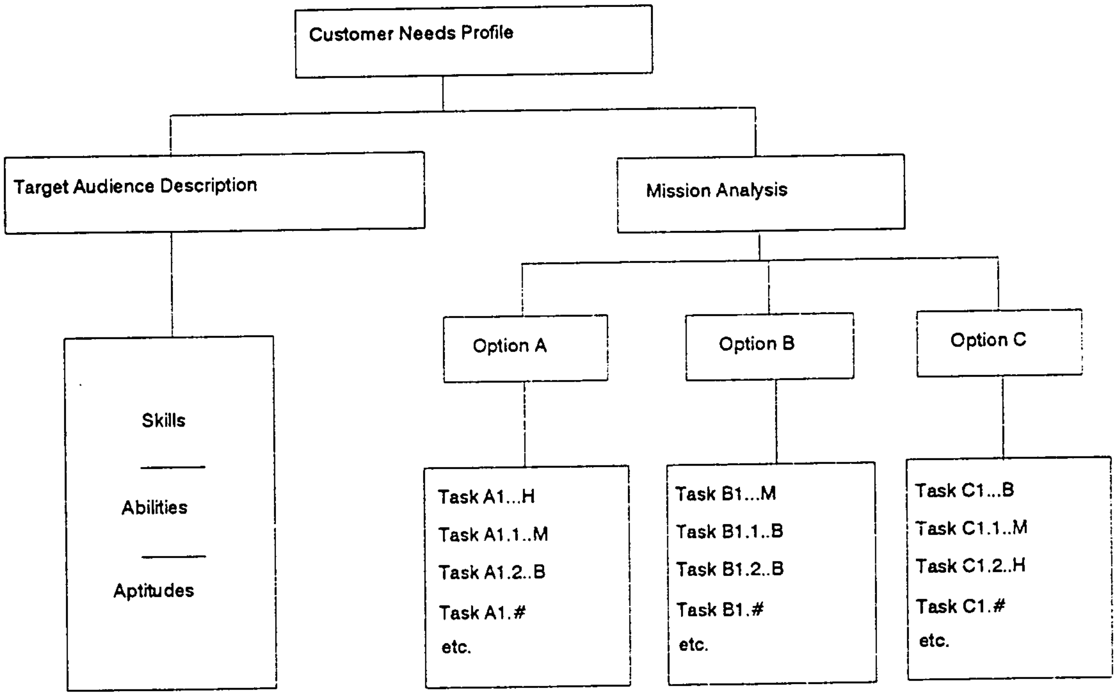
Knowing that the user is a human being is not really sufficient. The characteristics that are needed to guide successful system development include; aptitude for various tasks, existing knowledge, organisational structure etc. When considering real defence systems it is often very detailed information on the user's capability and existing knowledge base that will determine if the task would be better handled by human or machine. The characteristics that are normally used as illustrations of function allocation in human factors texts are usually so gross that they could not help in a practical way. Also, Most of the examples of allocation have centred around the pilot's cockpit and Air Traffic Controller's workstations. From a MANPRINT standpoint the user variability to be catered for in this system design is small compared with that which may be required for an infantry command system to be exported throughout the world. It is interesting to note that both of these user groups are subject to very stringent selection criteria.

3.2.3 What is the User's Job?

One of the principal lessons that has emerged from the application of MANPRINT has been the need to identify the jobs of the users. This must include ALL the component tasks that the users will have to undertake, not merely on the system under development, but also on other systems that they will be required to operate, and tasks that originate from their day-to-day military duties. In many cases the allocation of system tasks to human or machine is governed by the task (and work) loading imposed by activities outside the immediate system. Mechanisms are having to be found that can identify and communicate these outside tasks to the system developers in industry in a meaningful way.

3.2.4 What is the Contractor's Task?

The contractor's task (Figure 3.1) consists firstly of analysing the customer's requirement and translating it into a mission analysis and a description of the users that the customer will have available. The latter is referred to as the Target Audience Description, (or TAD). The contractor's task then consists of generating options that can match the mission requirements and analysing the tasks that those options entail. The contractor's MANPRINT task is to determine which of the feasible solutions best matches the skills, abilities, aptitudes, knowledge etc. that the target audience possess. It is during this matching that the allocation process is used to balance the tasks within each option between human and machine.



Key: H = Human, M = Machine, B = Both

Figure 3.1: The contractors MANPRINT task

3.2.5 Timetable for MANPRINT (Functional Allocation)

When MANPRINT was first introduced to British Aerospace many people expected to be able to pick up a MANPRINT package and apply it once they had designed their system. This was the way that human aspects such as training had been handled in the past. A major part of implementing MANPRINT within industry has been explaining to system developers that MANPRINT needs to be applied throughout the whole of the development life cycle. However, the major input should be in the early phases of Concept, Feasibility and Project Definition (in UK terminology). Changes to the allocation of tasks after Project Definition are usually fixes to cover technological shortcomings.

3.3 COMMERCIAL CONSTRAINTS

The allocation of tasks and functions between human and machine does not take place in a vacuum. The process of allocation has to recognise that certain tasks may be allocated as a result of constraints that range from technology to politics.

3.3.1 Technological Constraints

Technology constraints may include the need to incorporate a particular piece of equipment because the customer has made considerable investments in the item and insists that it is incorporated. The technology may be required to cope with a small proportion of cases, but because it has to be provided anyway it may have to cover all cases.

3.3.2 Organisational Constraints

There are often considerable constraints on which users within a customer's organisation have authority to undertake particular tasks. The organisational constraints within groups of operators can have a profound influence on the allocation process.

3.3.3 Political and Legal Constraints

With changes in legislation and associated commercial responsibility and accountability there are now many more tasks that it is not possible to allocate to the human component. The increased knowledge of toxic substances, sensitivity to public opinion and the fear of litigation are causing manufacturers to err very much on the side of caution. Many tasks that could be done 'better' by humans must now be assigned to machines.

3.3.4 Compatibility Constraints

Systems are now so complex and costly that where possible the reuse of existing designs and the increased use of Off-the-Shelf systems is the order of the day. It is unusual to start with a blank piece of paper, and so the flexibility available in allocation of functions is immediately limited. In addition the influences of the 'outside system' tasks that the user must perform will modify the scope for allocation (see "What is the User's job?").

3.3.5 Resource Constraints

The drivers for the allocation process on many modern systems are often the skill levels of personnel available to the customer and the training time he can afford. Training is probably the most significant aspect that has been poorly represented in any of the traditional allocation exercises.

In many of the through life cost calculations manpower and training costs can be many times the development and procurement costs. In these instances the availability of previously trained personnel and training courses are beginning to influence the allocation process on the prime equipment design.

3.3.6 Concurrent Engineering

There is a move within industry towards the concept of Concurrent Engineering. In the past great efforts have been made to get the requirements correct and adequately documented in such a way that the team responsible for the next phase in the system development life cycle could work from it alone. Concurrent Engineering is a recognition that for the complex systems that constitute a modern defence equipment this approach is no longer possible. The gestation period of modern systems can be up to fifteen years and, with the likely technological changes, this can cause a need for modification and consequently re-allocation. It is essential that each person involved with the development of the system is aware of the requirements and constraints that apply to others.

3.4 ARE FUNCTIONS TOO BIG TO ALLOCATE?

The traditional human factors texts often show a large number of steps that need to be followed to apply Ergonomics successfully to a project. These include :

System Requirements Analysis (or Mission Analysis),
Functional Analysis,
Allocation of Functions,
Task Synthesis,
Task Description,
Task Analysis,
etc.
(DEF STAN 00-25 (Part 12), 1989)

Jordan (1963) attributed the failure to develop a satisfactory methodology for allocation of functions to the fault of comparing humans with machines. In the majority of cases they have to work in a complementary manner to successfully achieve functional goals. In modern defence systems the majority of functions need both humans and machines to undertake complementary tasks.

During the development of the MANPRINT programme for BAe Dynamics the search has been for a simple, practical framework that can be used for as many differing projects as possible. It has been found that it can be very difficult to explain to engineers who have not been brought up in the human factors community the difference between a function and a task. Similarly, mission analysis and functional analysis blend together to such an extent that considerable time was being spent defining the boundary on a project by project basis. The solution that is beginning to be adopted is to remove the name functional and only have missions and tasks.

MANPRINT experience suggests that it is nearly always tasks that we allocate when trying to design for the user. Throughout the remainder of this paper the phrase allocation of tasks is used to signify allocation of function/task and function allocation.

3.5 THE ALLOCATION PROCESS

There are severe problems in trying to apply Fitts' type lists to modern systems. This has largely resulted from the vastly increased capabilities of machines. When function allocation came into being as a concept in the early fifties the allocation of functions between human and machine was fixed, barring major redesign, very early in the design cycle. Systems were relatively simple and the process of allocation was fairly obvious. Many of the early lists now look like Sotbos (Statements of the blindingly obvious).

The development of the MANPRINT programme has identified that a different approach to the allocation problem could be beneficial. It consists of identifying those tasks for which a human is clearly 'best' or required for legal, (or other reasons), and building a coherent job structure around those tasks. In addition to providing a sensible job content, the determination of an optimum workload is probably the clearest single driver for this allocation process.

3.5.1 Why does the Traditional Approach cause Difficulties?

The difficulties are caused simply because the machine content of the system has changed so much since 1951. As highlighted in the previous section humans and machines perform tasks in a complementary manner to fulfil functions or sub-mission goals. Whilst these higher level goals may have an obvious structure, the individual tasks that are necessary to achieve them may not in themselves have that logical structure when taken in isolation. Laughery and Laughery (1987) make the point that 'A function can be viewed as a logical unit of behaviour of a human or machine component that is necessary to accomplish the mission of the system.' When dealing with tasks the logical units may not be present. Allocation of these tasks to either human or machine purely on the basis of which can do that task best often results in the human being given those tasks that are too difficult or expensive to automate.

Whilst machines can operate on a task by task basis, humans faced with a random selection of tasks that have little logical connection tend not to perform very well. The automation represented by the allocation of tasks to the machine can remove many of the signposts from the user's mental model of the process. This in turn leads to the user's inability to provide the resource of last resort which is often his reason for existing in the automated system.

3.5.2 Which Tasks do Humans do better than Machines?

It could be argued that most tasks that can be clearly specified can usually be better done by machine. This is typified by the fact that recently computers have been beating chess grand masters on a regular basis.

There are many development engineers who believe in automating the humans out of the system as "people are a problem". Bainbridge (1987) proposes 'the ironies of automation'. The first concerns the system designers' perception of the human operator as unreliable and inefficient and better replaced by automation, and the second leaves the operator to do the tasks that the system designer cannot think how to automate.

One of the reasons often given for including humans in defence systems is for decision making purposes. This usually means making decisions with insufficient information as, given all the information, the machine would probably reach a correct solution more rapidly. Hitchings (1992) building on the work of Klein suggests that in most time constrained strategic decision making tasks 'satisficing' takes place. This consists of matching the current problem with one that has been encountered before and activating solutions that appeared to be effective on previous occasions. The user checks that the responses are in line with his predictions. If the responses are at variance with expectations a further matching takes place. This approach to decision making relies on the user having an understanding of how the system behaves. Indiscriminate automation can mask this essential overview and is one of the prime reasons for the current MANPRINT approach.

The one area where the human still appears to be better and quicker than the machine is in image processing. There are still good reasons for placing humans in such vulnerable situations as military aircraft, for example human beings are very good at detecting that something is odd. They may not know what is odd or why, but the very recognition of an inconsistency could be vital in a hostile environment.

3.5.3 Building Jobs

It is becoming more important that the user's mental model of the system is established early in the design process. If the unique strengths of the human operator are to be capitalised upon, then the way the operator perceives the system must be understood. The jobs (positions in US parlance) that the operator must perform must need to be designed to ensure that the way the operator views the system results in him performing actions that the system designer would have intended.There are two points here: firstly the user may view the system in a different way from the system designer, and secondly a recognition that the user is there to cope with situations that the system designer could not predict.

In many cases it is better to give to the human tasks which would have been better done by machine, but without which they would not have a complete enough picture of the world to perform those tasks that *are* his remit. Without constant exposure to the 'big picture' it is doubtful if the many of the potential users of modern defence systems will have sufficient understanding of the system's inner workings to be able to successfully intervene in the case of, either an equipment malfunction, or changes in the environment.

The challenge is to discover how the users visualise the system and ensure that any action that they may take is not at variance with the system developers because of their different perception of the system. If there is a conflict it is salutary to remember that the system designer may only live with the system for 5—10 years, the user has it for 25 !

3.5.4 Workload as the Allocation Metric

The foregoing was theory. How do we accomplish allocation of tasks practically. Firstly, we assign tasks according to a set of SOTBOS. That is, we assign those tasks that require the cube roots of a 5 figure number be calculated within 10 mSecs to the machine, and assign the launching of nuclear ballistic missiles to humans.

Secondly, we assess what understanding the human needs of the total system in order to perform his tasks correctly and efficiently. From this we assess which other tasks could he be involved in that would help him develop and reinforce an adequate mental model of the system. In other words to ensure that the action that the user performs corresponds sufficiently with the system's developers' models of the system that a satisfactory outcome is achieved.

Thirdly, the workload on the user must be assessed. It is this step that should determine which tasks are given to the human component, and it is also this step that should be the arbiter of which tasks can or should be the subject of automatic re-allocation. (If ease of automation is used to determine allocation of tasks situations arise such as that of the civil airliner flight deck. Automation of the boring long haul portions of the route are easiest and have been incorporated in the majority of modern aircraft. However this automation takes place when the air crew workload is negligible anyway. A change of runway on the final approach or a change to the holding pattern necessitates the pilot to become a data entry operative instead of looking out of the windscreen in what is clearly a confused situation.)

As stated earlier much of the work on allocation has been with very constrained populations and working environments. Fast jets, air traffic control and nuclear power plants. In most cases the target audience is highly screened and uniform. The work patterns are constrained and of fixed duration. These circumstances are rare for large numbers of military systems that have to be developed under the MANPRINT programme. The variability within most user groups could cause optimum allocation to change from one end to the other. It can often be necessary to design systems that will be issued to groups ranging from Armed Forces Qualification Test (AFQT) categories CAT I to CAT IV.

In addition, when dealing with systems when time on duty can greatly exceed those seen in cockpits, thechange in user performance with fatigue will also change the optimum allocation between the beginning and end of a 'watch' period.

The MANPRINT activities that have been undertaken indicate that it is this optimising of the workload that should be the driver to the allocation of function within any system. What are required are simple workload prediction tools that can be used early and quickly. Many of the tools that do exist have been designed for very demanding situations such as the cockpit of a modern fast jet. The precision being sought for these tools is neither necessary nor appropriate for the majority of allocation activities because of the variability that is to be expected in the performance of the user populations.

3.6 ADAPTIVE and DYNAMIC ALLOCATION

There are both dynamic and adaptive allocation systems that have been proposed to avoid the problem of the system designers having to make the decisions on allocation between human and machine. Rouse (1981) considered some of the interesting aspects of dynamic allocation of tasks, particularly the aspect of who is in control. Does the human delegate procedural aspects of the job to the machine or does the machine monitor the human's activities and assume control of those facets that are not being attended to adequately?

The most commonly used dynamic allocation technique currently used within defence industries is that of providing default settings. Where tasks can be performed by human or machine, the human is given the opportunity to override the default condition if he feels he has access to better information than the machine. Whilst this is not a very adventurous approach, it is pragmatic and most importantly it does meet with the approval of the users.

Dynamic allocation will carry with it a number of quality and safety problems. In particular there is likely to be considerable discussion with the Ordnance Board (OB) on how the safety of any system that changes its mode of control should be validated. Audits for both quality and for Failure Mode Effects & Criticality Analysis (FMECA) will need very careful consideration and again validation. Even then meeting the standards required by the OB may be very difficult.

3.7 THE WAY FORWARD

Developing the British Aerospace MANPRINT programme has revealed that the two crucial formal activities are the preparation of the Manufacturer's MANPRINT Management Plan (M3P) and the creation (and maintenance) of the Concerns Register. The former ensures that thought has been given to both the management and technical aspects of designing for the user, and the second provides a formal record of the problems encountered, solution paths and final decisions as to the way the problem should be overcome. The concerns register has proved invaluable on a number of projects as it contains information on the underlying assumptions that have been made when selecting a particular approach. Many of the MANPRINT concerns in modern defence systems are concerned with the allocation of tasks between human and machine. For this reason a short term aim has been to modify the concerns register to ensure that it is capable of capturing the factors and the thinking that goes into allocating tasks to either human or machine. It is also important that the record of allocation is linked to the best possible description of the users in question.

A long term aim is to produce a task database that carries information on learning difficulty, retention times etc. with links to specific user populations. The relative susceptibility of the tasks to fatigue effects and the human resources needed are also being included in the database. Figure 3.2 shows where the task database fits into the current development of a MANPRINT manpower, personnel and training trade off tool. This project is the subject of a research study within BAe's Dynamics Division.

Based on tasks analyses of some of the company's systems a number of common tasks have been identified. For each of these tasks efforts are being made to try and establish how performance on these tasks will vary with different user populations. Because of the potential enormity of this undertaking, we are confining our task base to those few tasks that are common to a number of our systems. By constraining the scope of the database it is hoped that it will be possible to build directly from project work and that an assessment of the approach can be carried out without committing large amounts of funds.

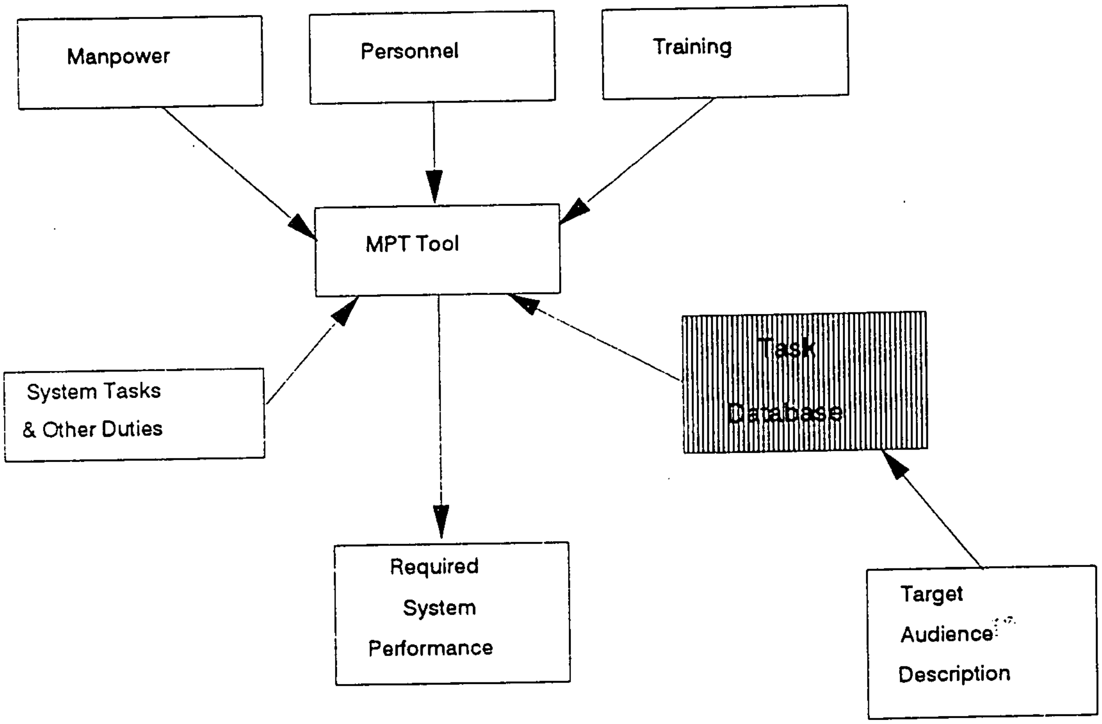


Figure 3.2: The MANPRINT task database

3.8 CONCLUSIONS

Allocation of functions (tasks) in complex weapon systems is traditionally not done well and is often done for the wrong reasons. It is important to recognise the users' characteristics and capabilities in the allocation process.

It is not sufficient to merely assess suitability of tasks for operator or machine implementation. The operator needs to retain sufficient understanding of the system to perform satisfactorily and predictably, whilst not being loaded beyond his capabilities. The BAe MANPRINT developments indicate some of the practical solutions to task allocation and some pointers for future attention.

3.9 GLOSSARY

AoF	Allocation of Function: Synonym for Functional Allocation.
FMECA	Failure Mode Effects & Criticality Analysis
OB	Ordnance Board: Branch of the Ministry of Defence concerned with the safety of weapon systems.
Sotbo	Statement of the blindingly obvious.
WBS	Work breakdown Structure: The method used within industry to sub divide major projects into clearly manageable accounting/deliverable units.

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14. Abstract:
Typically, function analyses concentrate on the functions which are necessary to meet system requirements: they seldom address all the functions performed by humans. Crew functions such as supervision, monitoring, direction, consultation and training are not included in function analyses or in the allocation of funtions. This is because such human functions are assumed, or are identified only once function allocation decisions have been made. Yet the performance of those human functions can have a major influence on the design and performance of manned systems. As one example, a major human factors engineering contribution to the CP-140 maritime patrol aircraft was the crew compartment layout. The layout was predicated on the need to produce an effective crew compartment which facilitated crew activities such as supervision, task off-loading, assistance, and training, Yet none of the function analyses produced for the CP-140 systems included those human functions. The crew compartment layout was established in parallel with the systems engineering efforts which established the functional analyses. The approach to analyzing the compartment requirements and the human and system functions is described. It is concluded that analysts must consider human functions as part of their function allocation decisions.

CHAPTER 4

HUMAN FUNCTIONS AND SYSTEM FUNCTIONS

D. Beevis

4.1 INTRODUCTION

Function allocation is "the process of deciding how system functions shall be implemented - by human, by equipment, or by both - and assigning them accordingly" (Beevis, 1992). Function allocation is one of a series of stages of iterative analysis used for the implementation of ergonomics or human factors engineering in the design of human:machine systems (Figure 4.1). Function allocation generates information for subsequent task analyses. It has been described as "one of the first and most important problems in man:machine systems design" (Chapanis, 1965). It has also been described as a "fiction" and an "artifact," a "purely post-hoc, descriptive analysis generating few, if any, particular results" (Fuld, 1993).

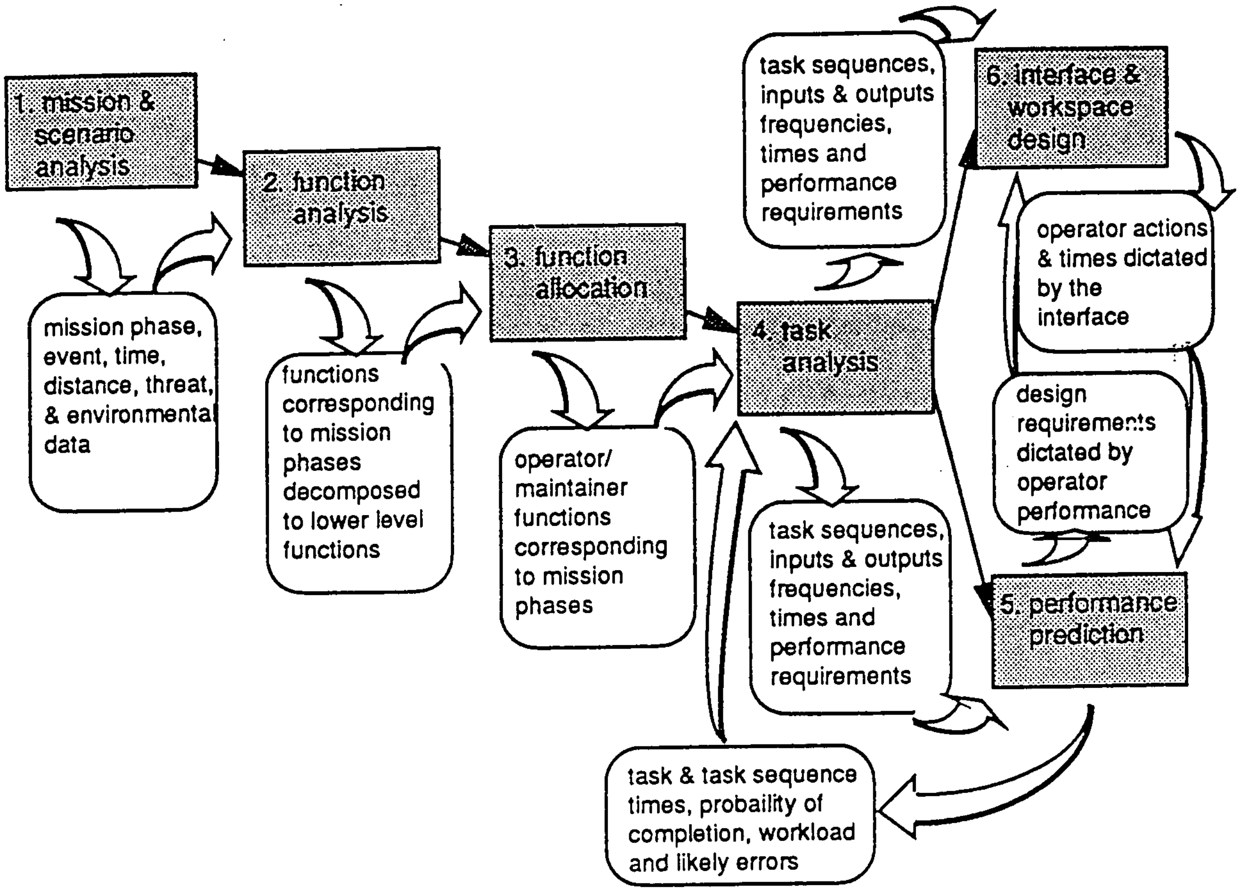

Figure 4.1: Stages of human engineering analysis (from Beevis, 1992)

The concept of function allocation originated in the idea proposed by Fitts in 1951 that system functions should be assigned by identifying those areas in which human is superior to machine and vice versa (See Fitts, 1962), an approach referred to by some as MABA:MABA (Men Are Better At: Machines Are Better At).

Subsequently, the concept of function allocation evolved though several forms (Singleton, 1974):

- comparative assessment of human and machine performance
- economic cost comparisons of human and machine
- design of tasks to exploit complementary human and machine characteristics
- grading of human tasks to match individual differences
- basing human functions on system functions and supplementing them with machines
- flexible delegation of computer facilities so that humans can vary their degree of participation in the system.

This evolution of the concept does not appear to have been matched by an evolution of techniques for performing function allocation. NATO AC/243 Panel 8 Research Study Group 14 (RSG.14) reviewed the techniques of human engineering analysis available and in use (Beevis, 1992). The RSG concluded that function allocation techniques were the least mature in terms of their relationship to system performance. The function allocation techniques which were in use employed nominal or ordinal information about the system and could not be related directly to system performance (Table 4.1). Admittedly, if it is possible to describe human performance in detail using ratio scale data it is likely possible to automate the function obviating the need for the human. Nevertheless, the level of description available for function allocation compares poorly with the system engineering activity of Requirements Allocation in which by specific system performance requirements are allocated to hardware items, software routines or personnel (US Defense Systems Management College, 1990).

RSG.14 also concluded that the state of the art in function allocation tech-niques had changed little in the previous 20 years. Although Price (1985) moved away from the tabular comparison approach with his use of a two-dimensional Decision Matrix, many texts continue to illustrate only the earliest approach to function allocation using a tabular comparison of human and machine abilities (Meister, 1985; US DoD, 1987). The MABA:MABA approach appears to have retained support despite the conclusion of its creator that is was misleading [1](Fitts, 1962). Kantowitz and Sorkin (1987) have suggested that "designers continue to use tables of relative merit either because they do not find ... [criticisms of the approach] convincing, or more likely because they are not familiar with anything better."

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[1] Fittts argued that the function allocation issue is really one of overall performance relative to cost, and that, since humans are uniquely versatile and adaptable, they should not be compared to machines.

Table 4.1: Links between function allocation analyses and system performance (from Beevis, 1992)

Technique	Output	Link to system performance	Scale of measurement
Ad hoc function allocation	functions allocated to sub-systems	indirect link via functions	ordinal (better/worse criteria)
Fitts' list	functions allocated to sub-systems	indirect link via functions	ordinal (better/worse criteria)
Review of potential operator capabilities	functions allocated to sub-systems	indirect link via functions	ordinal (better/worse criteria), ratio (times)
Function allocation evaluation matrix	functions allocated to sub-systems	indirect link via functions	ordinal (better/worse criteria) based on ratio scale ratings
Requirements allocation sheets	performance requirements for functions allocated to sub-systems	identifies sub-system performance requirements	nominal, ordinal, interval, or ratio scale

Despite the human focus of ergonomics and human factors, most approaches to function allocation treat the human as a mechanism, the abilities of which are comparable to a machine. A few approaches have tried to widen the scope of the function allocation analysis to include specific human needs. Fitts (1962) raised the question of job satisfaction. Clegg, Ravden, Corbett, and Johnson (1987) argued that function allocation should include human health and safety considerations in the decision.

Drury (1994) expanded on this approach to include the following factors in the function allocation decision:

System effectiveness	errors/reliability
	speed
	maintainability
	weight/size where limiting
System efficiency	initial cost
	running cost
	disposal cost
Human well-being	safety
	health
	satisfaction.

None of these approaches, however, takes into account the requirements of the human resources in a system for interaction, collaboration, monitoring, supervision, training, etc. As the RSG.14 report noted (ibid.), function analyses concentrate on the functions which are necessary to meet system requirements independently of the means of implementation. Human resource functions are not included in the function analyses of a system, they are assumed or are identified after function allocation decisions have been made. Reviews of the function analyses of five major military systems (aircraft, ship systems, communication system) selected at random did not identify any human resource functions such as interaction, collaboration, monitoring or supervision (Beevis, 1987).

This neglect of human resource functions is part of a general pattern. As Edwards noted (1993), "the balance of ergonomics activities does far less than justice to the issues of inter-personal relationships in the design and management of systems." Yet the performance of the human resource functions can have a major influence on the design and effectiveness of manned systems. This is reflected in the increasing emphasis placed on crew performance by such developments as the adoption of Crew Resources Management in aircraft operations (Alkov, 1994; Weiner, Kanki & Helmreich, 1993). The following case study is offered to show that human resource functions are important determinants of system design, and that the importance of function allocation lies in its contribution to a larger cycle of iterative analyses.

4.2 SYSTEMS ANALYSIS FOR THE CP-140 AURORA AIRCRAFT

4.2.1 The CP-140 Aurora Project

The Canadian Forces (CF) CP-140 Aurora Maritime Patrol Aircraft (MPA), was developed in the early 1970s to replace the CP-121 Argus, which dated from the late 1950s. The Argus used a tactical crew of 9 organized on the traditional basis of assigning an operator to each major item of equipment (radar, passive sonar, active sonar, navigation, etc.). The functional requirement for the CP-140 required "a tactical crew area aft of the flight station which shall include accommodations with necessary equipment for sensor station operators, tactical navigator, and combined routine navigator and communications operator, as directed by the Department" (Canadian Armed Forces, 1972). Thus, the functional specification for the aircraft implied a reduced crew complement and defined some operator roles.

Table 4.2: Assignment of functions to operators in four different proposals for MPA

OPERATOR ASSIGNED	TAC-NAV	NAV	RADNAV	RADAR OPR.	NAVCOM	COMMS	ASO 1	ASO 2	NASO 1	NASO 2
SUB-SYSTEM OPERATED										
Tactical Plot	1,2,3,4									
Navigation Systems		1,2	3		4					
Communication Systems					4	1,2,3				
Radar	1,4		3	2					1,4	
IFF/ ESM			3	2					1	3,4
ECM									2,3	4
Magnetic Anomaly Detection									1,3,4	
Forward Looking Infra-Red	1,2,4	2							3,4	1
Low Light Level TV	1,2,4	2							3,4	1
Infra-Red Line Scan	1,2,4	2							3,4	1,2,4
Sideways Looking Airborne Radar	1,2,4								3,4	1,2,4
Cameras	1,2,3,4									
Acoustics - Active							1,2,3,4	1,2,3,4		
Acoustics - Passive							1,2,3,4	1,2,3,4		
Acoustics - Bathy -Thermo		2					4			3

KEY: TACNAV = Tactical Navigator; NAV = Routine Navigator; RADNAV = Radar Operator/Navigator; NAVCOM = Routine Navigator/Communications Operator; ASO = Acoustic Sensor Operator; NASO = Non-Acoustic Sensor Operator

Proposals received from industry, however, included four different crew concepts, identified as numbers 1 to 4 in Table 4.2. The overall level of mechanization was similar for all four proposals. Thus, the allocation of functions between human and machine did not account for much variance in the proposals. It was the allocation of functions to individual crew members which accounted for most variance. The bidders had established their proposed crew complements by assigning system functions to the individual crew members based on considerations such as the operator's workload and need for information. The human factors analysts had completed the iterative cycle shown in Figure 4.2 from performance prediction (stage 5) back to function allocation (stage 3) to review the implications of function allocations for operator tasks and operator workload.

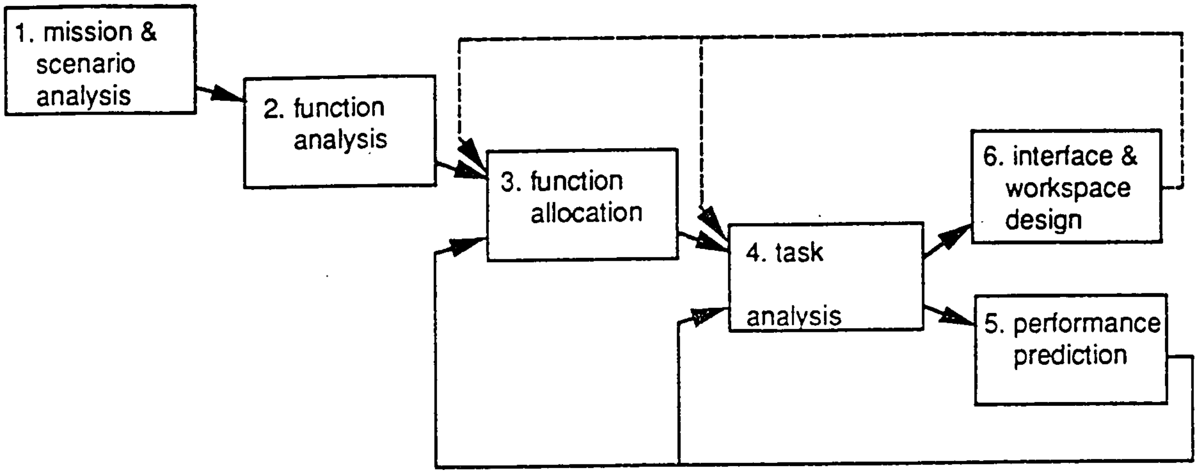

Figure 4.2: Feedback in the human factors engineering analysis process

The analyses had been conducted at a fairly gross level. The bidders' analyses appeared to have been made on the basis of 'second level' function analyses of the form 'conduct radar search', or 'operate passive acoustic sensors.' This was a deviation from the recommendation that function allocation be based on system functions analysed to the third or fourth level (Beevis, 1992). In using higher level analyses, two of the bidders had the benefit of information from existing maritime patrol aircraft, so they were able to base their designs on existing systems, a practice noted by Rouse and Cody (1986). Two bidders did not have such *ad hoc* information available from existing products but were believed to have expertise in MPA design available to them from sub-contractors.

As can be seen from Table 4.2, there was general agreement in the proposals about the allocation of functions for tactical navigation (TACNAV) and the operation of the acoustics sub-systems (ASOs 1 & 2). The major differences in allocation of functions arose in the operation of the radar and navigation systems and the employment of other non-acoustic sensors. These differences resulted in proposals for tactical crew complements of six or seven operators, depending on equipment fit. As might be expected, the differences in function allocation and crew composition resulted in quite different tactical crew compartment layouts. Detailed reviews of the proposed crew compartments by human factors specialists at DCIEM identified several areas in which the proposed functions and crew complements would not meet CF operational requirements in the most effective manner (Patterson & Beevis, 1973). As a result, DCIEM was tasked by the project management office to develop a CF preferred tactical crew compartment concept.

4.2.2 Development of the Crew and Crew Compartment Concepts

To develop the crew compartment concept, the human factors specialists at DCIEM reviewed the information required for workplace layout (Morgan, Cook, Chapanis & Lund, 1963), including:

- the system mission profiles
- specific tasks the operators would perform
- relative importance, duration, and frequency of the tasks
- information inputs to the operators
- outputs from the operators
- equipment committed to the design
- anticipated environmental conditions (aircraft movement etc.)

Thus DCIEM involvement in the analysis of interface and workspace design issues (stage 6 in Figure 4.2) resulted in re-examination of function allocation decisions and operator task analysis (stage 3 and 4 in Figure 4.2). A variety of crew complements and operator roles was studied, including:

- dedicated radar operator
- dedicated routine navigator
- dedicated communications operator
- combination of routine navigator and communications operator (NAVCOM)
- combination of navigator and radar operator (RADNAV).

Sources of information used for this work were observations of the operations in the then current CP-107 Argus and observations of the RAF Nimrod and USN P-3C Orion MPA aircraft. System mission, function and task analyses and timelines (Beevis, 1992) for the proposed CP-140 aircraft were also developed and analysed. This information was used to identify constraints on the allocation of operator roles and functions and to review possible function allocations.

Based on experience with the CP-107 Argus, it was concluded that a tactical navigator (TACNAV) role similar to the Argus TACCO, would be able to handle all crew coordination duties, particularly given the integration of sensor and display systems available in the then, new generation of ASW equipment. The RAF concept of a walking tactical crew coordinator was judged to be a function of the Nimrod crew compartment layout and not required for the CP-140. A review of USN experience with the combined navigator/communicator NAVCOM position in the P-3C aircraft suggested that such a role or position was feasible for the CP-140. Although the RADNAV role was justified by one bidder as involving minimum change to existing CF specialities and training, the question of retraining for the proposed roles was not considered in detail by DCIEM.

However, the question of crew structure had to be resolved early enough to permit the development of the necessary training programme. Therefore operational units produced position papers on training, crew complement, and on the two most contentious function allocations: NAVCOM and RADNAV. Two position papers produced conflicting conclusions.

One argued for the RADNAV role, on the basis of the following:

- training requirements
- "remoteness" of the communicator from tactical operations
- the obvious relationship of radar to the navigation function
- emergency situations which demanded immediate response by the navigator for position information and by the communicator for distress calls
- ability of a RADNAV to assist the TACNAV in high workload situations
- the workload imposed on the communicator in the event of tactical computer failure.

The other position paper noted that the P-3C NAVCOM position was "not without its problems" but that the disadvantages of the RADNAV role outweighed those on the NAVCOM. The principal disadvantages were thought to be:

- the high workload associated with the use of radar and ESM systems in tactical situations
- the need to avoid distractions to such work such as might be caused by navigation system updates,
- the need to rotate different operators through the function in a tactical situation to avoid vigilance decrements.

Overall, the major source of disagreement between the two position papers centred on the estimate of operator workload at different times in the aircraft mission.

The position papers which addressed the question of crew development and training suggested that either of the crew concepts could be trained. The more difficult issue was the question of tactical crew makeup, in terms of officers and NCOs. It was this latter consideration that decided the arguments in favour of a NAVCOM role rather than RADNAV. Because encrypted communications must be authorized by an officer, the communications function had to be performed by an officer. Both tactical navigation and routine navigation had to be performed by officer classifications as well, whereas radar operation in the Argus was performed by NCOs who were rotated through the position during a mission. A crew which included a RADNAV position would have required an officier for that position and two for the TACNAV and communications positions. In contrast, a crew with a TACNAV and NAVCOM would require only two officiers. Thus the allocation of functions to different members of the crew was decided on the basis of rank and trade speciality considerations.

4.2.3 Influence of Workplace Design on Function Allocation

In parallel with the review of crew functions, the requirements for a tactical crew compartment "arranged to conform to the best human engineering practices" (Canadian Armed Forces, 1972) were analyzed. Observations of RAF Nimrod operations highlighted the importance of crew coordination. The RAF used an Airborne Equipment Operator (AEO) as a walking tactical coordinator who moved from crew-station to crew-station coordinating crew operations, instructing, and resolving conflicts and ambiguities. Observations aboard a USN P-3C aircraft when an unforeseen event occurred during the mission confirmed the importance of crew coordination, particularly for consultation and problem solving. It was noted that the compartment of the P3-C had been arranged to minimize unnecessary crew interaction and to require such interaction through either the mission computer or the intercom.

Analytically, the issue became one of identifying the advantages of and requirements for an integrated tactical crew compartment. It was argued that, in a well planned compartment, emphasis is placed on close physical proximity and face-to-face communications. In this context, it was noted that the claim by one bidder that two crew members would be able to load-share was not supported by the design of the compartment, which separated them physically.

The potential advantages of an integrated layout were seen to be (Patterson & Beevis, 1973):

- i) it encourages a coordinated team effort:
  - should one operator be overloaded, another crew member can assist, provided their stations are adjacent
  - other crew members can be consulted in cases of ambiguity or conflicting information
- ii) senior crew members can more easily monitor the performance of junior crew members
- iii) crew rotation is facilitated
  - crew members can maintain an overview of the tasks at adjacent consoles, to which they may rotate
  - in-flight training is facilitated, since face-to-face communication is possible, leaving the intercom free for operational information
  - reversionary modes of operation are possible, in the event of equipment failure
  - crew interaction maintains attention during long periods of monitoring.

These advantages implied the following human-sub-system functions:

- coordination
- consultation
- resolution of ambiguity
- crew performance monitoring
- maintenance of awareness of system state
- training
- reversionary mode operation, and
- maintenance of alertness.

None of the function analyses provided by the bidders or prepared by the Canadian Department of Defence (DND) included these functions. Task analyses produced by contractors and the DND following the review of the proposals provided more detail related to the operation of the aircraft equipment but did not include tasks reflecting human functions. 'Function allocation' itself was not a work item in the human engineering project plan provided by the two contractors selected for the subsequent project definition studies, presumably because they considered the analysis to be complete. Yet the human sub-system functions listed above had a major influence on the development of the concept of the crew compartment as well as implications for operator workload and equipment design. The advantages of an integrated crew compartment were incorporated in a set of design requirements (Patterson & Beevis, 1973):

- the tactical navigation station should be adjacent to the routine navigation station
- the acoustic sensor stations should be adjacent
- the non-acoustic sensor stations should be adjacent
- the acoustic sensor stations and the non-acoustic sensor stations need not be adjacent
- both the acoustic sensor stations and the non-acoustic sensor stations should be as close as possible to the tactical-navigation and routine navigation stations

These requirements were embodied in two crew compartment designs for the CP-140 which were produced as simple mock-ups. The concept was developed further through extensive analysis and mock-up trials by DCIEM using operators with experience in a variety of MPA. The results of those analyses were then passed to the two contractors selected and funded for project definition.

Late in the project, the value of the integrated crew compartment was questioned, compared to the lesser cost of adopting the design of an existing aircraft. The question was interpreted in terms of the contribution to system effectiveness of the integrated compartment design. As noted above, the function, task, and workload analyses conducted by the contractors performing system definition studies had not addressed the functions which were facilitated by the crew compartment layout. Fortunately, questionnaire surveys to identify actual operator roles, duties, functions and tasks in USN P-3C and S-3A aircraft did identify tasks related to coordination and supervision (Helm, 1972, 1975).

To address the contribution of the integrated crew compartment concept, the P-3C function and task descriptions were compared with the equipment fit and tasks anticipated for the CP-140. Sufficient commonality was found at the system level to justify applying the task descriptions for the P-3C to the proposed CP-140. Of 418 tasks for the TACCO identified in the USN P-3C survey (Helm, 1972), 106 were judged to be facilitated by the adoption of the integrated compartment design (Beevis, 1975). Examples of those tasks are shown in Table 4.3 On the basis of that analysis, which related operator functions and tasks to the design of the workspace, the CF proceeded with the development of the integrated crew compartment for the CP-140.

Table 4.3: Examples of tasks performed by P3 TACCO which involved coordination, supervision and crew monitoring (from Helm, 1972)

Position: TACCO, Role: Coordinator

Coordinate information from radar with other system sensors using the computer or console display

Coordinate information from MAD with other system sensors using the computer or console display

Communicate with the sensor operators concerning analysis, classification, and evaluation of either acoustic or ECM contacts.

Evaluate signature characteristics of contact on [lofar] grams

Evaluate and compare the classification and analysis of acoustic/non-acoustic sensor contacts with the sensor operators

Direct sensor operators on appropriate watch rotations, monitoring cycles, and work-rest cycles during the flight.

Direct crew stations concerning all tactical actions to be executed by the crew or by individual stations.

Monitor and supervise voice communications and other related duties of NAVCOM operator.

Monitor status of navigation and communications equipment

Insure that the radar operator enters all contacts into the system.

4.3 DISCUSSION

One obvious question is whether the effort devoted to the human resource functions in the CP-140 was justified. Crew functions and the crew compartment design were not tested in the operational evaluation prior to the aircraft being phased into service (MAG, 1980). Once the aircraft was in service, however, unpublished surveys of aircrew identified few major problems. In general, reports about the crew functions and workload have confirmed predictions made during the concept development. In certain missions, workload at the NAVCOM station is reported to be very high for long periods. It should be noted that those missions were not included in the original requirements for the Aurora and were not included in the mission, function, task or workload analyses. As for the resulting crew compartment design, there have been many favourable comments from aircrew. A third party review of the tactical crew compartments of current NATO maritime patrol aircraft judged the Aurora as "perhaps the best integrated multi-crew/avionics system [in an MPA] flying anywhere in the world" (Lovesey, 1988.)

Another question is whether the issues arising during the Aurora project were typical. The CP-140 was not the only DCIEM project in which human sub-system functions became important determinants of function allocation and crew station layout. Questions of collaboration, supervision, and monitoring have arisen in several projects, including the design of ship's bridges (Beevis, 1978) and the development of ship's machinery control consoles (Gorrell & Beevis, 1985). More recently, in the CF Light Helicopter project, one issue was that the equipment fit might require a change in the crew concept from that of the existing CH-136 Kiowa in which the pilot is the crew commander and is assisted by an NCO. An investigation using knowledge elicitation techniques among CH-136 aircrew identified four constructs which distinguished different crew concepts: structure and composition, knowledge; workload, and effectiveness (Poisson, 1989). Measures of effectiveness used in a subsequent computer simulation of the two most promising crew configurations (pilot/commander plus observer, and pilot plus mission commander) showed differences between the two configurations. Those differences were due to extensive differences in communication between the crew configurations which affected operator workload (Hendy, Kobierski, & Youngson, 1992). Thus the allocation of functions involving crew supervision, coordination, consoltation, etc., was again shown to affect workload, system design, and system effectiveness.

On the more general issue of function allocation, the CP-140 case study shows clearly that the process of function allocation does not stand on its own, but that it is one of an interrelated series of analyses which must be reiterated. Initial solutions may be obtained on the basis of function decompositions to the second level only. However, the solutions derived from those initial analyses did not converge to one concept, but differed quite widely in allocation of functions to different crew members, in estimates of work-load, and in crew complement. Further iterations were necessary to converge to one preferred crew concept. The sequence in which various human factors engineering issues were addressed did not occur in the structured, sequential way described in human factors texts, but in a very fluid manner. This accords with more recent observations that the application of human factors in design is a continually changing problem environment (Burns & Vincente, 1994). Rather than being treated as sequential steps, the stages of human engineering analysis shown in Figure 4.1 can be treated as work items which must be completed (ibid).

In this context it is hard to agree with criticisms that allocation of function generates few particular results (Fuld, 1993). It may be that large tabular comparisons of human and machine capabilities on a third-level, function by function, basis do not add value to systems analysis efforts, but that was not the issue addressed here. The purpose of this paper is to argue that function allocation goes well beyond the simple concept of deciding whether a function should be performed by a machine or a human.

Some may consider that the issues raised are not part of 'function allocation' as normally practised. Those issues were raised, however, to illustrate that the allocation of functions among members of a crew is important and involves functions which are uniquely human. While the allocation of functions between humans and machines may not be contentious, the allocation of functions among different members of a crew may be. That some functions in CP-140 were allocated on the basis of rank and speciality demonstrates a potential link between human factors engineering and manning, personnel and training issues, that is important for 'liveware' (or human systems) integration (NATO RSG.21, 1993).

4.4 CONCLUSION

On the basis of the foregoing case study, the following conclusions are drawn.

- Although the actual design process is unstructured rather than sequential, human factors engineering analysis stages such as those identified in NATO DRG AC/243(Panel 8)TR/7 or US MIL-H-46855B can be used as milestones in that process.
- Within the human factors engineering process, function allocation contributes to the overall development of a system concept through its support to an iterative cycle of analyses.
- The initial cycle of human factors engineering analyses can be completed using second level systems functions if information is available from existing systems, but further iteration is probably required to converge to a solution.
- Analysts must consider human resource functions such as collaboration, monitoring, supervision, and training as part of their function allocation decisions.
- Personnel rank, speciality, and training may be important determinants of function allocation decisions and may provide a link for integrating manpower, personnel, training and human factors engineering considerations in system development.

4.5 GLOSSARY

ECM - Electronic counter-measures
ESM - Electronic signal monitoring
Lofargrams - low frequency recordings of undersea sound
MPA - Maritime Patrol Aircraft
NAVCOM - Combined navigator and communications operator
NCO - Non-commissioned officer
RADNAV - Combined radar operator and navigator
TACNAV - Tactical navigator
TACCO - Tactical coordinator

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Advances in digital electronics and software are causing revolutionary changes in the crew system. Offered an unprecedented amount of information, pilots have demanded more "situation awarness", only to complain of workload problems. Many believe effective function allocation has the greatest potential for solving these types of problems. This paper discusses the issues and special problems associated with function allocation, and its importance to the design of complex military systems while reviewing function allocation from perspectives of different levels, from top-level management in the Department of Defense (DOD) down to the human factors engineers that support the program, and laboratory scientists/engineers developing new design aids. Modern crew system design is a complex issue that should not be addressed piecemeal but requires an integrated process and design support system to help mange the process.

CHAPTER 5

FUNCTION ALLOCATION AND AUTOMATION IMPLEMENTATION IN THE U.S. AIR FORCE

J.W. McDaniel

5.1 INTRODUCTION

After aerodynamic and propulsion technologies matured in the late 1960s and early 1970s, the burgeoning technologies of digital electronics and software began to dominate aircraft design and are causing revolutionary changes in the crew system. Electronic technology can now offer pilots an unprecedented amount of information and control in the cockpit. Pilots have responded by expressing a need for more "situation awareness." The avionics (aviation electronics) engineers eagerly rushed to meet this need with a host of new capabilities so vast that pilots began to complain of workload problems. At the same time, the thoroughly investigated crashes of civil transports have increasingly pointed to sloppy implementation of automation as a cause. Sparaco (1994) identified poor human engineering as the cause of a crash of an A320 commercial transport in 1992 saying, "*Complex human factor issues that contributed to the accident underscore the need to more fully understand the implications of man/machine interface as increasingly advanced technologies are used on civil transport aircraft* ."

Sounding the alarm, the editorial in the same January 3, 1994 issue of *Aviation Week & Space Technology* , said "*Human error is the cause of the vast majority of civil aircraft accidents.... Getting the man-machine interface right is becoming more challenging as aircraft designers decide how many functions to automate and how to keep the pilot in the loop*." Federal Aviation Administration's chief human factors engineer, Mark Hofmann, confirmed this concern in his 31 January 1994 letter to the editor of *Aviation Week & Space Technology* , saying "*one major concern relates to deciding what aviation tasks and functions now being performed by humans should be automated. Such decisions should be based on enhancing overall system performance and helping the human to be more accurate and productive. Another concern is the availability and use of information by operators and maintainers due to the overwhelming pace and volume of data flow.*" The poignant cockpit voice recording of the last two minutes of the fatal China Airlines Flight 140 transcribed in the May 23, 1994 *Aviation Week & Space Technology* provides a clear statement of the problem: "*... the crew was making decisions that ran contrary to the reasoning of the aircraft system's automated logic.*" McDaniel (1988) cites other automation related air disasters and elaborated on how these relate to allocation of functions and automation.

Many believe effective function allocation is the key process that has the greatest potential for solving these types of problems. This paper discusses the issues and special problems associated with function allocation, and its importance to the design of complex military systems. Every level of the military's system acquisition process references function analysis/allocation. The different levels in the system acquisition chain make different uses of function analysis/allocation, however, and have customized the definition of function allocation for their own purposes. This paper reviews function allocation from perspectives of different levels, from top-level management in the Department of Defense (DOD) down to the human factors engineers that support the program, and laboratory scientists/engineers developing new design aids. The top-level model of how the DOD and the Air Force manage system acquisition includes function allocation as a means for selecting technologies that can be implemented to satisfy overall system-level requirements. At the bottom of the acquisition pyramid, the human factors engineers supporting the development programs think of function allocation as a process for assigning functions or subfunctions to automation or a human operator.

Today, multifunction controls/displays, multiple interconnected processors, and the need for a truly integrated crew system create engineering demands that are not being met effectively. Automation is often recommended as the solution to operator workload problems, but we are beginning to realize that problems with inconsistent automation *implementation* are emerging as the most significant human engineering nightmare. Traditional human engineering tools, such as the paper functional block diagram, are not able to deal with the multi-level complexity in the human system interface. Modern crew system design is a complex issue that should not be addressed piecemeal but requires an integrated process and design support system to help manage the process. Improved function allocation techniques are necessary to efficiently guide the automation of crew system functions. New approaches to crew system design include computer tools to assist in the function allocation process, and to relate function allocation to analysis of taskload and workload in complex systems. Some aspects of acquisition appear to be working against effective integration of the crew system. An analysis of cockpit design procedures in current use for military aircraft revealed that the aviation industry's cockpit design process was fragmented across departments, primarily according to the cost centers associated with the Work Breakdown Structure (WBS) and secondly, according to the components acquired directly by the government on other contracts and provided to the prime contractor as a component of the new system.

5.2 TOP MANAGEMENT VIEW OF FUNCTION ALLOCATION

Military system planners think of design and function allocation as a process to select a capability that best meets the needs of a system. Acquisition is the term the military uses to describe the process for developing and obtaining new systems. *Acquisition* is defined as "*a directed funded effort that is designed to provide a new or improved material capability in response to a validated need*," [DOD Directive 5000.1, Defense Acquisition, February, 1991]. This same document describes a *weapon system* as "*the prime operating equipment and all of the ancillary functions that comprise the maintenance capability, training, technical orders, facilities, supplies, spares, manpower, and anything else needed to provide an operational capability.* " Because modern weapon systems are complex beyond comprehension, the military's system acquisition process is almost as complex, requiring documents of hundreds of pages to fully describe it. Within the context of system acquisition, "systems engineering" is the term used to describe managing a development.

MIL-STD-499B Systems Engineering [formerly titled Engineering Management] defines *systems engineering* as: "*an interdisciplinary approach to evolve and verify an integrated and life-cycle balanced set of system product and process solutions that satisfy customer needs. Systems engineering: (a) encompasses the scientific and engineering efforts related to the development, manufacturing, verification, deployment, operations, support, and disposal of system products and processes, (b) develops needed user training equipment, procedures, and data, (c) establishes and maintains configuration management of the system, (d) develops work breakdown structures and statements of work, and (e) provides information for management decision making.*"

The military's model process for systems engineering is shown in Figure 5.1.

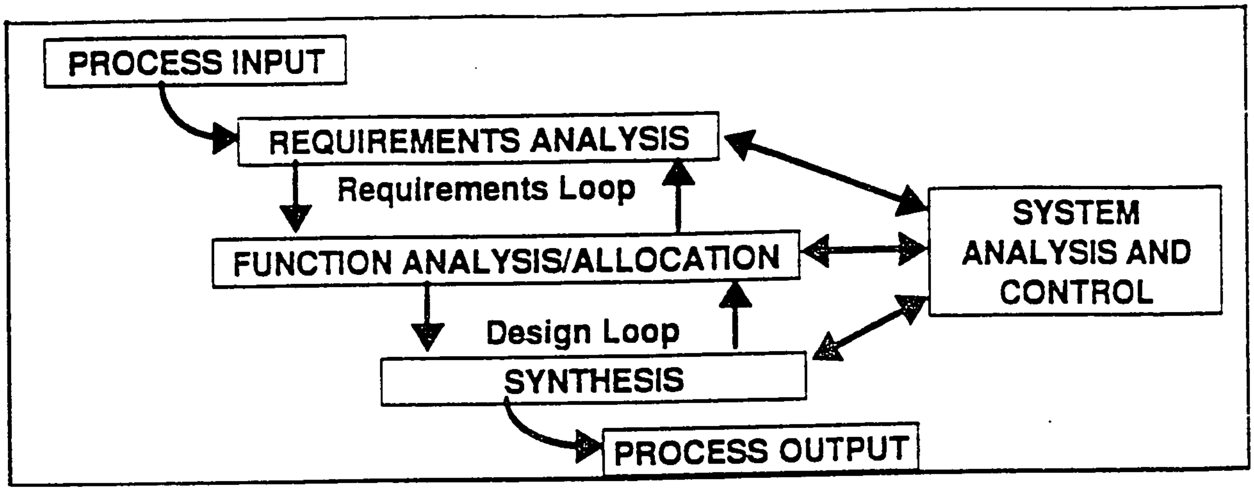

Figure 5.1: The systems engineering process

From the viewpoint of top management, function analysis/allocation is not defined in terms of allocating functions to operators or automation. Rather, *function analysis/allocation* is a top-down approach that decomposes function requirements to ever lower levels of detail, that is, a flow-down of requirements, until synthesis of solutions can occur. Once functions have been decomposed to lower levels, requirements are allocated to proposed *configuration items* (a term used to describe the low level products in the Work Breakdown Structure). The government model for system engineering intentionally avoids terms that involve uncertainty, such as "innovation, creativity, or invention." Creativity and invention are assumed to occur within industry. The management process involves trade-offs among alternatives and selection of the approach that best meets the requirements. The block titled "System Analysis and Control" refers to progress, cost, and schedule audits.

Synthesis is defined as the translation of functions and requirements into possible solutions. *Synthesis* is as close as the process comes to referencing innovation. Synthesis is conducted iteratively (the 'Design Loop' in Figure 5.1) with Functional Analysis/Allocation to define a complete set of functional and performance requirements necessary for the level of the design output required, and with requirements analysis to verify that solution outputs can satisfy customer input requirements. The iterative design loop includes the crew system, but it is generic and relates to all system-level requirements. "Turning the crank" is the phrase one often hears used to make this design loop generate the design alternatives and compare them with requirements. When the crank is turned, alternatives are generated, evaluated, and finally accepted or rejected based on formal and structured criteria derived from requirements.

5.3 CREW SYSTEM DESIGN VERSUS THE WORK BREAKDOWN STRUCTURE

One of the greatest impediments to integrating crew system functions may be the model Work Breakdown Structure (WBS) for aircraft systems in Appendix A of MIL-STD-881B Work Breakdown Structure For Defense Materiel Items (25 March 1993). The WBS is prescribed for use on new system acquisitions to aid definition, analysis, tracking, and control of each component of the system throughout the development period. The WBS is a hierarchical diagram that decomposes the entire system into components, subcomponents, sub-sub, etc. down to the level of each module of hardware, software, services, data, training, support equipment, management, and other work tasks. The WBS structure, in use since the early 1970s, has not evolved with hardware and software technology, and has yet to recognize the crew system as an important component of an aircraft.

The military's solicitation for a new system includes the first three levels of the WBS hierarchy, as tailored from a model prescribed in MIL-STD-881B. In the jargon of standards, "tailoring" usually means deleting non-applicable material, but not adding material. As part of their proposals, contractors expand the WBS by developing the lower levels of the WBS hierarchy. The total WBS becomes part of the contract, and directs the prosecution of the program from that time onward. In the WBS model for an aircraft, Level 1 has but a single element, the entire Aircraft System; Level 2 has 10 elements: Air Vehicle, Systems Engineering/Program Management, System Test and Evaluation, Training, Data, Peculiar Support Equipment, Common Support Equipment, Operational/Site Activation, Industrial Facilities, and Initial Spares/Repair Parts. The Air Vehicle is subdivided into Level 3 elements including the Airframe, Propulsion, Software, etc.

The WBS provides a consistent mechanism for tracking all the subcontracts and vendors contributing to the system. Its most important function is in tracking the cost and progress of each element, providing baseline cost data for estimating what the elements should cost, and how long the development should progress. The WBS, or something like it, is essential to managing a major system development. However, by assuming an obsolete structure of design priorities, the WBS unintentionally hinders effective function allocation. The problem is that the crew system is not defined as an identifiable component of the aircraft in the WBS, but is scattered among twelve of the seventeen level-3 elements under the Level 2 Air Vehicle WBS element. Below are excerpts of these from MIL-STD-881B (condensed and edited for clarity):

> *Level 3 Airframe*
> *includes support subsystems essential to the designated mission requirements, manual flight control system, fuel management system, furnishings (i.e., crew, cargo, passenger, troop, etc.), instruments (i.e., flight, navigation, engine, etc.), life support and personal equipment.*
>
> *Level 3 Propulsion*
> *includes engine control units, if furnished as an integral part of the propulsion unit.*
>
> *Level 3 Air Vehicle Applications Software*
> *includes all the software that is specifically produced for the functional use of a computer system or multiplex data base in the air vehicle.*
>
> *Level 3 Air Vehicle System Software*
> *includes software for specific computer system or family of computer systems to facilitate the operation and maintenance of the computer system and associated programs for the air vehicle.*
>
> *Level 3 Communications/Identification*
> *refers to that equipment (hardware/software) installed in the air vehicle for communications and identification purposes. It includes, for example, intercoms, radio system(s), identification equipment (IFF), data links, and control boxes associated with the specific equipment.*

Level 3 Navigation/Guidance
refers to that equipment (hardware/software) installed in the air vehicle to perform the navigational guidance function. This element includes, for example, radar, radio, or other essential navigation equipment, radar altimeter, direction finding set, doppler compass, computer, and other equipment homogeneous to the navigation/guidance function.

Level 3 Central Computer
refers to the master data processing unit(s) responsible for coordinating and directing the major avionic mission systems.

Level 3 Fire Control
refers to that equipment (hardware/software) installed in the air vehicle which provides the intelligence necessary for weapons delivery such as bombing, laun-ching, and firing. This element includes, for example, dedicated displays, scopes, or sights; and bombing computer and control and safety devices.

Level 3 Data Display and Controls
refers to that equipment (hardware/software) which provides visual presentation of processed data by specially designed electronic devices through interconnection (on or off-line) with computer or component equipment, and associated equipment needed to control the presentation of data. This element provides the necessary flight and tactical information to the crew for efficient management of the aircraft during all segments of the mission profile under day and night all-weather con-ditions. Excluded are indicators/instruments not controlled by keyboard via the multiplex data bus and panels and consoles which are included under the airframe.

Level 3 Survivability
refers to that equipment (hardware/software) which assists in penetration for mission for ferret and search receivers, warning devices and other electronic devices, electronic countermeasures, jamming transmitters, chaff, infra-red jammers, terrain-following radar, and other devices typical of this mission function.

Level 3 Reconnaissance refers to that equipment (hardware/software) for photographic, electronic, infrared, and other sensors; search receivers; recorders; warning devices; magazines; and data link.

Level 3 Automatic Flight Control
refers to electronic devices and sensors, which enable the crew to control the flight path of the aircraft as well as to provide lift, drag, trim, or conversion effects. This element includes flight control computers, software, signal processors, and data transmitting elements that are devoted to processing data for either primary or automatic flight control functions.

The dispersion of crew system design functions across these elements has significance that reaches far beyond cost accounting. The WBS itself *allocates* design requirements to specific organizations responsible for their development. In practice, the WBS has influenced the organizational structure of both the military program and the contractor. Responding to the product structure in the WBS, industry has organized into departments that correspond to each of these products, with a separate department head responsible to the contractor's program manager for those specific products.

Since the WBS model has no element for crew system, industry has no department head responsible for the crew system. Because of this structure, crew system integration requires coordination between several departments within the company. Integration is further hindered because many of the WBS elements are subcontracted out to other companies, with the prime contractor serving as the sole coordinating agent. Decisions made within individual departments can adversely effect the crew system function allocation without other departments being aware of a problem until it is too late to correct.

So far, attempts to modify the standard to consolidate and integrate the crew system into a single Level 3 WBS element have failed. As far back as May 1987, a tri-service laboratory study panel proposed a change to MIL-STD-881A to a group of tri-service aeronautical commanders. While the commanders supported this proposal, it was subsequently killed by the cost accounting officials who control the standard on the grounds that it would ruin their traceability and prediction models. This is a major change, for it involves more than adding a new element called "Crew System"; it also involves removing those functions from the existing 12 elements. This proposal would cause a significant re-organization of industry, removing some of the traditional responsibilities from these department managers.

While the WBS is unquestionably necessary for developing new systems, the hierarchical structure has not evolved to adequately reflect the way modern technology has changed the nature of the aircraft. When the WBS process began back in the early 1970s, the pilot's crew station was composed of several independent subsystems, usually supplied by different subcontractors. Then, it was the prime contractor's job to locate each of these subsystems in the aircraft. In the context of the cockpit design, the prime contractor's effort centered on the cockpit layout and installation of controls and displays, with less attention to functionality. The traditional cockpit design was a drawing of a cockpit showing the location of the seat, control panels, controls, and displays. The cockpit drawings showed the sizes, shapes, and even labels for every control and display. This one drawing could depict the entire human-system interface. The information interface was explicit in the labels of the controls and mechanical displays. Even the workload evaluations of that era were based on hand-travel and eye-travel distances, rather than the mental difficulty of the task.

Modern cockpits have an almost generic physical appearance, clean and uncluttered, consisting of a few multifunction controls and a few multifunction displays (CRTs, LCDs, or similar). Today, the critical design issues in the aircraft cockpit relate to information management and integration of data. Because of the massive amount of information flowing through the crew system, function analysis/allocation is critical to the effective integration of the modern cockpit. The pilots' demands for more 'situation awareness' are eagerly met by new technology that can layer more and more data on the multifunction displays, so that merely accessing the data has become a time-consuming and complex task in itself. As a result, pilot workload has increased.

5.4 GENERAL REQUIREMENTS FOR FUNCTION ANALYSIS/ALLOCATION

The Army, Navy, and Air Force jointly developed MIL-STD-46855 Human Engineering Requirements for Military Systems, Equipment and Facilities (26 May 1994) as the primary human engineering tasking document for the three services. In use since January 1979, this general-purpose standard establishes and defines the requirements for applying human work to be accomplished by a contractor or subcontractor. Tailoring and citing this document in a contract is the primary way the military tells the contractor how much and what kind of human engineering effort is expected.

The process of function analysis/allocation is the heart of MIL-STD-46855 as demonstrated by the following excerpts:

5.5 DETAILED REQUIREMENTS

5.5.1 Analysis

5.5.1.1 Defining and Allocating System Functions

The *functions* that must be performed by the system in achieving its objective(s) within specified mission environments shall be analyzed. Human engineering principles and criteria shall be applied to specify human-system performance requirements for system operation, maintenance and control *functions* and to *allocate system functions* to (1) automated operation/maintenance, (2) manual operation/ maintenance, or (3) some combination thereof. *Function allocation* is an iterative process achieving the level of detail appropriate for the level of system definition.

5.5.1.1.1 Information Flow and Processing Analysis

Analyses shall be performed to determine basic information flow and processing required to accomplish the system objective and include decisions and operations without reference to any specific machine implementation or level of human involvement.

5.5.1.1.2 Estimates of Potential Operator/Maintainer Processing Capabilities

Plausible human roles (e.g., operator, maintainer, programmer, decision maker, communicator, monitor) in the system shall be identified. Estimates of processing capability in terms of *workload* , accuracy, rate, and time delay should be prepared for each potential operator/maintainer information processing *function.* Comparable estimates of equipment capability shall also be made. These estimates shall be used initially in determining *allocation of functions* and shall later be refined at appropriate times for use in definition of operator/maintainer information requirements and control, display and communication requirements. In addition, estimates shall be made of the effects on these capabilities likely to result from implementation or non-implementation of human engineering design recommendations. Results from studies in accordance with 5.2.1 may be used as supportive inputs for these estimates.

5.5.1.1.3 Allocation of Functions

From projected operator/maintainer performance data, estimated cost data, and known constraints, analyses and tradeoff studies shall be conducted to determine which system *functions* should be machine-implemented or software controlled and which should be reserved for the human operator/maintainer. *Allocation of functions* shall consider the risks of making an incorrect decision for each alternative being evaluated so that designs may be simplified or enhanced to prevent or minimize situations where human decisions are made under conditions of uncertainty, time stress, or *workload* stress. The possibility of influencing human or equipment capabilities through personnel selection and training as well as through equipment and procedure design shall be considered, and the costs of such action shall be considered in trade-off and cost-benefit studies.

MIL-STD-46855 uses the same functional hierarchy as defined in several tri-service standards, MIL-STD-1908 Definitions of Human Factors Terms (24 December 1992), MIL-STD-1388-1A Logistic Support Analysis (11 April 1983), and the Army's MIL-STD-1478 Task Performance Analysis (13 May

1991). Figure 5.2 shows this hierarchy compared to the one typically used in crew system design. The Logistics Support Analysis computes the requirements for MPT (Manpower, or the number of people; Personnel, the job titles; and Training), hence the inclusion of the terms 'job' and 'duty'. While they have similar names, this hierarchy differs from the hierarchy used in aircraft development described below. The tri-service term 'Job', for example, would refer to a pilot, and 'duty' would refer to flying the aircraft. In the general purpose hierarchy, Mission, Scenario, and Function are major command functions and do not correspond to any terms used in crew system development. The lower level terms, Task, Subtask, and Task Element in the MIL-STD-46855 structure are similar to Function, Subfunction, and Task definitions of the aircraft development structure.

GENERAL PURPOSE SYSTEM

- Mission
- Scenario/Condition
- Function
    - Job
    - Duty
    - Task
        - Subtask
        - Task Element.

AIRCRAFT SYSTEM

- Mission Phase
    - Mission Event
        - Function
        - Subfunction
            - Subfunction
            - ...(subfunctions as required)
                - Task

Figure 5.2: Functional hierarchies

5.6 AIR FORCE IMPLEMENTATION OF FUNCTION ALLOCATION

While the tri-service MIL-STD-46855 was designed to be generic and applicable to all systems, the Air Force has developed its own special-purpose standard tailored to the super-critical needs of the aircraft crew system: MIL-STD-1776A Aircrew Station and Passenger Accommodations (25 February 1994). Section 4.1 of this document contains a Crew System Development Process (CSDP), which is tailored for complicated aircraft cockpits: "*It is recognized that designs do not start from 'scratch' but that a baseline (or similar) system is typically used from which to make improvements. ... The* ***function analysis*** *analyzes the events identified in the mission analysis and defines* ***functions*** *that the aircraft system has to perform in order to complete the mission. The* ***functions*** *are then* ***allocated*** *to be performed by the aircrew or other subsystems within the aircraft. ... Included in the* ***function allocation*** *process is the analysis of the information requirements of the aircrew in order to complete the mission. Control and display parameters are then identified to provide adequate information transmission between the aircrew and aircraft in order for the aircrew to perform the* ***functions allocated*** *to the aircrew subsystem. Based on these parameters, and the rest of the aircrew system implementation, task load, and workload for a given aircrew station can be analyzed.*" This process calls for verifying the effectiveness of the design by "*reviewing the analyses as they are developed, observing the mock-up and simulation demonstrations, and reviewing simulation test plans and results.*" The process also requires the generation and submission of reports in the formats specified in MIL-STD-46855.

Section 4.1.3 of MIL-STD-1776A has detailed requirements for function allocation: "***Functions*** *allocated to the aircrew shall identify which aircrew member performs that* ***function****. For* ***functions*** *assigned jointly to the aircrew and another aircraft subsystem and/or to more than one aircrew member, the subsystem or aircrew member which has primary responsibility for performing the* ***function*** *and the subsystem or aircrew member which has secondary responsibility for performing the* ***function*** *shall be identified. Functions may be* ***allocated*** *to more than one type of implementation. Functions may also be* ***allocated*** *to more than one subsystem.*" For practicality, it is also recognized that "*program schedule and resource constraints restrict* *designers to analyze only the problem areas perceived to be the most difficult.* " To conserve resources, new function analyses often use segments of old function analyses from the baseline system to fill in the gaps between the new, critical, or difficult functions of the new design. In many cases, functions in new systems are allocated as they were in the baseline system, particularly if the baseline functions were free of problems. Appendix C of MIL-STD-1776A contains a 30-page instruction for integrating the CSDP into the SEMP and SEMS (Systems Engineering Master Plan and Schedule), which integrate all development activities. This process emphasizes the Integrated Product Team (IPT) approach, and describes how the various teams interact to coordinate the entire system.

5.7 SYSTEM DEVELOPER'S VIEW OF FUNCTION ALLOCATION

When the Air Force begins to acquire a new aircraft or make a major modification to an existing aircraft, a System Program Office (SPO) is established by bringing members of various disciplines together as a team. These SPOs are located at Wright-Patterson AFB to be near the research and development expertise centered in the laboratories also located there. This SPO team translates the operational requirements into a contract and later manages that contract. Typically, the Air Force contracts with industry for aircraft design and production. Similarly, the engineering part of function analysis/allocation is contracted to industry as part of the overall system development. The official involvement of military personnel in the process is monitoring industry's efforts.

The contract tasks industry to perform function analysis/allocation in one of two ways. The first way is by requiring the contractor to perform a human engineering program in accordance with MIL-STD-46855 and/or 1776A, both of which include instructions for performing function analysis/allocation. The second method is to insert specific requirements for performing function analysis/allocation into the contract Statement Of Work (SOW). Either way, the military (program officials from the SPO and pilots from the using command) participate by reviewing the contractor's products at design reviews, attending mockup reviews, and observing simulations of the crew system. The format and contents of the function analysis/allocation vary from one company to another, and its quality depends largely on the expertise of company engineers and amount of resources available for effort. The function analysis/allocation is not an end in itself, but a means to acquiring an effective and efficient system.

To implement the Integrated Product Team (IPT) approach to system development, the Air Force's on-going F-22 program has made a radical departure from the WBS model in MIL-STD-881. Using its prerogative to 'tailor' the model WBS, the F-22 SPO completely overhauled it and made the Cockpit System IPT one of eight level 3 elements in the WBS (one element for each of the eight IPTs). The Cockpit System Element is subdivided into five subelements: Pilot-Vehicle Interface (PVI), Aircrew Station Accommodations, Escape, Life Support, and Canopy. The F-22 program did not make a total break with the traditional WBS model, however, for another level 3 element is Avionics, which contains the avionics controls and displays hardware. Notwithstanding this exception, the F-22 program is the first military program to experiment such a high level of integration of the crew system design activities. The results to date indicate this approach to be far superior to the traditional WBS, providing high visibility to crew system issues and getting problems resolved in favor of the pilot.

The specific definition of Cockpit Systems used by the F-22 program is as follows: "*This element comprises the systems and equipment that provide the pilot the capability to manage the aircraft subsystems and to function within the aircraft performance and threat envelope. This includes the pilot-vehicle interface, crew station design, life support, escape systems and human engineering/crew vehicle interface (CVI), and the canopy system. This element includes the coordinated functional efforts of the Cockpit Integrated Product Team associated with the task for each of the subelements listed above, including the tasks related to analysis, design, development, test, qualification, fabrication, assembly, installation, integration, verification, and documentation. Included as part of each subelement is the application of human engineering principles in the design and development process.* "

The function analysis/allocation process provides the key for military and industry personnel to develop better crew systems. Acquisition regulations that prohibit military personnel from directing, managing, or supervising contractors create a barrier to technical discussions. The requirements included in the contract's statement of work and specification are deliberately general so as not to unnecessarily hinder the contractor from developing the best possible product. Within this context, the function analysis/allocation provides a valuable communications mechanism so that industry can get a better understanding of how the military customer sees the contractor's design in the context of requirements, and so that the military can get a better understanding of the specifics of just what industry is planning to deliver. The function analysis/allocation turns out to be one of the most effective tools for understanding the crew system at a detailed level.

While most design and development work is done on contract by industry, there are occasions when quick reaction or restricted information requires that some design work be done in-house, including function analysis/allocation. All of the aircraft SPOs are part of the Air Force's Aeronautical System Center (ASC). ASC also has the Crew Station Evaluation Facility (CSEF). The CSEF performs a special design and evaluation role for some programs. For example, recently, the CSEF evaluated the functions of a KC-135 flight deck as part of a general redesign to eliminate the navigator position. After re-allocating the navigator functions to the pilot and copilot, workload analysis revealed the need for automating some functions. The CSEF developed an alternative design and configured a two-place simulator to test the revised design. The CSEF has crew system simulators for several existing aircraft that are used to perform special studies. Pilot-in-the-loop simulator evaluation was then used to validate the conceptual design and demonstrate acceptable crew workload. This proof-of-concept became the foundation of requirements documents for the KC-135 system upgrade that was later contracted to industry. By testing certain concepts in-house, the CSEF helps the SPO develop more efficient contracts. The CSEF can work directly with other military personnel as part of an Integrated Product Team (IPT), whereas contractors must be dealt with 'at arms length' through advance tasking on a contract and re-directed only through a time-consuming, formal contract change.

5.8 THE LABORATORY VIEW OF FUNCTION ALLOCATION

In 1951, Paul M. Fitts, the founder of the Armstrong Lab's Human Engineering Division, was the first to apply formal rules to function allocation. Table 5.1 shows part of his list of those functions where humans excel over machines and those functions where machines excel. Today, similar listings are still called "Fitts' lists." Because Fitts' functions are general in nature, they remain valid, for the most part. One might argue that remote sensing technology now excels at detecting small amounts of energy, but recognition and identification continue to be better done by humans. The ability to store large amounts of data now favors the computer, but humans are still required to interpret and understand the nature of data.

Between 1984 and 1992, the Paul M. Fitts Human Engineering Division sponsored a three-phased contract effort called Cockpit Automation Technology (CAT) which involved five major aircraft companies (McDaniel, 1986; McDaniel, 1988; Kulwicki, McDaniel, & Guadagna, 1987). In the late 1980s, the work begun with the CAT effort was extended under a project named Crew-Centered Cockpit Design (CCCD) (Storey et al., 1994). CCCD is developing a new and integrated Crew System Design Process (CSDP) with formal procedures and tools for function analysis/allocation. Importantly, the CSDP methodology is implemented with CCCD's computer-based toolset providing support both for the design of new and upgraded crew systems. Martin (1994) described the application of the toolset in an example F16 cockpit upgrade to illustrate the new process.

Table 5.1: Fitts' list

Humans appear to surpass present-day machines with respect to the following:	Present-day machines appear to surpass humans with respect to the following:
1. Ability to detect small amounts of visual or acoustic energy.	1. Ability to respond quickly to control signals, and to apply great force smoothly and precisely.
2. Ability to perceive patterns of light or sound.	2. Ability to perform repetitive, routine tasks.
3. Ability to improvise and use flexible procedures.	3. Ability to store information briefly and then to erase it completely.
4. Ability to store large amounts of information for long periods and recall relevant facts at the appropriate time.	4. Ability to reason deductively, including computational ability.
5. Ability to reason inductively.	5. Ability to handle highly complex operations, i.e., to do many different things at once.
6. Ability to exercise judgment.	

The CCCD process currently has about 120 activities, most supported by separate software design tools. It is beyond the scope of this paper to describe all of them. The 120 activities of the CSDP are divided into five categories of activities: Program Planning/ Scheduling, Requirements Analysis and Predesign, Crew System Analysis, Crew System Design, and Crew System Evaluation. The *crew system design* category accounts for the majority of the activities. A key element in this toolset is a structure and discipline to perform function analysis/allocation.

A survey of industry users by Lehman et al. (1994) revealed that the major of aircraft manufacturers have developed their own rapid-prototyping simulators and make extensive use of simulation to verify the function allocation and assure that pilot workload is acceptable. The weakness of such simulation is that the data are almost entirely subjective, relying on critique by pilot subjects in the idealized ground based simulation. Because of the critical role of the simulation, the industry human engineers are at the mercy of scarce, highly sophisticated programmers as well as electrical and hardware engineers to modify and run these simulators. Loss of access to key personnel to higher priority projects can stop an evaluation. To prevent such limitations, the CSDP toolset is directly linked into a generic crew system simulator, called the Engineering Development Simulator (EDSim), which is reconfigurable without sophisticated programmer support (Givens, 1994). Built with object oriented software, a journeyman programmer can modify or even create a new display for the system. The EDSim is an integral part of the CSDP toolset, allowing the analytical tools and the EDSim to share data.

CCCD's CSDP is structured in accordance with the general guidelines in MIL-STD-46855, and even has utilities that generate reports in the format required by MIL-STD-46855. An earlier version of CCCD's CSDP was used as a model for the CSDP now included in the MIL-STD-1776A, discussed above, and is compatible with the Integrated Product Team (IPT) concept to design support. The CSDP uses the aircraft function hierarchy in Figure 5.2. In this hierarchy, functions and subfunctions refer to activities that must be accomplished, but without specifying how they will be accomplished. At the lowest level, after a function or subfunction is allocated to an operator or automation, and is implemented with a specific procedure for accomplishing the function, it becomes a task.

The CCCD toolset contains specific aids to help with function analysis/allocation. At the top level, a Mission Decomposition Tool assists in identifying the top-level functions and assigning a target timeline. To avoid mistakes caused by the designer assuming the role of the user, a new Concept Mapping technique allows the user to play the role of designer and effectively influence the function allocation and design decision making (McNeese et al., 1995). The Timeline Management Tool includes three modules: the Information and Control Requirements Analysis Tool, the Function Flow Analysis Tool, and the function allocation Trade Analysis Tool. These provide input to taskload and workload analysis programs.

5.9 CONCLUSIONS AND RECOMMENDATIONS

Mission Analysis, Function Analysis, and function allocation have long been recognized as necessary to the design of complex systems. Yet, there has been little standardization in terminology, and many people use the terms 'function' and 'task' interchangeably. Attempts to cobble together taxonomies that serve both design and MPT purposes have disappointed both camps. At the crew system level, functions refer to specific activities that must be accomplished. The term 'function allocation' refers to the process of assigning a function either to the operator(s) or to automation.

Function analysis has proven useful in detailing the requirements for components of a complex system, providing a common ground for understanding and communication among the members of the development team. The creation of an unified crew system design team to address all crew system issues marks an advance in the design process. Currently, the Air Force calls the teams Integrated Product Teams (IPTs). The F-22 SPO believes that IPTs have proved to be effective, and their use will likely continue and spread to other programs.

For new aircraft systems, piloted simulation continues to be the preferred method of testing the effectiveness of function allocation. Using simulators for testing is expensive and time consuming. In an attempt to reduce the cost of testing a design and to accomplish analysis earlier in the design process, laboratory programs are attempting to develop analytical tools to support the crew system design. The computer tools can share data where useful, and minimize the labor of working with data. The difficulty in developing a computer tool to automate function allocation is in the implementation of the function. The problem is subtle, but highly significant. The most fundamental problem with function allocation is that its effectiveness cannot be evaluated at the *conceptual* function level. Analysis can only be done after the *implementation* of the function. A human operator and a machine will not perform a task the same way or at the same speed. It is axiomatic that only implemented functions can be assigned task times and their interaction with other functions assessed. Implemented functions should be called 'tasks' to distinguish this characteristic.

Previous computer tools aimed at function analysis have failed because they aim at analyzing the function itself, rather than the implementation of the function (task). The reason implementation of a function cannot be automated is because it is a creative and an inventive process that involves application of specific technologies. To design, after all, is to *conceive and plan out in the mind.* After a function is allocated to an operator or automation, some creativity is required to implement it effectively into a human-system interface or some automated equipment. In practice, our inability to objectively prescribe the creative elements of function implementation has prevented totally automated analysis of design candidates.

Nor can function implementation be superficial. Functions can usually be implemented in more than one way, whether assigned to a human or automation. Analysis can err when evaluating a sloppy or half-baked implementation. It often happens that when a new implementation is compared to an old implementation in a baseline system, the newly implemented function appears more efficient because some of the details were overlooked. Unless all function implementation alternatives are optimized to the same degree, there will be no equal basis for comparison. If functions are assigned to and implemented for a human operator, the effectiveness should be tested by a person who first learned to operate the function with a reasonable proficiency. In a complex crew system, a function implementation should not be evaluated in isolation, but in the context of the total crew system in a realistic environment to judge the interactions of functions.

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The objective of this paper is to discuss various aspects of function allocation from the perspective of system/software engineering practices and point to possible consequences on and contributions to function allocation within human engineering. Function allocation approaches in system/software engineering are briefly described and discussed. A major issue affecting the function allocation process is the quality of the behaviour modelling. Use of formal languages for behaviour modelling as well as object orientation in system/software engineering is discussed. Developments within these areas should be considered in human engineering in order to advance integration of system development efforts and improve the function allocation process.

CHAPTER 6

THE FUNCTION ALLOCATION PROCESS AND MODERN SYSTEM/SOFTWARE ENGINEERING

E. Nordø and K. Bråthen

6.1 INTRODUCTION

In Human Engineering (HE) function allocation (FA) to human or machine is considered as a main step of system development and a number of FA techniques have been proposed. The role of FA seems to be much less pronounced in Systems/Software Engineering (SE) and is usually considered as an inherent part of design. This paper discusses the issue of allocation in the system development process in general and how modern SE practices might affect FA within HE in the future. System modelling and in particular Object Oriented (OO) techniques are addressed. FA within HE is briefly introduced before FA within SE is described in some detail. It is concluded that SE puts less emphasis on the allocation itself and more on the analysis and evaluation of the allocation decisions. For HE to be able to take advan-tage of the advances in modern SE, an important issue is how the modelling concepts used within SE are applicable for modelling of the complete human-machine system.

6.2 ALLOCATION WITHIN THE SYSTEM DEVELOPMENT PROCESS

A behaviour model of the system is the main result from the initial SE effort. The mission and scenario analyses and the subsequent function analysis result in a description of the desired functional, or behavioural, characteristics of the proposed system. A function represents a logical unit of what we denote as the *behaviour model.* The term behaviour refers to both the human and the machine parts of the system and is used in the SE sense of the word, i.e., behaviour is defined by a system's inputs, outputs and states as a function of time according to certain performance requirements. Later on we will discuss necessary ingredients of this model in the context of FA.

Functional analysis is concerned with decomposition of functional requirements and behaviour. In parallel with the function analysis, system components and their hierarchy are identified in what we denote as the *component model.* In order to analyse functions in a meaningful way it is in general necessary to consider the main characteristics of these system components. A component is in general an abstract concept, but will at a certain level of detail be associated with real components. The main types of system components are humans (liveware), hardware and software.

The mapping of the behaviour model onto the component model is called *function allocation.* This mapping implicitly establishes the links between the components and the required behaviour of the interfaces. The main types of interfaces are human-human, human-machine and machine-machine. Interface requirements as capacity of and delays on the links connecting the components must be considered. In practice function analysis/FA is iterated until finally a real system that implements the required system behaviour is proposed, (Figure 6.1).

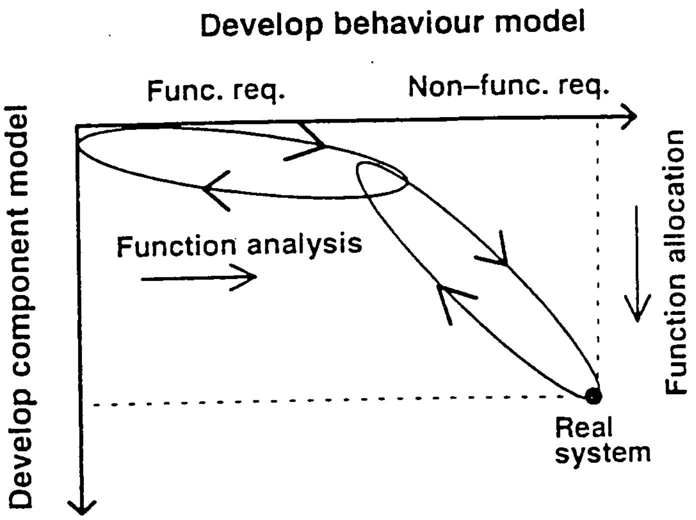

Figure 6.1: Combined development of behaviour and component model

Information processing capacity of the components is limited and performance requirements associated with allocated behaviour must be checked. Behaviour must be specified in order to manage resources in situations with both normal and extreme workload. It is also necessary to consider various types of *non-functional requirements* such as maintainability and redundancy. Components may fail in various ways and it is thus necessary to perform a failure mode effects analysis and thereafter to specify error detection and recovery requirements. The main goal of error handling is to return the system to its normal behaviour. The system engineer must be assisted by component specialist engineers of various backgrounds in order to analyse the components' functional, interface and non-functional requirements in detail. Consideration of all these requirements makes it necessary to extend and refine the original behaviour model. A new implementation dependent model is then defined. However, the original model should be preserved as it is easier to understand.

The implementation of the Human-Machine Interface (HMI) and the error handling at various levels often constitute more than half the software development effort. Since software often is the major cost item, this emphasizes the importance of analysing interfaces and non-functional requirements. An important motivation behind an analytical approach to FA is to reduce the number of changes to implementation (including prototypes) later on in the system development, thereby achieving cost savings.

6.3 MODELLING OF SYSTEMS

The requirements of a modelling language, in which the functional model is expressed, depend on the application domain and the purpose of the modelling. Approaches to modelling can differ both in formality, abstraction and perspective. The emphasis may be on the information processing involving complex data structures or on the dynamical aspects involving control sequences.

The importance of a defined syntax for the modelling language is widely recognized. A mutual understanding of the semantics (meaning) of the model, between people (and computers), is also required. The need to develop formal descriptions is obvious from the SE point of view and the primary example is, of course, programming. It is important to realize that a formal behaviour model also can be executed in much the same manner as a program. However, there is often a conflict between the desire to formalize and the need to understand the resulting description.

A function is usually conceived of as an information processing activity. At a certain level in the description we focus on the output and the required input and consider the function itself as a black box. The backbone of a behaviour model is a hierarchy of functions decomposed to a level with which the designer is satisfied (Harel, 1992).

Data elements and stores are specified and associated with the input and output flowing between functions (also denoted as activities, actions, transformations or processes). This relationship between the functions is termed *data flow* and is usually depicted in Data Flow Diagrams (DFD). It is important to realize that the data flow relation only stipulates that information *can* flow. Additional information is required to describe *when* this will happen and by *whom* the functions are performed. It can be argued that the semantics of functions and data flows are informal and therefore restrict analysis (Bræk & Haugen, 1993). A reader invariably associates sequences of processing with DFD, an interpretation which in principle is invalid, and more importantly, potentially in conflict with the understanding of others involved in the development. Likewise, use of Structured English in order to describe how functions transform the information is equally error prone without a rigorous defini-tion of its semantics.

The (timewise) sequential relationships between functions is termed *control flow* and is mandatory in order to deal with real-time systems. *The main (or only) purpose of a number of functions will be to sense or control such dynamics.* The function analysis techniques reviewed by RSG.14 (Beevis, 1992) focus on either the data flow or the control flow, *but only to a certain degree on both these dimensions*. In this paper we consider behaviour to include both data and control flow. The human is viewed as an event sensitive information processor and a complete behaviour model also includes information flow into and out of tasks, and sequencing and concurrency between tasks.

6.4 OBJECT ORIENTED SYSTEM/SOFTWARE ENGINEERING

In Jobling et al. (1994) a major problem with traditional function decomposition is pointed out. The decomposition violates the principle of dynamic system decomposition by attempting to model a dynamic system with a hierarchy of state-less functions and a global state reservoir from which any function may draw its inputs and deposit its outputs. That is, state and behaviour are not preserved within the boundary of the decomposed functions. In object oriented SE this problem is addressed in a way which is more in accordance with a control engineering view of a dynamic system. Other drawbacks of functional decomposition are the lack of support for instantiation and reuse of function types which are concepts considered fundamental in OO analysis and design.

The use of OO is currently expanding upwards into design and analysis (Coad & Yourdon, 1991; Rumbaugh et al., 1991) and is often introduced as extensions to traditional techniques such as DFD. The focus of OO in system analysis is typically on roles and responsibilities of objects. An object is a concept, abstraction or thing with crisp boundaries and meaning for the problem at hand. Objects serve two purposes:

- to promote understanding of the real world, and
- to provide a practical basis for computer implementation, i.e., behaviour is allocated onto an object.

An overview of OO approaches can be found in Monarchi and Puhr (1992). The following discussion is based on Bræk and Haugen (1993) and Madsen et al. (1993). Traditionally, a number of techniques are utilized in order to manage complexity:

- Abstraction (consider whole system, but ignore aspects and remove implementation details)
- Projection (system is perceived from different angles, e.g., data and control flow views)
- Aggregation and partitioning (e.g., functional or structural hierarchy)

Another powerful technique introduced in OO is generalization/specialization. This kind of complexity management is based on a description and understanding of individuals in terms of similarity by extracting general patterns of properties (*types*). Components of a system will be *instances* of these types. Instances and types are often referred to as objects and classes in OO. Types are made in two ways:

- By composition, i.e., aggregation of components which again may be instan-ces of other types.
- By inheritance and specialization, i.e., a new type is defined by inheriting, specializing and/or redefining the properties of an existing type.

Objects contain data items (called *attributes*), including state, and action sequences (called *methods* in OO) that process data items and received inputs. The use of methods provides a well-defined interface that hides the internal structure of data items and action sequences from the environment (encapsulation of the object). Methods represent an OO implementation of functions in DFD. It is important to realize objects may execute action sequences *without* external stimulus. For example, actions can be executed periodically. Action sequences can be executed coordinated with other objects (using their methods), as *alternating* (interleaved) with other objects (only one object active at a time) or *concurrent* with other objects (more than one object active at a time). The need for these types of action sequences can be exemplified by considering the modelling of a travel bureau operator. The operator alternates between various sequential activities as invoicing or reservation and the alternation is typically triggered by telephone interrupts. The operator can also perform tour planning together with a customer in his office, i.e., concurrently with the customer.

An OO approach to system development typically concentrates on the development of an *object model*, i.e., creation of types (classes). The object model contains a description of types with their attributes and methods. The objects are linked by aggregation, inheritance or other kinds of relations. The control flow is typically thereafter described by *a dynamic model* which is based on the finite state machine formalism with various types of extensions. At last, the information processing itself is described in what often is called the *functional model*. Object Modelling Technique (OMT) is an example of a technique using these three modelling projections (Rumbaugh et al., 1991).

Another OO modelling method is SDL-92 (Specification and Description Language) which is a standard language for specification and description of real-time systems used within the telecommunications community. A system and its environment are in SDL conceived of as a structure of *blocks* connected by channels. Blocks can be decomposed and their behaviour is described in *processes*. Each process is modelled by an Extended Finite State Machine (EFSM) and communication between processes is possible only by signals that are produced and consumed by the EFSMs. A block type may be reused when a new block is defined. The new block then inherits data, EFSM and actions. These may then be (partly) redefined and/or extended. The ability to inherit and modify behaviour in this way is a powerful feature. Processes can be regarded as objects. In SDL the function allocation is performed as part of what is called implementation design. The result of the implementation design is a description of the system structure and its associated behaviour. The function allocation is described by an implement-relation between the implementation and the behaviour description. SDL models can be executed and their implementation in software (or hardware) may be partly automated.

6.5 FUNCTION ALLOCATION TECHNIQUES IN HUMAN ENGINEERING

Overviews of FA techniques used within HE can be found in Meister (1985), Rouse (1991), and NATO (1992). In the following we summarize an iterative approach to allocation advocated by Rouse (1991) which consists of three passes through the allocation, design and evaluation sequence.

Comparitive allocation approaches are first used in the *'initial design phase'*. Functions allocated to humans are thereafter converted to tasks by designing displays, input devices and operating procedures. Human performance and workload are predicted with emphasis on single-task performance/workload at different points in time. The *'design integration phase'* focuses on relationships between multiple tasks at similar points in time. Complementary tasks could point to more integrated displays, input devices and/or procedures to improve performance and reduce workload, while conflicting tasks could indicate the need to redesign displays, input devices and/or procedures. In the *'final design phase'*, earlier decisions are reviewed and possible use of dynamic allocation is investigated. Use of prototypes or human-in-the-loop simulators is considered necessary in order to evaluate the final allocation.

6.6 FUNCTION ALLOCATION WITHIN SYSTEMS/SOFTWARE ENGINEERING

The term 'function analysis' is well established within SE, in contrast with 'function allocation' which often is treated as part of 'implementation design' and/or software design. (A database search resulted in 44 matches with regard to FA, but none when combined with systems or software engineering!) Nevertheless, FA is implicit in distributed system design, hardware/software codesign, general and real-time software design, and distributed AI system design. Since SE puts more emphasis on the evaluation of the design than on techniques for the FA itself, techniques for computer systems performance analysis are also relevant.

6.6.1 Distributed System Design

Many functions are today allocated to software to be run on a distributed computer system comprising a network of general purpose computers. The allocation is often dynamic. Two or more computing resources are interconnected if they can communicate, i.e., exchange messages. The *client-server model* is the most pervasive for interconnectivity (Nicol et al., 1993). This model organizes a distributed system as a number of distributed server processes that offer various services to client processes across the network. Many experts now agree that modelling of a distributed system as a distributed collection of interacting objects is appropriate. Objects are clients and servers within the system according to the roles allocated to them.

6.6.2 Hardware/Software Codesign

A prominent allocation problem facing SE is, of course, whether a function should be implemented in hardware (including firmware) or software. For most functions the decision is clear-cut. However, functions, or operations, that can be implemented in hardware or software or both are called hardware/software *codesign operations* (Woo, 1994). These types of functions is in general primitive, specialized and has strict performance requirements. Effective partitioning (allocation) of codesign operations into hardware or software depends on many factors including performance, cost, maintainability, flexibility and size. The resulting trade-off analysis closely parallels the comparison or economical allocation techniques within HE (Rouse, 1991).

6.6.3 Distributed AI System Design

Multi-agent problem-solving, a sub-field of distributed AI, is concerned with coordination, task decomposition, *task allocation* and interaction/communication among 'intelligent' agents. An intelligent agent may be defined as an entity capable of performing at least one of sensing, decision making or acting. Agents may need to share knowledge, goals and plans to achieve a single global objective or separate individual objectives that interact. Agents often need to reason about the coordination process and the intentions or beliefs of other agents. An OO architecture is often used in multi-agent systems. Objects, representing agents, communicate by asynchronous message passing which in turn changes the internal state of the objects.

Multi-agent planning tackles the problems of task decomposition and task allocation (i.e., finding agents that can execute them). Agents must possess the capability to perform a task, have necessary resources (e.g., time) and required knowledge. Note that task allocation is itself a task and that tasks are allocated to agents in run-time. A development framework for agent oriented applications, CADDIE, has been deve-loped as reported by Farhoodi (1993). There are, however, few examples of large scale operational multi-agent systems and the technology must be considered as immature.

6.6.4 Software Design

The main allocation problems in SE are the allocation of behaviour to software components and the allocation of software components to various computers. The basic software components of traditional software engineering are *processes* (programs, tasks) with independent behaviour which is built from *modules* (functions, subroutines, procedures). The basic components in object oriented SE are objects and methods. An object might implement a process.

Various general guidelines to implementation design in software engineering have been proposed, examples from Bræk and Haugen (1993) are:

- Analyse requirements to physical distribution of interfaces and services. Minimize the bandwidth needed over channels covering physical distances.
- Allocate processes to computers such that the mean peak load on a single computer does not exceed about 30 % of its total capacity.
- Ensure that response time requirements are satisfied for time-critical sections by use of priority and isolation.
- Add redundant units and restructure system until reliability requirements are satisfied.

In order to cope with uncertain and increasing workload during the life cycle of a product, it is common to require a certain spare processing and memory capacity. The frequent use of such crude guidelines is an indication of the difficulties involved in predicting the performance by analytical means.

Several guidelines concerning allocation of behaviour onto modules have also been proposed. The best known are (Yourdon, 1989):

- *Cohesion:* Measure of how well a particular module's contents, its code and local data structures, belong together. Cohesion (measure of locality) should be maximized. Modules should perform only one or a small set of operations which are grouped for some logical (not arbitrary) reason.
- *Coupling*: Degree of interconnection between modules. Coupling should be minimized. When triggered, the module's operation should not depend on values in global data structures or inside other modules.

Similar guidelines have also been extended to OO software engineering, (Coad & Yourdon, 1991). The most important motivation behind these guidelines is not increased processing performance, but reduction of programming errors and increased maintainability (i.e., reduction of life cycle cost).

6.6.5 Real-time Software Design

The need for information processing in a real-time system varies in a more or less stochastic manner. Given finite resources (as processing capacity and memory) in the system, it is necessary to manage the allocation of these resources to the processes performing the information processing in order to fulfil deadlines. This allocation is referred to as scheduling and is an important part of the operating system software. Systems with absolute timing requirements are called *hard real-time systems*. There are two distinct approaches to scheduling in hard real-time systems: run-time scheduling (on-line scheduling, dynamic scheduling) and pre-run-time scheduling. The first require that the schedule is calculated at run-time and is very common in real-time systems. Advantages of this approach are flexibility and adaptability to changes in the environment. Disadvantages can be complexity and high run-time cost. In Xu and Parnas (1993) it is argued that, given certain reasonable assumptions, this type of scheduling cannot guarantee that all timing constraints will be satisfied. A mixed strategy including pre-calculated schedules (i.e., fixed allocation) in addition to run-time scheduling is necessary in order to fulfil absolute timing requirements.

6.6.6 Evaluation

Performance analysis of computer systems (Jain, 1991) has several objectives:

- Determine number and size of components (capacity planning).
- Evaluate design alternatives.
- Compare two or more existing systems.
- Determine optimal parameter values (system tuning).
- Identify performance bottlenecks.
- Characterize system workload.

There are three techniques for performance evaluation: analytical modelling, simulation and measurement. The latter requires the existence of a prototype as opposed to the two first *analytical* methods. The criteria for selecting an evaluation technique, for example time, cost and validity, parallel those used in HE in studies involving operators. The main advantage of simulation is that a sufficiently accurate evaluation might be achieved within limited time and cost. Further, collecting measurements from a complex distributed computer system is difficult due to lack of control with the environmental parameters and might be compared with a human-in-the-loop simulator evaluation.

The increasing use of simulations at various levels, in order to *select* among alternatives, *validate* (are we building the right system?) and *verify* (are we building the system correctly?) design solutions, is a major trend within SE. The trend concerning trade-off analysis is commented in the RSG.14 report (Beevis, 1992).

6.7 DISCUSSION

FA is in itself not a big issue in SE and this seems to parallel the state-of-practice concerning FA within HE as reported by RSG.14 (Beevis, 1992). The FA to human and machine seems to depend on both a formal analytical and a prototyping approach. The general agreement is that the success of allocation decisions concerning operators depends heavily on the implementation and that a proto-type or rather an operational system is required in order to determine the success.

The dichotomy between human and machine with regard to FA seems somewhat artificial since the functions usually in some way or other are shared. The main assumption underlying so-called 'human-centered system design' is that people are responsible for system objectives (at some operational level). The implication with regard to design objective is therefore to support humans to achieve operational objectives for which they are responsible (Rouse, 1991). Even though a function is allocated to the machine (automation), the operator will usually have a supervisory control role, with possibility and responsibility to intervene if necessary.

The allocation is often regarded as a mapping from the lowest level functions to a set of system components. However, consider a function allocated to the operator. He will need a description of *what* to do (task analysis) and *how* (MMI, procedures). But he should also know *why*, and this makes it necessary to consider functions (really behaviour) at one or more higher abstraction levels. An operator performing a job consisting of a number of tasks and responsibilities needs a model of the system at various abstraction levels. This type of knowledge is denoted as the operator's internal model. The need for behavioural and structural information at various levels is discussed by Rasmussen (1986) in what he denotes as the 'abstraction hierarchy'. Likewise, the machine may need a model of the operator's behaviour in order to provide adaptive aiding and an intelligent interface.

6.7.1 Consequences on Function Allocation from System/Software Engineering Practices

Development of formal behaviour models and their subsequent analysis is an important trend in SE. However, the human system component and his behaviour are usually modelled only superficially. There is still a tendency within system engineering to draw the system boundary too close to the machine and away from the human. The implication of the MMI on the total operator job, or vice versa, is thus not analysed in a sufficient degree.

The attitude towards FA seems to be rather pragmatic in current SE practice. System/software engineers are in general exploiting technology as much as possible in order to increase the automation level, build a repertoire of decision aids and make better and more intelligent MMI. Partitioning of functions into more or less mutually exclusive human and machine sets is not really addressed. This coincides with modern HE views that such a partitioning does not take full advantage of overlap in intelligent capabilities between human and machine.

The impact of decision aids on system performance is rather difficult to analyse. Few software/system engineers consider the potential cost associated with the introduction of decision aids, e.g., that operator workload and system performance (man and machine) will be a function of the reliance on the aid.

It is in general agreed thát OO development is bound to have a major influence on the manner in which systems are built (Loy, 1990). Differences in terminology and modelling practices among SE and HE might therefore increase, and in turn affect the FA process.

6.7.2 Contribution from Systems/Software Engineering to Function Analysis

The most promising developments with regard to formal behavioural modelling languages have, and will probably also in the future, come from the SE community. A formal behaviour model is an important input to the FA. Further, allocation (and its basis) should also be formally described. This would simplify impact analysis of changes during a system's life time and reuse of existing designs in new projects.

Whether HE can benefit from OO system modelling techniques is still an open question. Proponents of OO in system development argue that the modelling concepts used in OO more closely resemble the way humans organize knowledge and information, i.e., OO modelling concepts fit more closely the internal model. Modelling an operator is actually modelling his internal model, so it could be hypothesized that OO modelling concepts should be more suited for operator modelling.

Modern SE modelling languages could be used to describe normative, rule based operator behaviour and information needs of knowledge based behaviour. Note that we are talking about the capabilities of the modelling language. The identification of such operator behaviour, however, is often difficult. In those circumstances where the operator can be modelled as a computer system (of arbitrary complexity, if needed) and the crew as a distributed system, SE could possibly contribute with expertise.

HE might benefit in modelling of operators from various behaviour modelling constructs in SE such as alternation, concurrency and inheritance. Behaviour might in some cases be easier to understand if alternation or concurrency is used. Alternation can for instance simplify the description of interrupt handling.

A formal behaviour model can be simulated directly and might itself include the details required to yield useful performance data comparable to a SAINT (Sys-tems Analysis by Integrated Networks of Tasks) simulation. A more realistic scheme is an automatic translation of a behaviour model to a discrete event simulation program to which more details can be added. This would enforce a certain consistency with the behaviour model. Likewise, partly automatic generation of prototypes, necessary in order to evaluate FA, might be supported.

Traditional HE function allocation techniques based on comparison or cost will not necessarily result in a set of functions that are coherent and satisfactory to the operator. The guideline of maximum cohesion, however, is to a certain degree consis-tent with the definition of a meaningful operator job. The 'coupling guideline', on the other hand, advocates a design that would isolate the operator from the rest of the system and thus complicate updating of his internal system model. The need to keep the operator in the loop requires a design which is contradictory to the 'coupling guideline'. This is suggested by Price (1985) as one of four allocation rules: Allocate functions for effective and cognitive support".

6.8 MAIN CONCLUSIONS

We see an increased interest in using OO techniques also in system and functional analysis. This will inevitably affect HE. For example, will FA and task analysis benefit from system functions modelled with OO concepts? Will OO concepts make it easier or more difficult to construct models of the human-machine system appropriate for typical HE activities? The claim that OO modelling techniques more closely map to internal model constructs should be researched by HE. If this is valid, OO modelling techniques could possibly have something to offer cognitive task analysis as well.

As we have seen, SE puts little emphasis on developing techniques and guidelines for FA. The reason, we believe, is that allocation decisions depend heavily on the application domain, the capability of the technology and on the constraints under which a system is developed. Techniques and guidelines applicable across a broad range of systems must necessarily be so general that they are of little value. Much more emphasis is put on techniques to evaluate and predict how a certain FA fulfils requirements. The main analytical techniques for these tasks are modelling and simulation. For HE to be able to adopt these analytical techniques for evaluation of FA decisions and design, models of cognitive operator tasks applicable for system development are much needed.

As the human-machine systems steadily become more software intensive, it is important to see how the *complete human-machine system*, including the users, can be modelled and analysed within the frameworks used by SE. A more comprehensive modelling of the human part of the system requires the expertise and involvement of HE. However, an integrated modelling and analysis would, to a large extent, require that HE use the same modelling languages as SE.

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14. Abstract:

Function allocation is generally defined as the process that assigns broadly defined activities to humans and machines in a system. Information software systems, such as exemplified in Command and Control systems, require a different model of function allocation than do traditional human-machine systems. A two-stage process of function allocation was developed which adds support-based allocation to traditional human-machine allocation. In stage 1 focus is on human-computer strength and weaknesses, but absolute and final allocations are not the goal. Rather, the results of stage 1 are used to address the requirement for the computer to support the human; a process which occurs iteratively with stage 2. The model was applied in the context of the development of a Canadian Forces Artillery Regimental Data System.

CHAPTER 7

FUNCTION ALLOCATION IN INFORMATION SYSTEMS

G.U. Campbell and P.J.M.D. Essens

7.1 INTRODUCTION

Function allocation is generally defined as the process that assigns broadly defined activities to humans and to machines in a system. These activities are described as work roles, or functions, and the tasks associated with the work roles. It has been noted by several authors (e.g., Meister, 1991) that the decisions concerning what to automate in software-based systems differ from the decisions taken in more traditional human-machine systems. Traditionally, the allocations were treated as dichotomous decisions. In human-machine systems, if a function required lifting heavy weights or rapid calculations then allocation could be unambiguously assigned to a machine. If complex pattern recognition was required, then the function was equally-unambiguously assigned to the human operator. In software-based systems, automation relates less to the automation of labour and far more to human information processing and cognitive models. Specification of functions and tasks shifts toward a more cognitive focus.

Given the shift in focus, traditional function allocation is not appropriate in the development of software systems. Rather than to discard function allocation altogether, its value can be retained and enhanced by adding new concepts. In the new conceptualisation the possible roles that the computer and the human can play in the developing system are of primary concern. Guidelines to define such concepts should specify that the capabilities of human and machines should augment and enhance each other. Function allocation should be done on the basis of combined human-computer strengths and weaknesses; with the overriding goal being to optimise the performance of work. Three general categories for allocation can be distinguished: Operator primarily, human-machine mix, and machine primarily (Meister, 1985).

7.2 HUMAN-COMPUTER-PROCESS RELATIONSHIPS

Recently, concepts such as 'support systems' and 'joint systems' have become popular (Woods & Roth, 1988). Together with the concept of 'supervisory systems' (Sheridan, 1988) these concepts address the relationship between the human and the computer in dealing with the processes they must control or manipulate. Four human-computer-process interactions can be distinguished (see Figure 7.1):

Split model. The Split model represents the more traditional allocation approach. In that the interaction with the process is statically divided between a human and a machine or computer.

Mediation model. In this model the computer is the mediator between the human and the process. The Mediation model is typical of supervisory control defined in the strict sense (Sheridan, 1987). Essentially, the computer acts on input from the process. Within this conceptualisation the relationship between the computer and the human can have several definitions. For example, this model includes the case where the computer selects an action and informs the human who can then opt to stop the process. Similarly, the computer may complete the entire job and inform the human of the results, if requested or required.

Support model. In the Support model the human interacts with the process and the computer supports the human whenever the human requests support. This tool-like configuration is characteristic of many decision making situations. For example, an intelligence system that supports the commander in identifying enemy organisations by drawing from a database of past activities would be representative of this model.

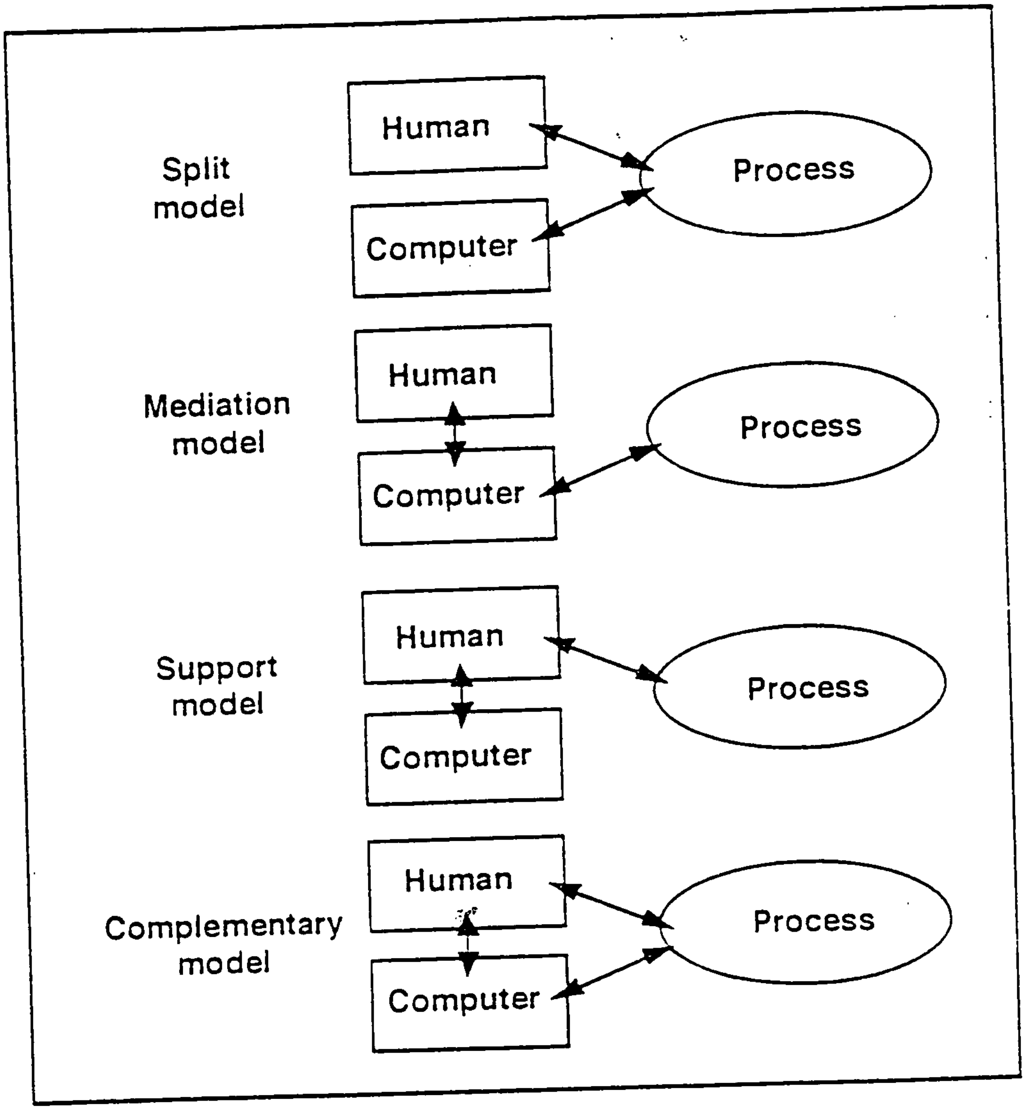

Figure 7.1: Roles of human and computer in handling the processes in the world

Complementary model. A Complementary model can also be described. In this model there is a shared role in managing the process. Both human and computer act on the process in a dynamic role allocation. The allocation is based on operational conditions, workloads, and priorities.

A fifth interaction model is also conceivable. In this final conceptualisation the human becomes the mediator and the computer dictates what should be done. This model is currently employed by some science-fiction writers.

The central issue is that conceptually different roles for computers and for humans are possible within a system. The concept of respective roles suggests specific allocation questions to be considered in the design of the system. Information systems that are emerging in Command and Control typically serve functions such as handling and storing large volumes of data and facilitating communications. At the same time, they provide opportunities for the introduction of support concepts in the Command and Control process. In these systems one role of the computer is to support the human operator as described in the Support model, above.

Software engineers are paying increased attention to and are more aware of the human operator as an integral part of system design. Attention to the operator as part of the system is a fundamental shift from the traditional engineering approach to integrated system development. However, without an appropriate process, software systems designers tend to focus on developing the elements of the system *per se* and pay scant attention to the tasks or cognitive models of the operators (Beevis, 1992). The two-stage function allocation process presented here helps designers focus on and address the role of the operator and the computer in the system in the light of the system goals that must be achieved. It encourages the designers to think in terms of supporting operators in their performance.

7.3 A TWO-STAGE FUNCTION ALLOCATION PROCESS

Although the multi-purpose use of the computer in software systems allows roles to be combined in one machine, allocation decisions should reflect and optimise the possible different roles of the human and the computer. Since one role of the computer is to support the human, allocation questions should address the capabilities and limitations of the human and the interaction with the process. To accommodate this concept of function allocation an iterative process comprised of two stages is proposed here (see Figure 7.2). The two-stage process can be thought of as a way to integrate the Split model and the Support model. The first stage addresses the Split model and the second stage addresses the Support model. The result approximates a Complementary model without discussing dynamic allocation but instead focusing on the roles of the human and computer and the integration of the models.

Preliminary Stage: Function Analysis. Prior to any function allocation process a function analysis of the system's objectives is conducted. The result is a specification of functions; usually relative to each other against time.

Stage 1. Essentially traditional questions of human and machine capabilities are asked. Allocations are made to human, computer, or a combination of the two based on a combination of 18 criteria (shown in Figure 7.3). These criteria reflect the traditional allocation dichotomy.

Stage 2. Allocations from step one are further analysed. Exclusively computer allocations are subjected to computer function analysis via systems engineering methods. Exclusively human and combined human/computer allocations are analysed to determine what support can be provided to the human and what joint operations require an interaction between the human and computer. Joint operations are then examined to determine how the roles can be optimised.

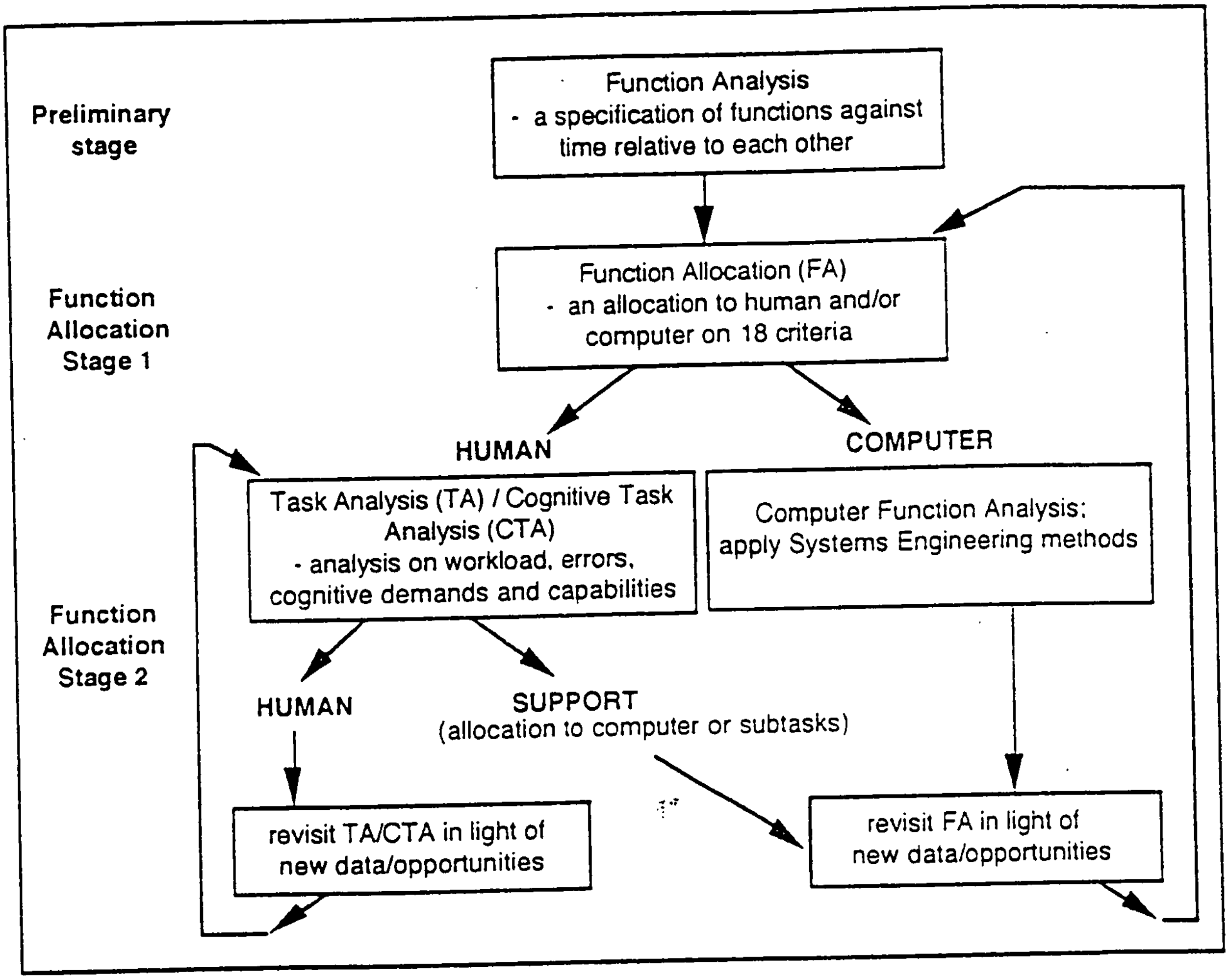

Figure 7.2: Two-stage model of function allocation in information systems

In essence, then, we propose an iterative process in which the first step highlights the relative strengths and weaknesses of humans and computers. The second step uses the information from the first to focus and to direct further analysis. Because the process is iterative, the allocations may change as new data or opportunities become clear. In the following, we describe how the first stage was applied in an information system project. Methods for the second stage of the allocation process, task analysis and cognitive task analysis, can be found in, for instance, Beevis (1992), and Essens, Fallesen, McCann, Cannon-Bowers, Dörfel (1994).

7.4 THE APPLICATION OF FUNCTION ALLOCATION IN ARDS/ADM

The two-stage process was developed at MacDonald Dettwiler and Associates (MDA) in interaction with the TNO Human Factors Research Institute and applied to the systems development of the Advanced Development Model of an Artillery Regiment Defence System (ARDS/ADM).

Only after the start of the ARDS/ADM project did it become clear that focus on the human operator would be necessary for successful development of the system. MDA's project team recognised the need to ensure that the delivered system be usable and acceptable in the field. A prime consideration in successful user-oriented design is to ensure that the users' tasks are addressed as part of the system development; as opposed to adhering strictly to a traditional engineering model which focuses on the hardware and software of the system itself.

The function allocation process presented here was developed in response to a variety of requirements. First, to be successfully adopted in industry any analytical approach must be cost-effective. It must provide maximum utility at minimum cost. The ARDS/ADM project encompasses a large problem-area which embodies a complex set of human tasks. An absolutely exhaustive function and task analysis was beyond the scope of the project and was a risk to be avoided. A feature of the function allocation process described here is that it discouraged over-analysis of the ARDS/ADM functions. That is, initial function allocation (Stage 1) began with reasonably high-level functions specified. In instances where the Stage 1 process suggested mixed allocation, the function was decomposed further. The process was repeated as necessary until the tasks and functions were sufficiently defined. Essentially, overspecification was reduced.

Secondly, as is common in the industry, few engineers on the ARDS/ADM project team had experience in structured function or task analysis. The iterative approach fostered an acceptable comfort level because the function allocation process was perceived as flexible.

Thirdly, because absolute judgements required by traditional function allocation methods are difficult to make, the new process used paired comparison judgements to make allocation assignments. This shift in technique meant that domain experts (subject matter experts) could learn to apply the process with minimal training and the process was completed very quickly even for large numbers of functions.

Fourthly, the traditional model (the Split model, Figure 7.1) was determined to be inadequate for ARDS/ADM software development. ARDS/ADM development falls into a model of human-computer-process interactions in which the computer supports the human (the Support model). The traditional approach did not take adequate account of the cognitive models and information processing that led to particular allocations, nor did the traditional approach focus design attention on how to support the user in the tasks allocated to the humans. In general, then, the process presented here provides more useful and appropriate analysis of the user's role as part of a complete system.

In addition to fostering an improved understanding of the mutually-supportive roles of the human and the computer, the ease with which the process can be applied ensures proper and capable application. Simplicity is particularly important because many contractors do not have human factors specialists on staff. Some companies assign an engineering team member the responsibility for the human engineering aspects of a project. That party often does not have any training in human-related analysis. Accordingly, the method presented here was designed to be applied with little training.

Prior to applying the two-stage function allocation process described here, the functions are specified. (In the ARDS/ADM development, the specification was done by an MDA Human Factors Specialist and two expert artillery officers). Identified functions are placed in a function allocation Decision sheet which allows easy comparison of each function against a set of allocation criteria. The Figure is comprised of a set of allocation criteria pairs developed from the seminal work of Fitts (1951, cited in Salvendy, 1987) and of Bekey (1970), and is presented in Figure 7.3. The allocation comparisons allow the domain expert to allot functions to humans or computers (or both) based on the capabilities of each. The comparisons address capabilities such as short-term memory, ready access to information, and inductive versus deductive processes. The comparisons describe inherent capabilities and so are independent of the hardware available, details of design, or implementation options.

In Stage 1 of the function allocation process one or more domain experts review each specified function against each pair of criteria. (On the ARDS/ADM project the primary domain expert was a trained artillery officer. A second domain expert, an MDA employee familiar with the domain, also completed part of the allocation process.) The allocation of the function on each of the criteria is then tallied. The resulting sum is examined to determine how many of the criteria favour human strengths and how many suggest computer implementation. At the completion of Stage 1, each function is allocated to humans, machines, or a combination of each. The allocations are examined further in the second stage of the function allocation process.

When the function allocation tally from Stage 1 points to a machine implementation the designer takes into account the actual capabilities that led to the allocation of the function to the computer in the first place. For example, the function may require computation, a skill at which humans are notoriously weak. The appropriate implementation can then be addressed by the software design team.

Figure 7.3: Function allocation decision sheet

Allocation to Human (H)	Proposed			Predefined[1]			Score		Data Sensing Monitors low-probability events.	Low absolute sensitivity thresholds.	Can detect masked signals.	Can acquire data incidental to task.	Not subject to jamming.	Good pattern recognition.	Sensitive to a variety of stimuli.
to Computer (C)	C	H	Both	Regt	Mgt	Oth	C	H	Poor at unexpected events.	Higher thresholds.	Poor signal detection in noise.	Insensitive to extraneous factors.	Subject to disruption.	Little perceptual constancy.	Sensitive beyond human range.
Functions															
1. Warning Phase															
Receipt of warning order.		√				√									
Anticipation of future operations.		√				√									
Conduct quick time estimate.		√					2	5	H	x	x	H	x	x	x
Conduct quick map estimate.		√					2	6	H	x	x	H	x	H	x
Get status of ammo.	√						8		C	x	x	C	x	x	x
Get Enemy info.	√						8		C	x	x	C	x	x	x
Prepare warning order.	√						4	1	C	x	x	C	x	x	x
Issue warning order.	√						6	0	C	x	x	C	x	x	x
2. Main Planning Phase															
Receipt of orders from higher HQ.	√						3	0	C	x	x	C	x	x	x
Conduct time estimate.			√				3	4	C	x	x	H	x	x	x
Do an estimate.			√				3	4	H	x	x	H	x	x	x
Do an outline plan.	√						5	0	C	x	x	C	x	x	x
Issue outline plan to Ops Officer.	√						7		C	x	x	C	x	x	x
Recce to confirm plan.		√					1	7	H	x	H	H	x	x	x

Note- x = not relevant for this function

[1] Predefined by Regiment, Management, or other reasons

Figure 7.3: Function allocation decision sheet (continued)

Data Processing							Data Transmission			
Can choose alternate strategies.	Can generalize from limited data.	Computation weak and inaccurate.	Limited channel capacity.	Can store large amount of info. and recall relevant facts.	Can handle a variety of transient overloads.	Short term memory poor.	Poor tracking.	Can adapt to situations.	Performance deteriorates with time.	High response latency.
Best for repeated strategies.	Deductive processes.	Accurate and rapid computation.	Channel capacity can be enlarged.	Can store and recall large amounts of info. quickly.	Overloads can seriously disrupt.	Short term memory good.	Good tracking.	Cannot adapt to situations.	No fatigue, other time effects. Can do repeated tasks.	Can have low response latencies.
C	H	C	x	H	x	x	x	H	x	x
C	H	C	x	H	x	x	x	H	x	x
C	C	C	x	C	x	x	x	x	C	C
C	C	C	x	C	x	x	x	x	C	C
C	C	x	x	H	x	x	x	x	x	x
C	x	x	C	x	x	x	x	x	C	C
x	x	x	x	x	x	C	x	x	x	x
C	H	C	x	H	x	C	x	x	x	x
C	H	C	x	H	x	C	x	x	x	x
C	C	x	x	x	x	C	x	x	x	x
C	x	x	x	C	x	C	x	x	C	C
H	H	x	x	H	x	C	x	H	x	x

If the allocation tally from Stage 1 points to human strengths then further decomposition helps determine any information that can help support the person to perform the tasks related to the function.

Any allocation which is at least partially assigned to the human operator is further examined to determine if machine support of that function is appropriate. Mixed allocations are decomposed to determine which functions should be allocated to the machine and which tasks to the human operator, and again, human tasks are examined to see if computer support had potential benefits. Strictly machine functions are not analysed further.

As expected, many functions in ARDS/ADM require capabilities of both human and machines, because the Command and Control functions involve human decision making. Decomposition of these functions indicated which parts of the function should be assigned to machines, which to humans, and provided initial information which was used to determine how the human tasks could be supported. For example, the allocation of the function Quick Time Estimate under the Warning Phase in the function allocation decision sheet (Figure 7.3), indicates that repeated strategies and complex, rapid calculations are areas for support in a mainly human-operated function.

7.5 TRAINING / INSTRUCTIONS

To achieve a valid function allocation analysis the evaluator must be familiar with the domain. On ARDS/ADM the primary domain expert was a trained artillery officer. A second domain expert, an engineer familiar with the domain, also conducted part of the function evaluation. After as little as 30 minutes training each domain expert was conversant enough with the process to continue without support.

As part of the training process the evaluators walked through a number of the functions with a human factors specialist (the first author of the current paper). The eighteen comparisons were repeated for a sufficient number of functions to allow the domain experts to feel comfortable with the process and their role. The domain experts were encouraged to make relatively quick decisions and were assured that their first impression is most likely to be the most valid.

Not surprisingly, in many instances the analysis led to assignments that were counter-intuitive to the domain experts. To prevent the domain experts from re-evaluating the assignment in order to make it match expectations, the domain experts were assured that these discrepancies are valuable results of the process. Comfort with the process was also enhanced by assurance that the function allocations are not absolute, that the results of the analysis would be used to further understand the entire human/computer system rather than be applied as fixed answers.

7.6 CONCLUSIONS

A systematic allocation process is vital to optimising automated support of any mission. The method presented here provides a generic tool that allows the designer to allocate functions to people or machines based on systematic consideration of computer/human capabilities. While function allocation can be done on an *ad hoc* basis, and often is, the process developed here enforces consideration of each function on a specific set of factors ensuring that all factors are considered and providing an objective basis for the decisions.

In addition, the process addresses a user-centred approach which forces consideration of the user as a part of the system. The model under which the approach was developed assumes that the interaction with the process is not statically divided between the human and computer. Rather, the human interacts with the process. To optimise that interaction and ensure adequate support for the human, the results of an initial function allocation process are further reviewed to determine where and how the computer can best support the person. To do so the designers must take into account human and computer strengths and weakness and the cognitive models of the user.

The results of a function allocation process provide a systematic basis for making judgements and an objective basis for design decisions. As well, the results point explicitly to those functions which need to be understood in more detail while allowing the remainder to be addressed immediately.

Certainly the method presented here applied to the development of ARDS/ADM pointed the way to allocations that were counter-intuitive both to the domain experts and to the design engineers. Equally important, the method focuses attention on the operators tasks, missions, and cognitive models. Finally, the method is effective, efficient, and usable.

7.7 FURTHER DEVELOPMENT

To be most effective this method should be applied early in the development of a software system. It is less effective to apply the results of a function analysis in a project that has already begun system design, data modelling, or software development. The functions should be defined and the allocation process begun in the first phase of the project.

Unfortunately, on the ARDS/ADM project the analysis was delayed until after the project had begun and system design was well under way. While the process had utility and was beneficial to the development of the project, it would have had greater impact had it been conducted much earlier. This would have provided much better understanding of the users' tasks in the initial system concepts and earlier focus by the design team on the human element of the ARDS/ADM system.

The process itself requires some modifications. To increase comfort levels of the domain experts, the instructions should include assurances that allocations that are counter-intuitive provide valuable information. As well, assurance that the allocations will be examined in more detail increases the domain experts' confidence in their own decisions and allows them to complete the process more quickly and use their experience to make rapid decisions.

Domain experts rarely have experience in human factors analysis. Asking them to complete the figure requires some preparation, although it is not arduous or extensive. It is worthwhile to take a few minutes to provide a detailed explanation of the meaning of each of the criteria. This guide should be targeted to users with little or no knowledge of human information-processing or perception. It should be available for the domain expert for reference.

We caution that no one function allocation process is appropriate for all software systems development. The process presented here is effective as an initial step, in many environments it may be the only step. Its use does not preclude the application of other processes. Ideally the results of this allocation method will form the basis for other processes. For example, using the outputs of this function allocation process as a base, prototypes can be built exploring various combinations of allocations and support structures to maximise effectiveness.

7.8 ACKNOWLEDGEMENTS

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The emergence of highly automated information processing systems being developed by the Army Command, Control, Communications, and Intelligence (C3I) community raises certain questions related to the design of crews and interfaces for these systems. The US Army Research Laboratory (ARL) at Fort Huachuca, with expertise in information processing and behavioral science, has recently evolved their research support to the C3I community to develop systematic and quantitative methods to address these questions. This paper describes the approach taken in the development and application of job and workload assessment methods for new Army C3I systems, and the implications for function allocation. Methodologically, what was adopted was the measurement of C3I task and job demands associated with new system and new operating contexts, so that these demands could be compared to current performance baselines. Critical parameters for comparison are the demands placed on soldiers due to new job factors and mission conditions, and soldiers' knowledge, skills, and abilities. A series of six method steps for C3I task and workload analysis are described and illustrated using two case studies.

CHAPTER 8

TASK AND WORKLOAD ANALYSIS FOR ARMY COMMAND, CONTROL, COMMUNICATIONS, AND INTELLIGENCE (C3I) SYSTEMS

B.G. Knapp

8.1 INTRODUCTION

The US Army continuously reviews its missions, develops new tactics and plans, and acquires new equipment, in order to fulfill its modern defense roles. A critical issue for Army decision makers is insuring that soldiers, as currently selected and trained, are capable of operating the new equipment and performing effectively. In particular, the emergence of highly automated information processing systems being developed by the Army Command, Control, Communications, and Intelligence (C3I) community raises certain questions: How well do current Army personnel capabilities match the demands and designs of high technology, supervisory control systems being developed?; Do the new systems differ *incrementally* or *exponentially* in workload from immediate predecessor systems?; and, What are the tactical operating procedures and training implications of introducing the new automation components?

The US Army Research Laboratory (ARL) at Ft. Huachuca, with expertise in information processing and behavioral science, has recently evolved their research support to the C3I community to develop systematic and quantitative methods to address these questions. Efforts have been targeted to assessing task performance during C3I system design stages, prior to final testing, to ensure that functions and tasks are optimally distributed among soldiers and automated processors, so that information processing workload does not exceed resource capabilities. This paper describes the approach taken in the development and application of job and workload assessment methods for new Army C3I systems, and the implications for function allocation.

8.2 METHOD DEVELOPMENT

The methods being developed by ARL are designed to assess the impact of mission, task, personnel, and environment variables (e.g., new equipment, expanding scope of tactical missions, increased battlefield tempo, new operating tactics, changing personnel characteristics in an all-volunteer Army, etc.) on C3I soldier performance, by augmenting or supplanting conventional task analysis and workload estimation techniques. The conventional methods have been adequate for the procedure-oriented, perceptual motor tasks characteristic of aviation, maneuver, and weapon control systems, but not sufficient to address the process-oriented, cognitive tasks central to C3I systems. It was clear that function allocation for C3I systems must be supported by a more comprehensive and elaborate task and workload definition and analysis process, allowing collection of data that can be persuasively used in deciding among alternative soldier and machine function allocation designs.

Methodologically, what was adopted was the measurement of C3I task and job *demands* associated with new system and new operating contexts, so that these *demands* could be compared to current performance baselines. Critical parameters for comparison are the demands placed on soldiers due to new job factors and mission conditions, and soldiers' knowledge, skills, and abilities.

This departs from conventional task decomposition and time studies that rely on time per task and additive network models to detect work overload. Instead, information processing tasks are measured not so much in terms of *time spent* but on *resources* used to produce information products (situation report, battle plan, operations order, etc). A strong case can be made that increased cognitive demands, *along with* decreased timeframes for information processing, will cause information output products to be compromised. Add to this any degradations in environmental and communications factors, and the designation of functions between persons and automation becomes critical.

8.3 METHOD STEPS

Task and workload analysis for C3I missions, based on resource demands, involves a series of process steps described below:

a. State Issues and Objectives of Analysis to Focus on Methods Needed. Depending on the questions being raised, this allows data collections to be targeted to exactly what is needed. For example, is allocation of soldier functions related to declining personnel inventories, design of training plans, need for equipment specifications, or a combination of factors?

b. Derive Mission-Event Flow and Anticipated Scenario Sequences. Sessions with subject matter experts must proceed beyond eliciting traditional task lists, to depicting graphical representations of task and workflows triggered by scenario and information events. This allows subsequent analysis to account for task loops, decision points, and communication lines (person and machine). An example of a simple task flow diagram is shown at Figure 8.1.

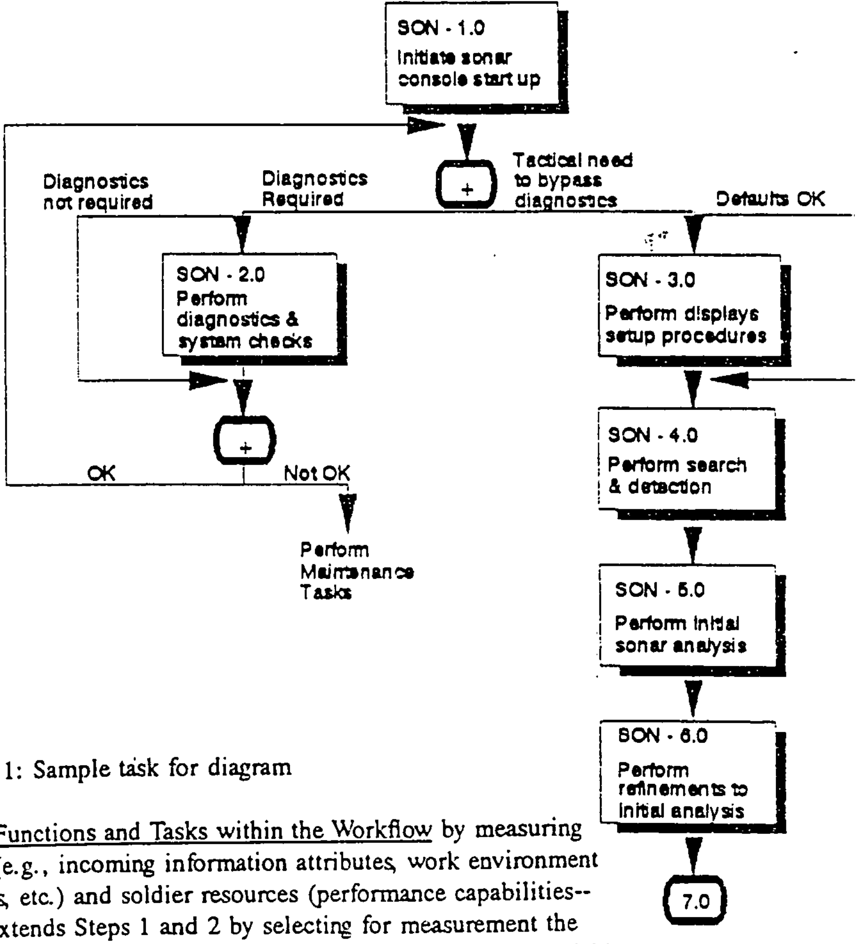

Figure 8.1: Sample task for diagram

c. Conduct Assessment of Cognitive Functions and Tasks within the Workflow by measuring relevant task and environment characteristics, (e.g., incoming information attributes, work environment design, ambient conditions, mission conditions, etc.) and soldier resources (performance capabilities--knowledge, skills, abilities--and limits). This extends Steps 1 and 2 by selecting for measurement the variables pertinent to the job within the context of the issues. An example listing of potential job variables from which such selections could be made is shown in Figure 8.2.

1.0 Operational Environment
    Scenario Pace (threat complexity - # entities, time pressure, scope of mission)
    Operational Mode (plan or execute)
    Tactic Mode (offenses or defense)

2.0 System Environment
    Automation Level (manual, Auto 1, Auto 2, Auto 3)
    System I/O Complexity (high, medium, low)
    Required Protocols (difficult, moderate, easy)

3.0 Incoming Information and Database Environment
    Form (text, voice, face-to-face, map graphics, imagery)
    Source (commander, staff, subordinate, flank unit, higher authority)
    Content (orders, guidance, status, situation report, system alerts)
    Rate (frequency of incomings by type)

4.0 Linking Demands
    Interaction-Autonomy Level (high, moderate, low)
    Input-Output Channels (number and type)
    Network Complexity (many links and nodes, moderate, few)

5.0 Cognitive Processing State
    A. Information Acquisition (complex, moderate, nearly automatic)
    B. Information Transmission (complex, moderate, routine)
    C. Data manipulation (complex, moderate, simplistic)
    D. Wargaming (prediction-inference, analysis, option generation)

6.0 Workspace Attributes
    Soldier Machine Interface (user-unfriendly, mixed, user-friendly)
    Ambient Conditions (extreme, moderate, just right)

7.0 Group Integrity
    Mobility State (stationary-all together, stationary-distributed, mobile-stationary mix, all mobile)
    Information Exchange Capability (face-to-face, voice, digital)
    Cluster Configuration (functional area, matrix, novel)

8.0 Personnel Status
    Skill Mix (experienced, experienced-inexperienced mix, inexperienced)
    Composition (technical, analytical, supervisory)
    Shift Protocol (all dedicated, trade-offs)
    Numbers Per Cell

Figure 8.2: Example job variables for workload assessment

d. Identify Potential Information Inputs and Decision-Action Outputs. Incoming information is the stimulus to action (task performance), and outgoing information products result from data transformation and analysis tasks which produce operator decisions and actions. This step provides initial insight into how the work could be distributed among crew members and machine processors, since various diagrams, variable listings, and preliminary values form a 'picture' of the job situation.

e. Assess Workload by Formally Measuring Task Demands, Under Differing Mission Conditions, soldier capabilities, and environment variables. Depending on the issue, task demand is measured on one or a combination of variables; measures are drawn from existing human performance databases. or data collected from experts using available -or custom designed measurement instruments.

f. Construct Integrated Task and Workload Models. A 'model' of the C3I tasks and associated workload for a given job may be as simple as a paper-and-pencil tally and comparison of the measures on a few variables. Or it may involve a complex network representation of tasks, task interrelationships, and workload parameter values for the tasks, necessitating a more sophisticated, computer-based analysis. In either case, workload 'profiles' are developed and compared, in order to derive the impacts of the factors of importance affecting task performance.

8.4 METHOD APPLICATION: TWO CASE STUDIES.

8.4.1 Army Aircrew Requirements for JSTARS (Joint Surveillance/Target Acquisition Radar System)

8.4.1.1 Step One (Para 3a above)

Of immediate interest for certain Army Intelligence systems is the assessment and comparison of skill and ability requirements needed for tasks by prospective soldiers. For the JSTARS, a new, high technology, intelligence sensor system designed to provide real time imagery information on the tactical battlefield, a question arose regarding suitability of current personnel to perform job tasks on both the prototype and objective system. At issue was whether imagery operators, who operated the prototype JSTARS with a manning level of two operators, would be overloaded by proposed capabilities of the objective system. The initial job was performed by two imagery operators using a limited, prototype version of the JSTARS system in OPERATION DESERT STORM (the 1991 Gulf War); the objective system could accommodate three operators, if needed.

8.4.1.2 Step Two (Para 3b above)

The JSTARS job flow was obtained from JSTARS experts: those familiar with functions performed in predecessor and prototype systems, and those designing the objective JSTARS. The functional job flow is shown at Figure 8.3. Six functions were identified: mission planning, prebrief, preflight, outbound flight, on-station mission performance, and post-mission duties and debrief. Of greatest interest for demand assessment was the on-station mission function; a further decomposition of which is at Figure 8.4.

8.4.1.3 Step Three (Para 3c above)

To compare cognitive task demand on the JSTARS prototype and Objective JSTARS, a job assessment method which included cognitive skills and abilities was required. Taxonomies which include knowledge, skills, and abilities for many jobs exist in the literature (Muckler, Seven, & Akman, 1990a), and an *evaluation* taxonomy was developed specifically for C3I jobs. The evaluation taxonomy provided the hie rarchy of variables specific to the job domain, and is used to structure evaluations, and point to measurement methods.

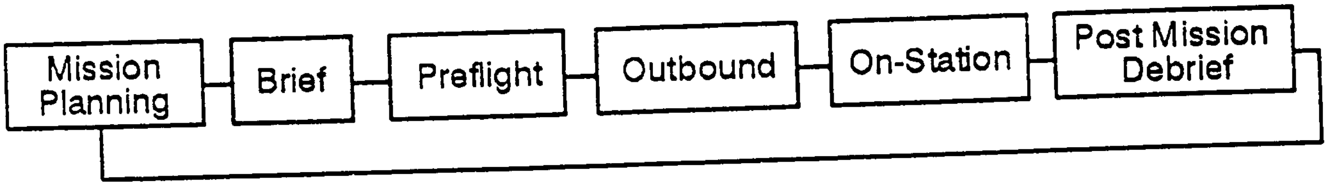

Figure 8.3: JSTARS functional job flow

The evaluation taxonomy (Muckler, Seven, & Akman, 1990b) is shown at Figure 8.5. For the soldier skills and abilities questions raised for JSTARS, variables in the taxonomy were selected from the "soldier characteristics-abilities and skills" category. These were decomposed to establish a core list of abilities and skills to be measured. The listing selected as most relevant to C3I, well-defined, and empirically based, was drawn from the work of Fleishman and Quaintance (1984) and is shown at Figure 8.6 (extensive discussion on the rationale for this selection is found in Muckler, Seven, & Akman, 1990a).

Modifications to the Fleishman work involved clustering skills and abilities according to higher level, logical aggregates to address questions and obtain measures at differing levels of detail. The taxonomy shown in Figure 8.6 is organized by the skill and ability clusters that were devised.

The abilities and skills taxonomy led to the design and development of a flow-diagram and scaling measurement method, the *Job Comparison and Analysis Tool* (JCAT). This is based on a technique originally used by Mallamad, Levine, and Fleishman (1980), but also included a matrix of job functions to further isolate skill and ability demands.

8.4.1.4 Steps Four, Five, and Six (Para 3d, e, f above) for task and workload assessment were combined for the JSTARS case study

In this single-system study, one information input condition was assumed (step four), where operators are triggered to "conduct the entire mission," defined as a "typical JSTARS targeting and surveillance mission for a Corps sector." Cognitive demands were assessed (step five) using the JCAT instrument with the JSTARS functions. Other potential loading factors (see Figure 8.2) were held constant (environment, information conditions, group dynamics, etc.), and the essential factors for increased loading on JSTARS operators was the introduction of the new equipment. Thus, the model of tasks and subsequent workload (method step six) is a set of quantitative profiles of the mission functions under two conditions: prototype JSTARS and objective JSTARS, which discriminate job demands for two and three operator positions.

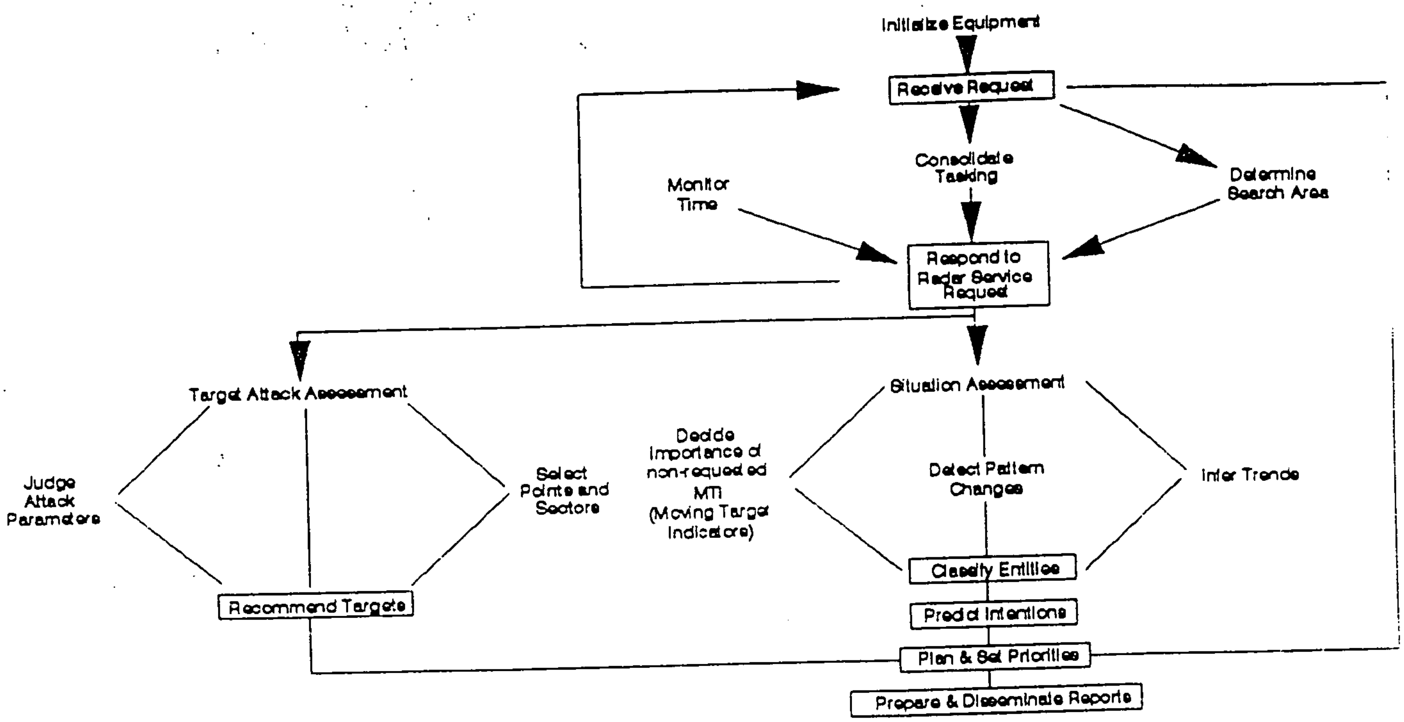

Figure 8.4: JSTARS functional flow decomposition: On station/mission operations function

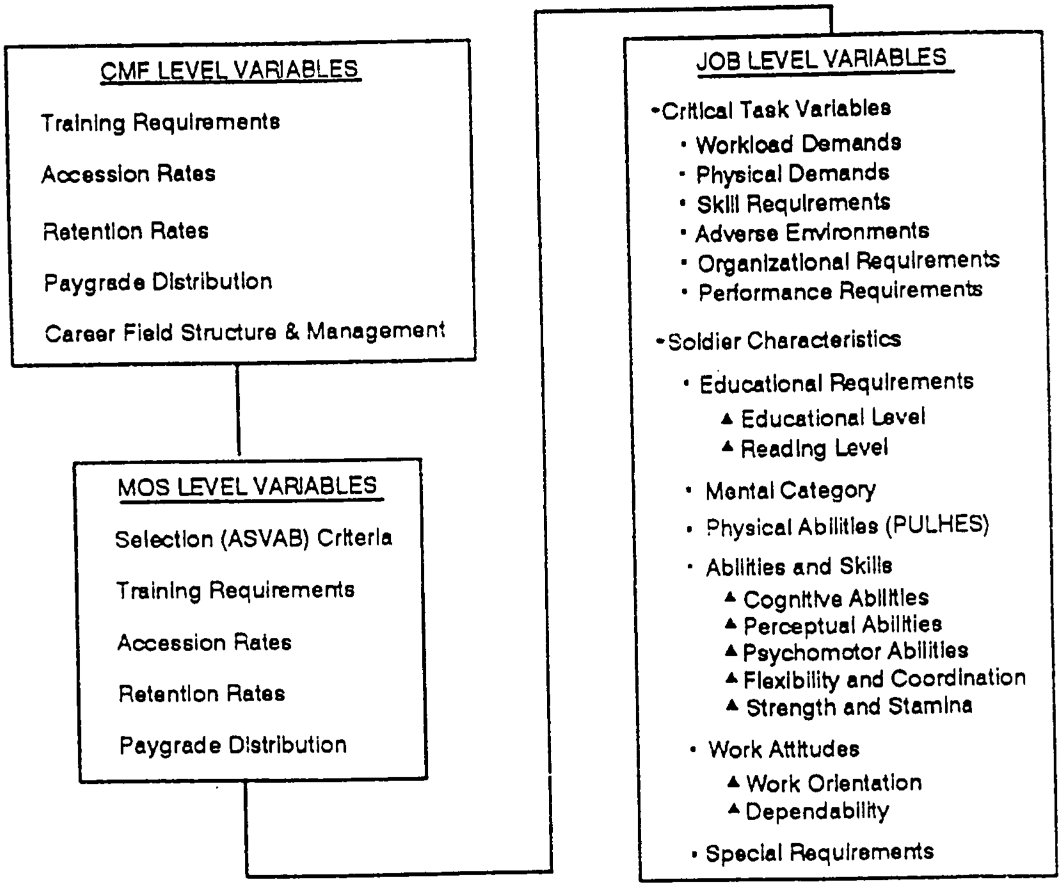

Figure 8.5: C2I occupational specialty evaluation taxonomy

COGNITIVE SKILL & EXPERIENCE CLUSTERS

COMMUNICATION

1. *Oral Comprehension*
2. *Written Comprehension*
3. *Oral Expression*
4. *Written Expression*

CONCEPTUAL

5. *Memorization*
6. *Problem Sensitivity*
7. *Originality*
8. *Fluency of Ideas*
9. *Flexibility of Closure*
10. *Selective Attention*
11. *Spatial Orientation*
12. *Visualization*

REASONING

13. *Inductive Reasoning*
14. *Category Flexibility*
15. *Deductive Reasoning*
16. *Information Ordering*
17. *Mathematical Reasoning*
18. *Number Facility*

SPEED-LOADED

19. *Time Sharing*
20. *Speed of Closure*
21. *Perceptual Speed & Accuracy*
22. *Reaction Time*
23. *Choice Reaction Time*

GREATER SKILL & EXPERIENCE RESULTS FROM
EXTENSIVE TRAINING & JOB EXPOSURE

PERCEPTUAL-MOTOR ABILITY CLUSTERS

VISION

24. *Near Vision*
25. *Far Vision*
26. *Night Vision*
27. *Visual Color Discrimination*
28. *Peripheral Vision*
29. *Depth Perception*
30. *Glare Sensitivity*

AUDITION

31. *General Hearing*
32. *Auditory Attention*
33. *Sound Localization*

PSYCHOMOTOR

34. *Control Precision*
35. *Rate Control*
36. *Wrist-Finger Speed*
37. *Finger Dexterity*
38. *Manual Dexterity*
39. *Arm-Hand Steadiness*
40. *Multilimb Coordination*

GROSS MOTOR

41. *Extent Flexibility*
42. *Dynamic Flexibility*
43. *Speed of Limb Movement*
44. *Gross Body Equilibrium*
45. *Gross Body Coordination*
46. *Static Strength*
47. *Explosive Strength*
48. *Dynamic Strength*
49. *Trunk Strength*
50. *Stamina*

HIGHER LEVELS OF ABILITIES ARE A FUNCTION OF INNATE CAPABILITIES & LOW-LEVEL PRACTICE DRILLS

Figure 8.6: Fleishman and Quaintance (1984) modified skills and abilities taxonomy

8.4.1.5 Study Execution and Results

The JCAT instrument was used to select and scale ability and skill requirements for the JSTARS prototype and objective system. JCAT elicits judgments of ability and skill demands using behaviorally anchored scales along with a matrix of the six job functions (Figure 8.3). JCAT was administered to six subject matter experts for each job, and profiles of job task demands for each version of JSTARS were computed. Comparative analyses were then performed to determine the impact of any profile mismatches.

Figure 8.7 shows example results from the JSTARS JCAT profiles. Numerical values in the matrix indicate demand level (high, medium, low) for the skill and ability clusters for operator positions in each system. (Ranges are taken from the behavioral anchors validated in previous research.) For the "GLO" position (Ground Liaison Operator), communication skills present the highest demand (5.83) for the prototype system; when presented with the objective system (job position title changed to DMCC-Deputy mission crew commander), communication demand increases (6.12). The tabular data for the GLO-DMCC comparison are shown in the strip chart display in Figure 8.8.

COGNITIVE SKILL & EXPERIENCE CLUSTERS (TRAINING-EXPERIENCE)	POSITION GLO Operation Desert Storm	DMCC Objective System	AST Operation Desert Storm	AST/TSS Objective System	ARSM/STO Objective System
COMMUNICATION (4)*	5.83**	6.12	4.86	5.25	3.82
CONCEPTUAL (8)	4.66	4.68	4.91	4.87	4.95
REASONING (6)	4.19	4.66	5.16	4.91	4.72
SPEED-LOADED (5)	4.43	4.50	4.26	5.10	4.70
PERCEPTUAL MOTOR ABILITY CLUSTERS (SELECTION & PRACTICE)					
VISION (7)	2.38	3.35	3.04	4.00	3.04
AUDITION (3)	4.44	5.16	4.33	5.16	4.44
PSYCHOMOTOR (7)	2.19	3.14	2.85	4.00	2.57
GROSS MOTOR (10)	1.86	2.75	1.83	2.85	1.90

*NUMBERS IN PARENTHESES REFER TO NUMBERS OF SKILLS OR ABILITIES IN EACH CLUSTER.
**NUMBERS IN EACH CELL REPRESENT THE AVERAGE OF RATINGS ON AN 0-7 SCALE.

SKILL/EXPERIENCE LEVELS	
0-4	ENTRY-LEVEL
4-6	MID-LEVEL
6-7	HIGH-LEVEL

ABILITY LEVELS	
0-4	LOW
4-6	MEDIUM
6-7	HIGH

GLO - Ground Liaison Officer
DMCC - Deputy Mission Crew Commander
AST - Aerial Surveillance Technician
TSS - Target Surveillance Supervisor
ARSM - Army Radar Systems Manager
STO - Search/Track Operator

Figure 8.7: JCAT demand matrix for JSTARS Army aircrew positions

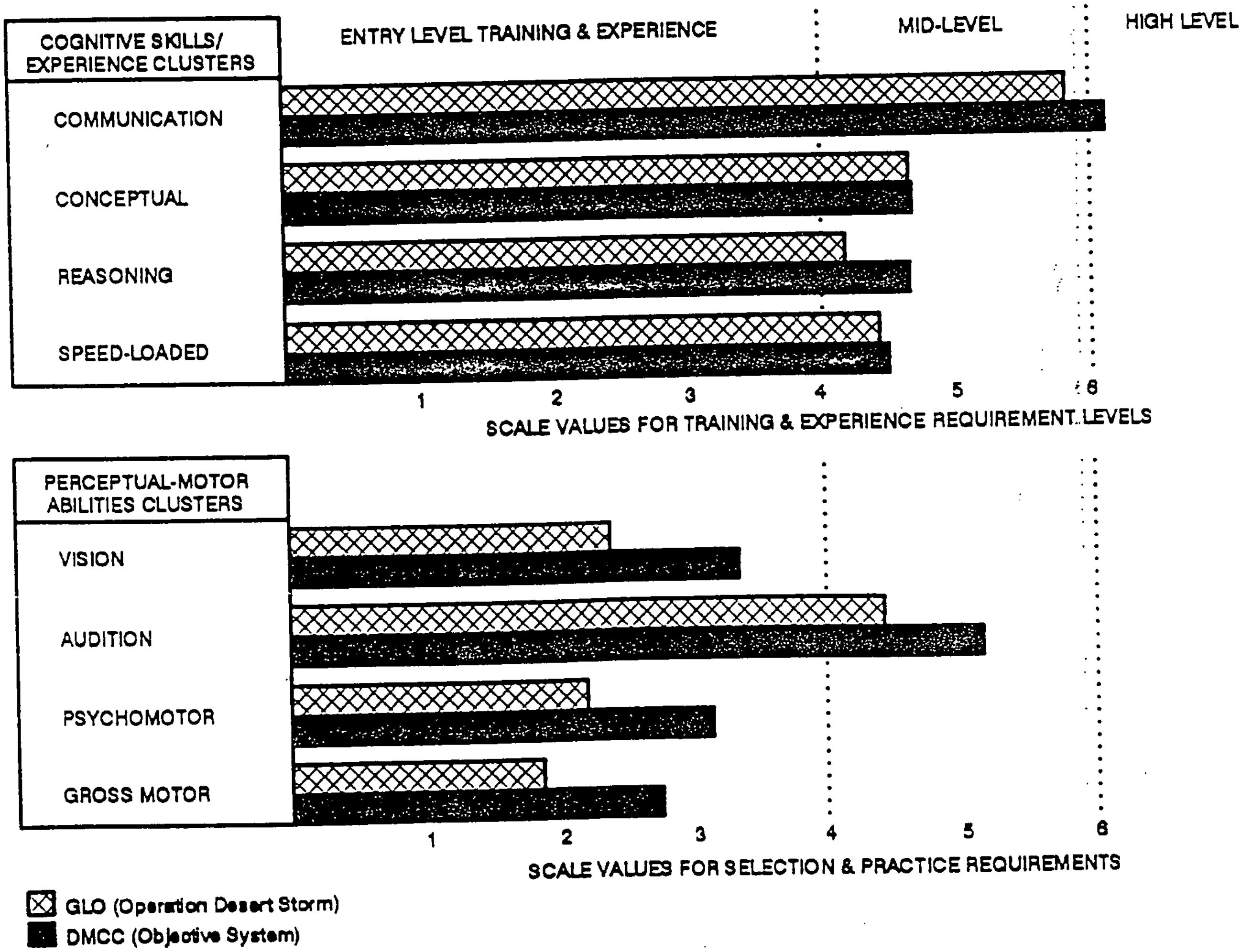

Figure 8.8: Strip chart of JSTARS job demands from JCAT data table

SKILL/ABILITY CLUSTER	MISSION PLANNING		BRIEF		PREFLIGHT		OUTBOUND		ON-STATION		POST MISSION DEBRIEF/ OFF-STATION	
	GLO	DMCC	GLO	DMCC	GLO	DMCC	GLO	DMCC	GLO	DMCC	GLO	DMCC
Communication	4.04	5.87	5.37	5.87	3.66	4.12	3.58	4.12	4.95	5.00	5.37	5.87
Conceptual	3.60	3.94	2.51	3.56	2.37	2.88	2.99	3.31	4.37	4.62	3.72	3.69
Reasoning	3.60	4.67	2.44	3.58	1.44	2.25	1.60	2.50	4.03	4.50	3.89	4.41
Speed-Loaded	2.86	3.60	1.99	2.80	2.46	3.70	2.86	3.90	4.43	4.50	1.99	2.90
Visual	2.04	2.79	1.94	2.86	2.09	3.07	2.09	3.07	2.28	3.14	2.04	3.14
Auditory	2.66	3.33	2.66	3.00	3.88	4.50	3.99	4.83	4.44	5.17	2.66	3.00
Psychomotor	1.33	1.93	1.28	1.86	2.19	3.14	2.19	3.14	2.19	3.14	1.52	2.29
Gross Motor	1.09	1.60	1.09	1.60	1.66	2.45	1.76	2.60	1.86	2.75	1.50	2.00

Performance Demand Levels: 0-4 Low 4-6 Medium 6-7 High

Figure 8.9: Skill and ability demands by JSTARS mission functions

CLUSTER	SKILL/ABILITY ELEMENT	(AVERAGE DEMAND LEVEL, 0-7 SCALE)
Auditory	*Auditory Attention	(4.75)
	*General Hearing	(4.58)
	Sound Localization	
Communication	*Oral Comprehension	(5.58)
	*Oral Expression	(5.16)
	*Written Expression	(5.00)
	*Written Comprehension	(4.83)
Conceputal	*Originality	(4.50)
	*Problem Sensitivity	(4.41)
	*Memorization	(4.50)
	Selective Attention/Visualization	
	Flexibility of Closure	
	Fluency of Ideas	
	Spatial Orientation	
Reasoning	*Inductive	(4.75)
	*Deductive	(4.25)
	*Information Ordering	(4.08)
	Category Flexibility	
	Mathematical Reasoning	
	Number Facility	
Speed-Loaded	*Speed of Closure	(4.33)
	*Time Sharing	(4.08)
	Perceptual Speed & Accuracy	
	Reaction Time	
	Choice Reaction Time	

Figure 8.10: Decomposition of critical JCAT clusters for JSTARS DMCC

Using the high demand skill-ability clusters identified in the profiles, JCAT data was further analyzed to determine the source of loading from two aspects: the underlying skill(s) or abilit(ies) within the cluster(s) responsible for high demand, and the function and task area(s) where the high demand was indicated. Figures 8.9 and 8.10 show the data for GLO-DMCC comparisons. Together these data form a picture or *profile* of the job, (detailed discussion and full data tables for the JSTARS positions are found in Knapp (1994), and indicate that only moderate to highly experienced operators should be considered--not entry level personnel for the aircrew. The communications, conceptual, reasoning, speed-loaded, and auditory clusters are key to workload and considerations for selecting and training these operators.

In general, most requirements for the objective system exceeded those for the prototype, so workload is best absorbed by a third operator (or additional automation) for future missions. Since the increase is for communications skills and auditory ability for over half of the mission functions (planning, briefing, on-station, debriefing) and increased cognitive demands (time sharing, inductive and deductive reasoning, problem sensitivity, etc.) are evident mostly during the *on-station mission operations*, automation as a design alternative may be difficult. Off-loading of comms and auditory functions is better addressed by increasing personnel proficiency and ensuring that other non-demanding mission functions (preflight duties, aviation specific duties) are handled by other aircrew personnel.

8.4.2 Task and Workload Demands for Army Command and Control Staff

A more comprehensive task and workload analysis using the six steps detailed above, is currently underway. The objective is to evaluate whether soldiers in an Army command and control (C2) staff, which supports Brigade and Division commanders, can perform adequately with proposed new automation tools, during on-the-move operations, and in distributed communications environments. Command staff support groups are now set to be replaced by smaller, more mobile support teams who will share and analyze digitized information more autonomously, rather than hovering over a shared map-board and routinely conversing in person.

The variables of Figure 8.2, encompassing a range of mission conditions, information conditions, personnel and environmental conditions are being assessed using a combination of new measurement and modelling techniques. The goal is to quantify the impact of all variables listed, singularly and in combination, and to differentiate the command staff job demands in current and proposed tactical environments. The framework of analysis has begun with the development of a workflow model, shown in Figure 8.11. An underlying assumption is that, regardless of job conditions (new technology, increased battlefield tempo, or configuration of C2 staff personnel, etc.) the staff functions to be performed are invariant, and consist of a basic functional flow of information input tasks (acknowledge data, compare to "picture"), information processing tasks (estimate impact of new data, recommend changes to plans and orders, etc.), and output tasks (adjust plans, issue orders and directives).

What defines the workload is the nature and pace of information within the workflow, the working conditions, and the personnel capabilities and dynamics. Incoming information is the "trigger" to processing and action, and information "events" account for demand on operator resources. In a simplistic example, Figure 8.12 shows one information event: "firing battery down" (incoming data to a fire support element staff operator that an outlying firing battery is out), and how this triggers a series of tasks and skill requirements at varying levels of processing complexity. For example, the "compare to picture" task involves detection and discrimination skills including visualization and speed of closure (refer to Skills and Abilities listing in Figure 8.6).

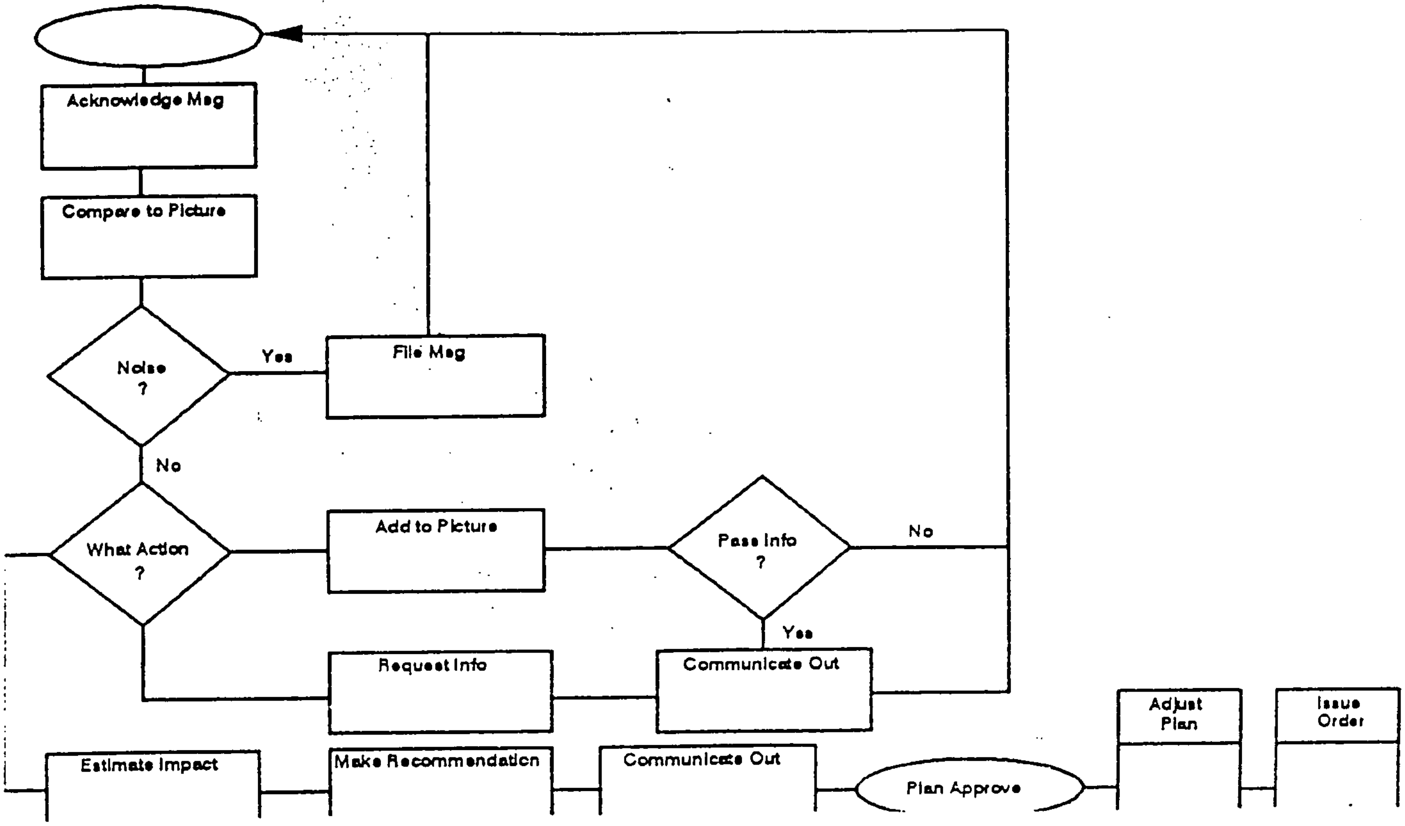

Figure 8.11: Generic workflow for Army C2 staff

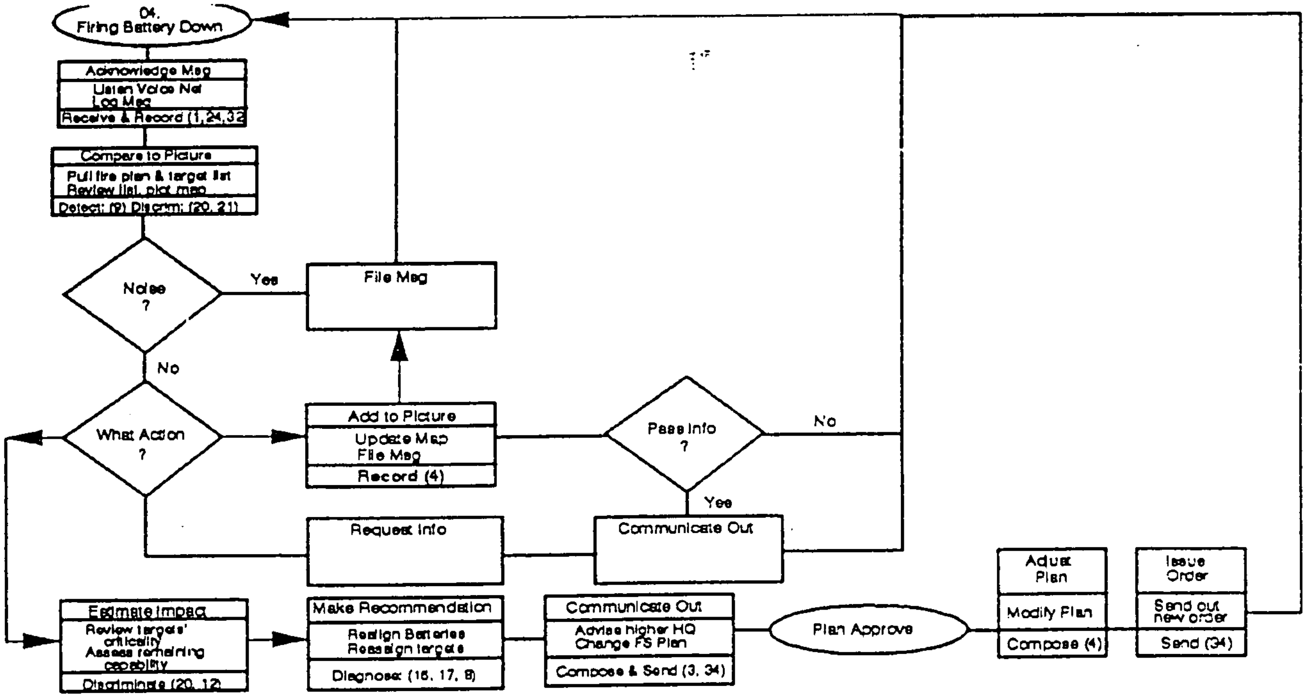

Figure 8.12: Information event 04. triggers workflow for fire support staff. Numbers in parentheses refer to skills and abilities list of Figure 8.6

The next step in workload estimation for this single information event is to assign demand estimates for the skills triggered. Separate information events within and between staff sections could be compared at this point to get a rough estimation of differing workload; however, a more operationally realistic picture of the mission is obtained using additional parameter values for sequential and concurrent information events, different information event rates, environmental, automation technology, and group dynamics variables listed in Figure 8.2. This results in a *library* of command and control mission profiles, which can be executed in a task *network and resource demand* computational model or models (e.g., ARLs CREWCUT, 1993).

The determination of the parameter values, to populate the mission profiles, involves detailed elicitation of data from command and control experts on the current and expected distribution of information event types and rates, and the characteristics of the automation technology proposed. Research will be required to develop and assign scale values for the personnel and environmental variables, such as the knowledge, skill, and abilities demands for each mission and staff section. Model "runs" then produce output reports which show points of overload in task demands under differing variable condi-tions. These are the data from which the function allocation decisions will be made.

8.5 SUMMARY

Function allocation decisions for Command, Control, Communications, and Intelligence systems are dependent on sound task and workload analysis to provide quantitative profiles of the jobs being designed. Since the tasks in these systems are mainly cognitive in nature, and linked to control of automated systems, a systematic approach to the analysis and measurement of job demand is essential. The work presented in this paper has illustrated one such method being taken for new Army C3I systems, which shows considerable success in meeting the challenge of measurement and evaluation of the information processing tasks characteristic of these systems.

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Improvements of sensor and effector technologies in modern command, control, and communication (C^3) systems increase the amount and complexity of information to be processed and greatly decrease the time available to process that information. Supporting the operators of these systems by means of intelligent and adaptive human-machine interfaces can contribute to handle at least partly this situation. This approach requires a situation specific allocation of functions between operators and machine system components. The presentation starts with a general description of human tasks in military decision situations. Principles for supporting human decision making in C^3 systems are presented. The support concept of a knowledge based user assistant that comprises a dialogue monitor, a situation monitor, an action planner, and a display manager is explained in detail. On the basis of a hierarchical function analysis an object-oriented implementation and prototyping of the assistant is explained using tasks of the principle warfare officer in a Navy combat information centre as example.

CHAPTER 9

ADAPTIVE FUNCTION ALLOCATION FOR SITUATION ASSESSMENT AND ACTION PLANNING IN C^3 SYSTEMS

W. Berheide, H. Distelmaier and B. Döring

9.1 INTRODUCTION

Improvements of sensor and effector technology in modern command, control, and communication (C^3) systems increase the amount and complexity of information to be processed and greatly decrease the time available to treat that information. This situation can be handled partly by increasing processing speed through a higher degree of automation. But human decision makers cannot be replaced in military systems. In unforeseen and emergency situations in complex military environments, a higher degree of automation leads to reduced decision time with increased information complexity that results in an intolerable workload level for human operators and decision makers with the consequence of increased human errors and reduced overall system performance. Supporting the operators (users) by means of intelligent and adaptive human-machine interfaces can help to reduce these problems. This approach requires situation specific allocation of functions between system users and machine system components.

Information processing functions to be performed normally in C3 systems are situation assessment, action planning, action command, and checking of action accomplishment. These functions describe the course of action in military decision situations. Looking from a behavioural point of view, Wohl (1981) identified generic elements that describe the military decision making process and constitute the basis of his SHOR model. These elements are: Stimulus, Hypothesis, Option, and Response (Figure 9.1).

The stimulus element includes data collection, correlation aggregation, and recall activities. In a tactical air-threat situation on a ship such data are, e.g., distance, bearing, and speed of a target, and sensor and weapon range of own ship. Often those data are available only sequentially over time and the operator has to store them in his memory. On the basis of the collected information the decision maker creates an hypothesis concerning the actual threat situation. When getting, e.g., new target data such as its classification, sensor and weapon range, the evaluation of the initial hypothesis results in its confirmation or rejection. In the latter case a new hypothesis will be generated considering the newly available data. Often due to the uncertainty of data, hypotheses can be generated only with certain probabilities. Then, one hypothesis as the most likely cause of the data must be selected. For each hypothesis the decision maker has to generate and evaluate alternative options for solving the problem. The evaluation has to consider the option effectiveness on mission accomplishment and system safety. The most appropriate option is selected. On the basis of the selected option the decision maker takes action that includes the planning, organization, and execution of the response to the problem situation.

When accomplishing these decision making functions the human decision maker has to deal with two possibilities of uncertainty (Wohl, 1981): (1) information input uncertainty which creates the need for hypothesis generation and evaluation, and (2) consequence-of-action uncertainty which creates the need for option generation and evaluation. Generally, a human decision maker has specific deficiencies in performing these elementary functions due to human capabilities and limitations (Anderson, 1988; Wickens, 1984). Edwards (1990) points out that such deficiencies are especially likely in pilot performance. Comprehensive deficiency listings have been compiled for the design of decision support systems (Cohen et al., 1985; Sage, 1991). Only some examples will be given here. In performing the function "gather data", e.g., a human decision maker tends to use only easily available data; (s)he considers only a few samples of data.

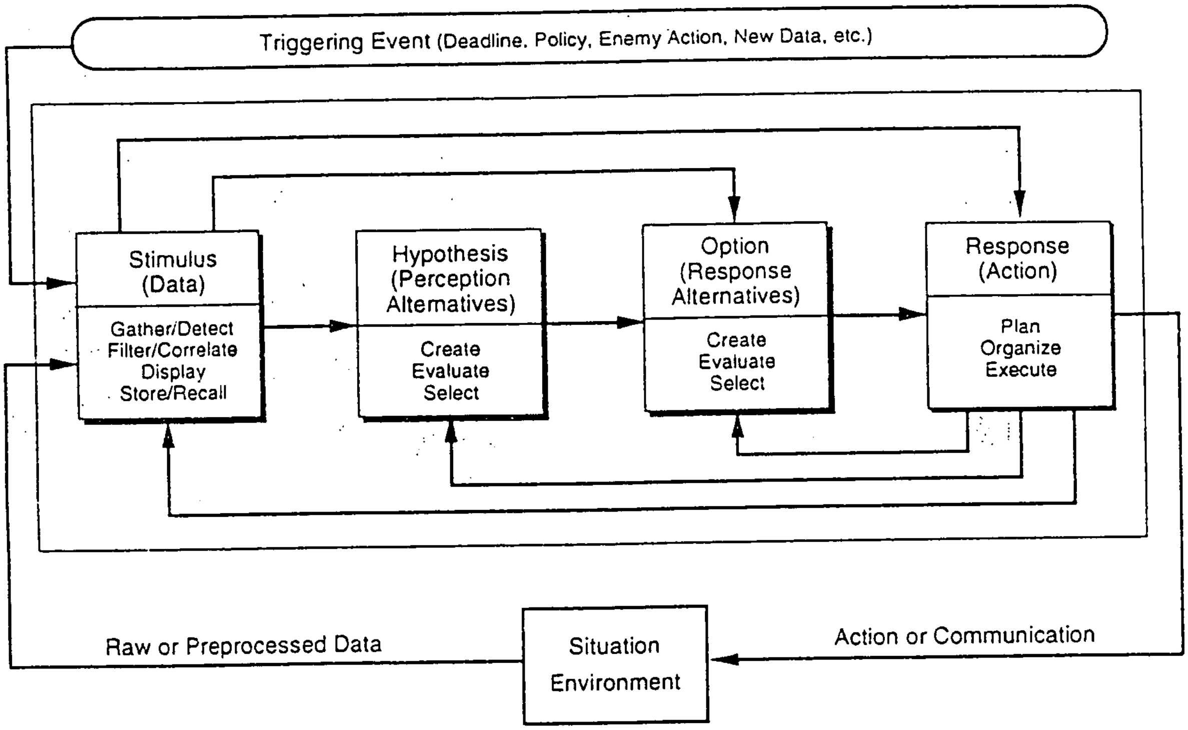

Figure 9.1: Elements and functions of the military decision proces (Wohl, 1981)

With functions "create and evaluate hypothesis", e.g., (s)he is likely to ignore data that disconfirms the hypothesis currently being considered, tends to generate recently used hypotheses once more, and has difficulties in assessing probabilities. In performing the functions "create, evaluate and select option", e.g., (s)he segments complex options into "natural" components, and treats the elements as if they were independent choices, leading to sub-optimal portfolios. (S)he has difficulties recalling all situation relevant options, and tends to give more weight under time pressure to negative evidence concerning alternatives then to positive evidence.

9.2 CONCEPT FOR SUPPORTING HUMAN DECISION MAKING

To overcome mentioned deficiencies and to support the human operator in decision making situations in complex systems, adaptive aiding concepts have been developed (Rouse et al., 1988; Rouse, 1991). Recently, these concepts have been mainly applied as support for aircraft pilots (Amalberti & Deblon, 1992; Banks & Lizza, 1991; Dudek, 1990; Rouse et al., 1990; Wittig & Onken, 1992). Basic to these concepts is the philosophy, that total automation cannot be the utmost objective of system development. The consequence of this philosophy is that the role of an operator as decision maker has to be accepted prior to system design. This is important because the overall performance of complex systems depends heavily on human performance, particularly when abnormal and emergency situations arise.

The operator should be involved in the decision making process, as long as his abilities are sufficient. An aid is provided only, to enhance human abilities (e.g. detect and evaluate complex patterns or react on unforeseen events) and to overcome human limitations and complement individual human preferences.

This idealistic concept is based on the philosophy of human centered automation and imagines a computerized assistant that behaves like a human partner to the operator, i.e., can be commissioned and automatically takes over tasks. Like the operator, the assistant monitors states of the system and the environment and, in parallel, the actions of the operator (Figure 9.2). If it encounters emergency situations or inappropriate operator behaviour, it automatically performs some operator functions. Faulty behaviour of the operator will be identified, announced, and if there is no reaction from the operator, possibly corrected by the assistant. This concept prefers the idea of a variable rather than fixed automation. The automation is related to the classic problem of allocation of functions between humans and machines, but in this approach adaptive to situations, missions, tasks, etc.

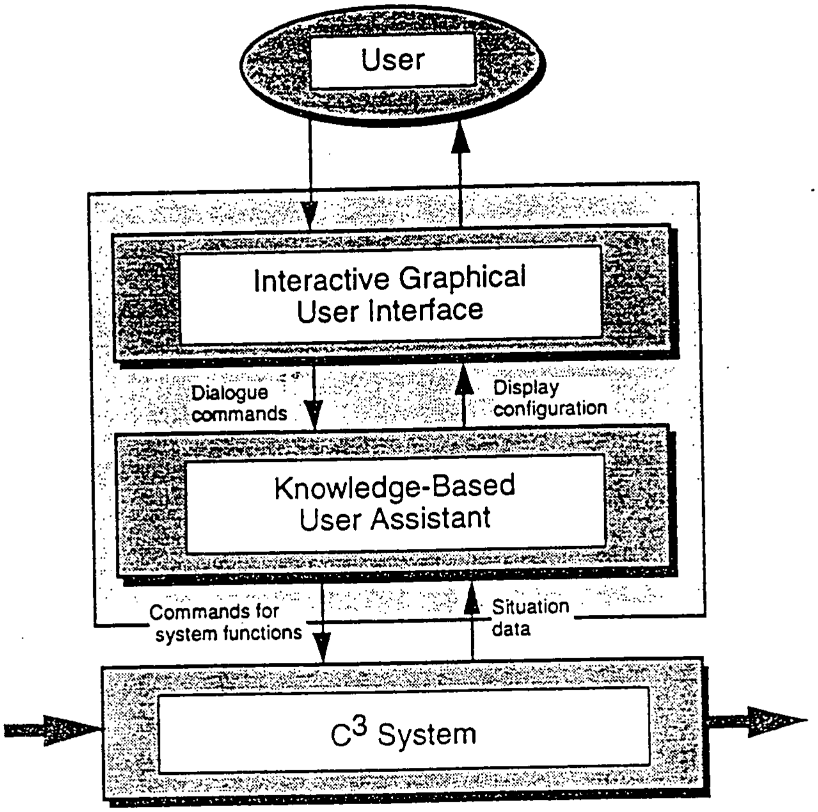

Figure 9.2: Structure of knowledge-based user interface

One of the key issues in adaptive automation concerns the method by which adaptation is accomplished. Two main approaches can be distinguished (Rouse, 1991; Parasuraman et al., 1992): The operator driven approach considers the actual state of the operator which can be identified either by measuring and/or modelling operator performance. The event driven approach considers critical situation events which arise during a mission, e.g., by state changes of the tactical situation or the system.

Basis of most adaptive systems is the event driven approach that later can be supplemented by the operator driven approach. Therefore, we also used the first approach for starting the development of a knowledge-based user assistant. In this method the implementation of automation is linked to the occurrence of specific tactical events. Such an automation method is inherently flexible because it can be tied to current military doctrine during mission planning (Parasuraman et al., 1992).

9.3 THE KNOWLEDGE-BASED USER ASSISTANT

To support the decision making task of the principle warfare officer (PWO) in Navy combat information centres (CIC) on board ships, a concept of an aiding system has been developed. In general, CIC functions to be performed by the PWO are situation assessment, action planning, action command, and checking of action accomplishment. During a mission, assessments are made on different aspects of situations ranging from states of the tactical and physical environment, states of personnel and the logistic supply, and states of the ship and its sub-systems, e.g., sensor, effector, and propulsion sub-systems, etc.

At present we are working on an aiding concept that supports the operator, i.e., the PWO, especially in threat evaluation and weapon assignment (TEWA) in anti-air warfare (AAW) situations. To identify functions for supporting the operator during these situations a function analysis has been accomplished in a top-down manner (Beevis, 1992) which resulted in a functional hierarchy. This hierarchy comprises different levels with functions of decreasing complexity shown partly in Figure 9.3. In this figure the decomposition proceeds from left to right. For instance, the high level function 'Supervise target selection' in Figure 9.3 has been decomposed into sub-functions like 'Evaluate TEWA target selection', 'Support changing TEWA target selection', and 'Confirm TEWA target selection'. Continuing the decomposition of the sub-function 'Evaluate TEWA target selection', its sub-functions 'Select threatening target' and 'Compare target selection' have been identified.

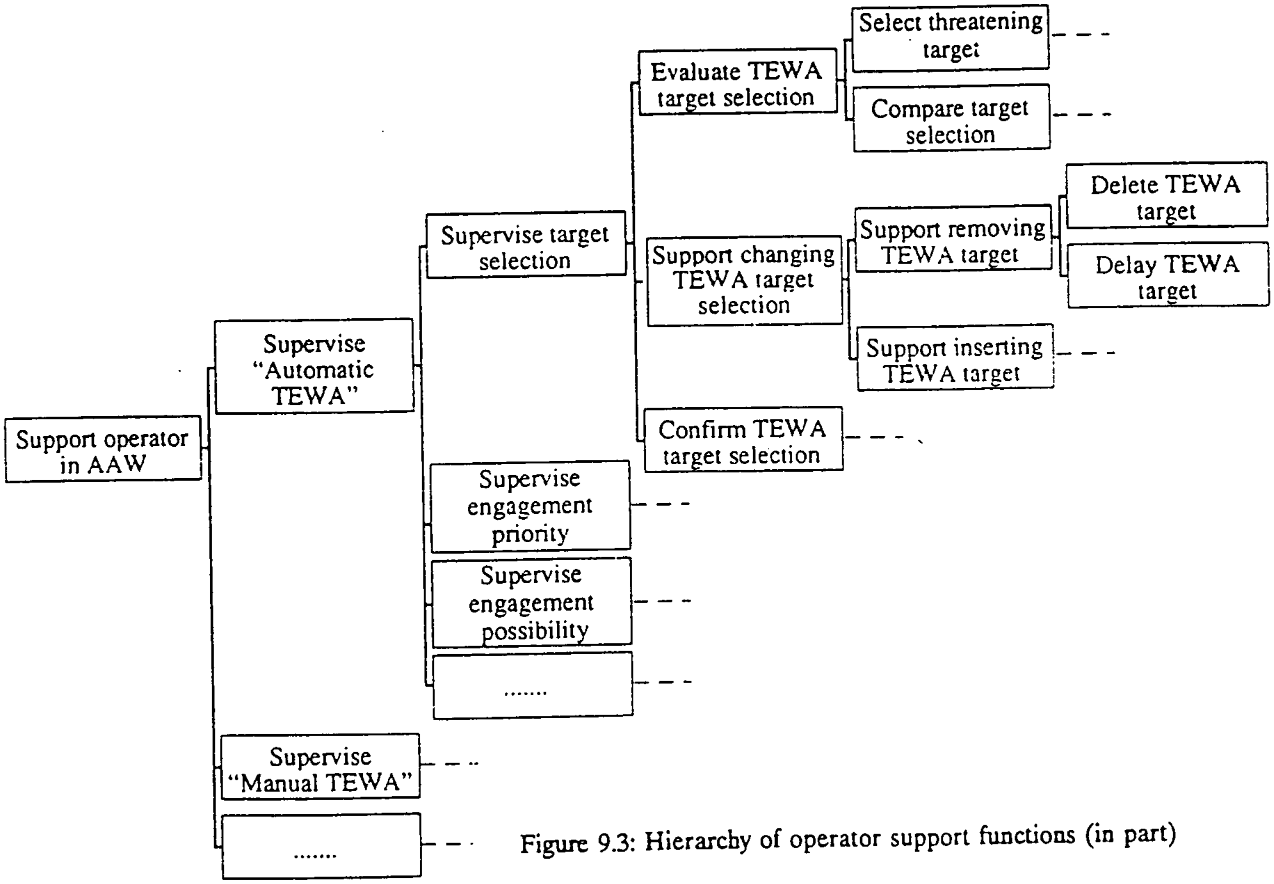

Figure 9.3: Hierarchy of operator support functions (in part)

As part of an adaptive aiding concept each of the identified operator support functions (OSF) in Figure 9.3 is conceived as consisting of four functional components, namely monitor situation, monitor dialogue, select action, and specify display. Figure 9.4 depicts the general structure of an OSF with its four components and their input/output relations. The inputs and outputs of the generalized OSF in Figure 9.4 have the same generalized categories as that of the knowledge-based user assistant (KBUA) in Figure 9.2, i.e., dialog commands and situation data inputs, and system function commands and display configuration outputs. Every function thereby contributes to all aspects of the KBUA. For instance, in reaction to the detection of an environmental situation event any function on any level function could give prompts both to the controlled TEWA process and additionally a corresponding display configuration on the user interface.

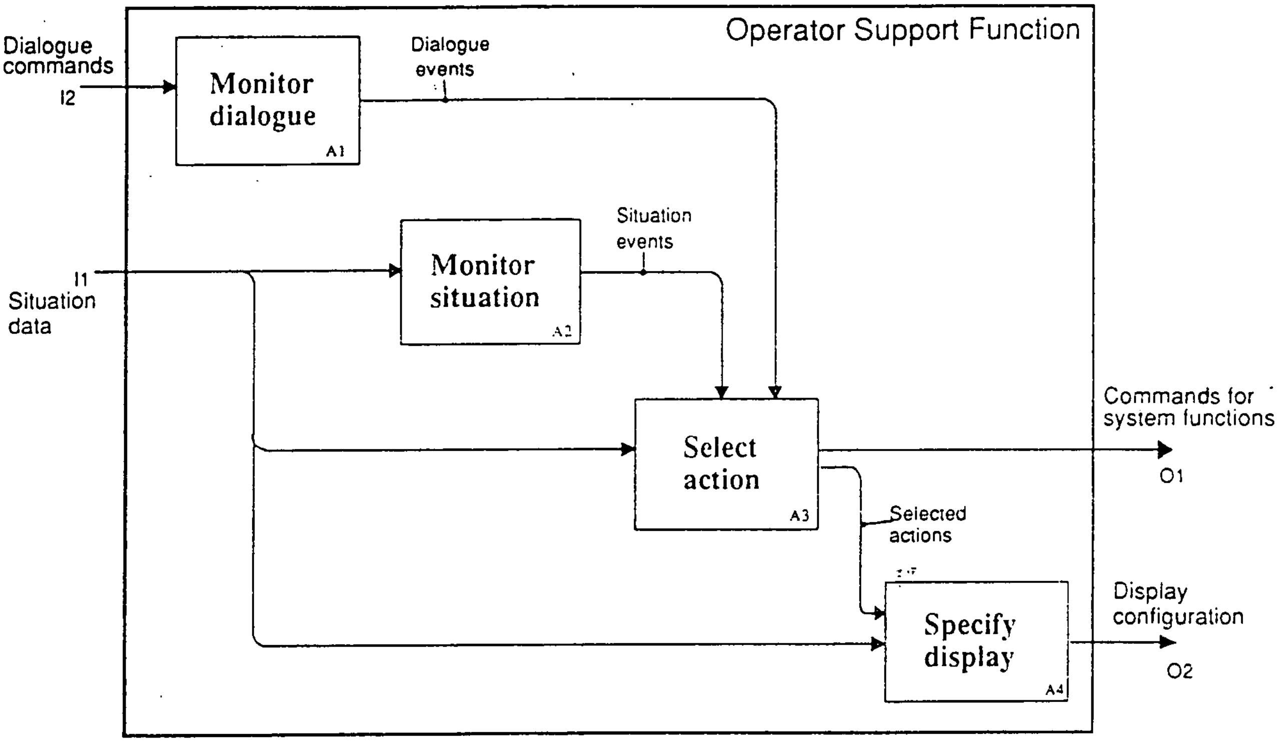

Figure 9.4: General structure of an operator support function

The functional component "Monitor situation" of an OSF supports the first two steps of human decision making, i.e., data collection and hypotheses generation (Figure 9.1). This component reviews situation-relevant data and decides about the current state of affairs. If a situation event has been detected it is given to the functional component "Select action" for performing appropriate actions. The component "Select action" is to support the operator in performing the third step of human decision making (Figure 9.1), i.e., option generation, evaluation, and selection by identifying all actions which are necessary and possible for responding to the current situation event. Normally, all identified and evaluated actions are provided by the "Specify display" component to the PWO who decides which action should be taken. In critical threat situations, e.g., incoming air-to-surface missiles detected within critical envelopes, a reaction process is executed without PWO intervention. In this case the component "Select action" generates commands for required fast automatic system functions (Figure 9.4). The resulting decision about this automatic reaction is also presented to the PWO via the "Specify display" component. For each situation, the appropriate display and dialogue elements are stored as display resources. To assist the operator in an actual situation, the component "Specify display" activates the corresponding elements and presents them via the graphical user interface.

The operator dialogue commands are monitored by the functional component "Monitor dialogue" which helps the operator to avoid negative consequences of inappropriate commands. This component compares the actual dialogue commands with those that are permitted due to the present situation and gives the resulting dialogue events to the "Select action" component. If an actual dialogue command does not correspond to what is permitted the component "Monitor dialogue" blocks its execution and provides a prompt via the graphical user interface to the PWO.

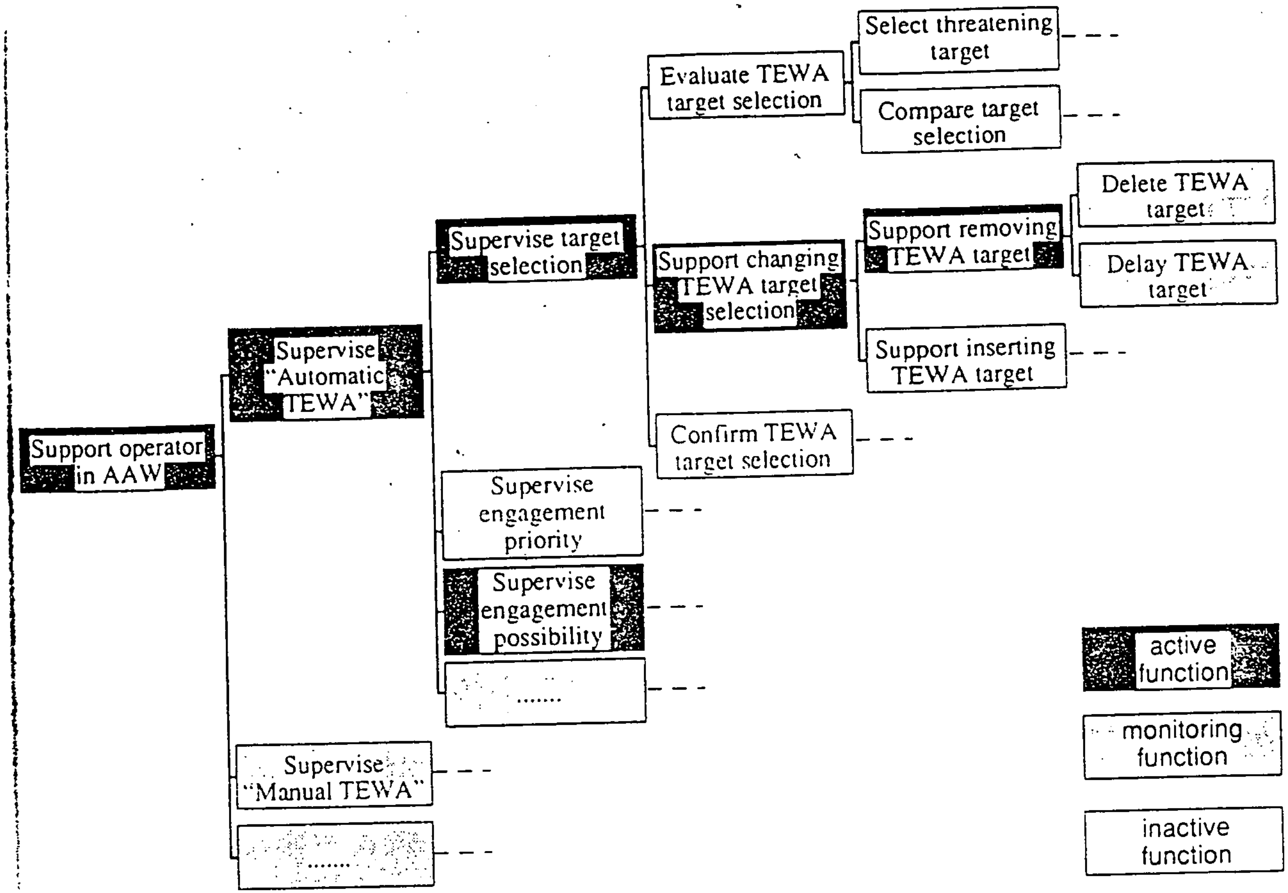

Figure 9.5: Example of operator support functions and their states

For each operator support function (OSF) three different successive states have been defined: inactive, monitoring, or active. With an inactive function none of its functional components are in operation. In the monitoring state of a function only the two functional components "Monitor situation" and "Monitor dialogue" are operating and no output is generated. In the active state all of its four functional components shown in Figure 9.4 are in operation. A function in the function hierarchy will be automatically transfered into the monitoring state, if its encompassing function on the next higher hierarchy level is active (Figure 9.5). A function will be active if the monitoring components detect an activation event. It changes its state from active to monitoring, if the monitoring components detect a deactivation event.

The example shown in Figure 9.5 represents a situation in which the knowledge-based user assistant (KBUA) supports the PWO in supervising target selection during an automatic threat evaluation and weapon assignment (TEWA). In this case the KBUA decided that a target should be deleted from the list of engageable targets. In the activated OSF "Support removing TEWA target" the functional component "Specify display" gives the reason of this decision via the graphical user interface to the PWO who has to agree. If the PWO acknowledges the KBUA decision by pressing the "DELETE" button at the user interface, the function "Delete TEWA target" which now is in the monitoring state will be activated and a deletion command for the TEWA function will be generated. The PWO can also decide to delay the engagement by pressing the "DELAY" button. Then the OSF "Delay TEWA target" that is in the monitoring state will be activated and a delay command is given to the TEWA system process. After sending the command, the function itself will be stopped and the encompassing function "Support removing TEWA target" eventually will be deactivated.

The hierarchically structured operator support functions (Figure 9.3) together with their four functional components "Monitor situation", "Monitor dialogue", "Select action", and "Specify display" (Figure 9.4) constitute the concrete functional model of the KBUA shown in Figure 9.2 for a specific application, in this case for supporting the operator in AAW situations. The described event oriented control of each function enables the KBUA to react to environmental situations. Depending on an actual event, a sub-function for controlling automatic system functions or for prompting required operator actions will be activated. In this way the support concept allows a situation dependent activation of automatic system functions or required operator actions in an adaptive manner for every function. The possibility to react to the broad variety of situations characterize the large adaptability of the KBUA to different situations. It should be stressed that all of these situations have to be analyzed and functionally modelled for the concrete support system.

Each operator support function in the function hierarchy has to be described in a form that contains function related specifications, e.g., activation events, deactivation events, information processing procedures, control commands for system functions accomplished automatically, relevant display information and action requirements of the operator, display elements for presenting the information and action possibilities on the graphical user interface, and sub-functions.

9.4 OBJECT-ORIENTED IMPLEMENTATION OF THE KBUA

For supporting the implementation of the functional KBUA model and the prototyping of the human-machine interface of the PWO, we applied an object-oriented approach (e.g. Coad & Yourdon, 1991; Embley et al., 1992; Rumbaugh et al., 1991) that results in an object-oriented KBUA model. An object is considered as an encapsulated entity that accepts messages for activating its processes and changing its state and that sends messages to other objects. The central part of that object-oriented KBUA model consists of a hierarchy of objects analog to the function hierarchy (Figure 9.3). As every encompassing function consists of subfunctions, every aggregate object consists of a set of sub-objects. As with a function, three different states of an object can be distinguished, namely inactive, monitoring, and active. Figure 9.6 depicts an object with its states, state transitions, and the messages it accepts and delivers.

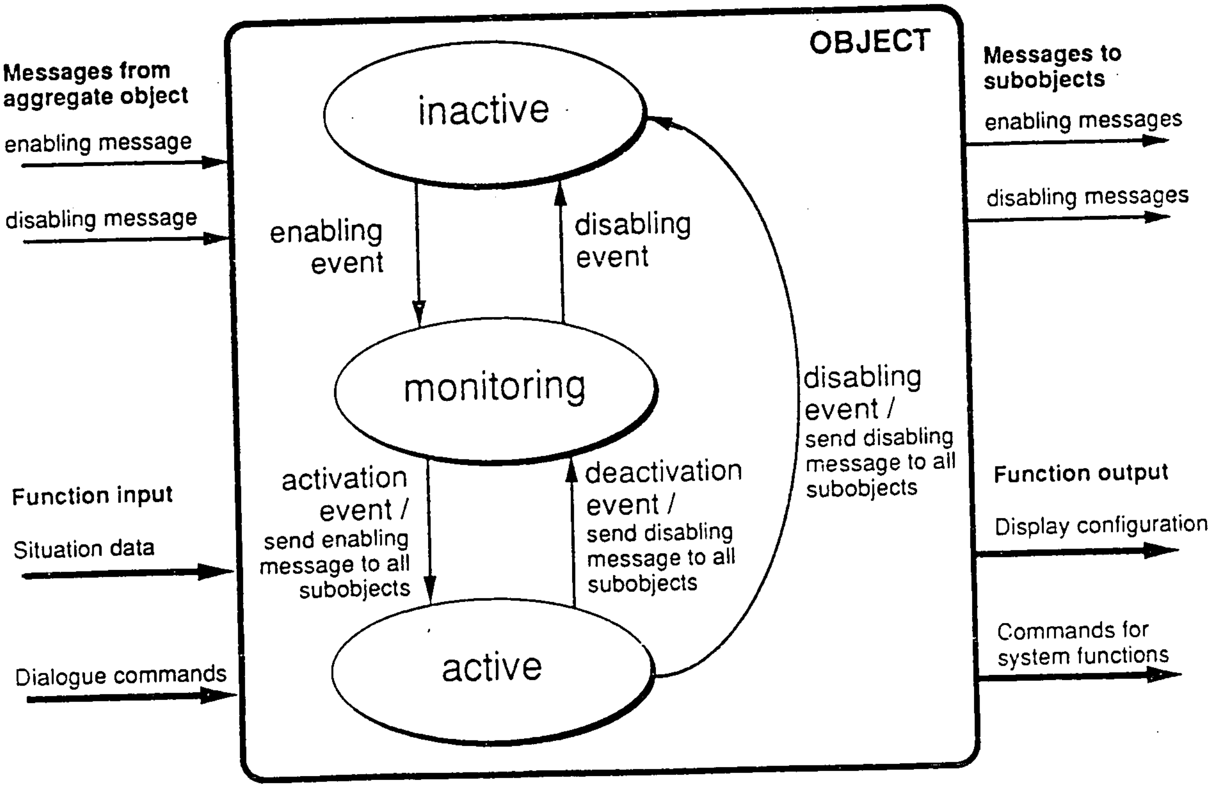

Figure 9.6: Messages and state transition structure of an object

Like the generalized function input and output shown in Figure 9.4 an object receives messages with situation data and dialogue commands and sends messages with display configurations and commands for system functions (Figure 9.6). Additionally, it receives enabling and disabling messages from its aggregate object and sends enabling and disabling messages to its subobjects. The received enabling and disabling messages cause the corresponding events within the object. Messages in the form of situation data and dialogue commands cause activation and deactivation events within the object. As schematized in Figure 9.6, those triggering events cause state transitions with accompanying actions.

In general, a functional object has data and procedural aspects, i.e., it is characterized by data (properties) and will activate procedures. Data are peculiar to each object, e.g., its state. Procedures specify the above described functional components of an operator support function (OSF), i.e., "Monitor situation" (MS), "Monitor dialogue" (MD), "Select action" (SA), and "Specify display" (SD). As with an OSF, in the monitoring state of an object, MS and MD procedures are in operation. In the active state of an object SA and SD procedures will be performed additionally. MS and MD procedures generate the activation and deactivation events by interpreting situation data and dialogue commands. They are specified as rules decribing the event conditions. SA procedures are represented by information processing algorithms that generate commands for system functions and data used internally.

SD procedures are implemented as a set of control commands that describe the display configuration messages. The display system decodes these messages and activates appropriate display elements, e.g., windows, icons, menus, buttons, etc. These display elements will be added to the interactive graphical user interface, for instance, to the already provided display configuration activated by parallel or higher level objects. When objects are suspended or terminated, the affiliated information and action alternatives are removed from the interface.

In Figure 9.7 the resulting structure of the implemented object-oriented KBUA model is shown. The presented object hierarchy is equivalent to the structure of the functional hierarchy of operator support functions (OSF) shown in Figure 9.3. Each object presented in Figure 9.7 behaves as described above. In this way, every object contributes to the overall behaviour of the knowledge-based user assistant depicted in Figure 9.2. An advantage of this object-oriented KBUA model is its easy adaptation to additional requirements. Additional objects and sub-objects can be added for additional situation events and their corresponding functions and sub-functions identified during the analysis.

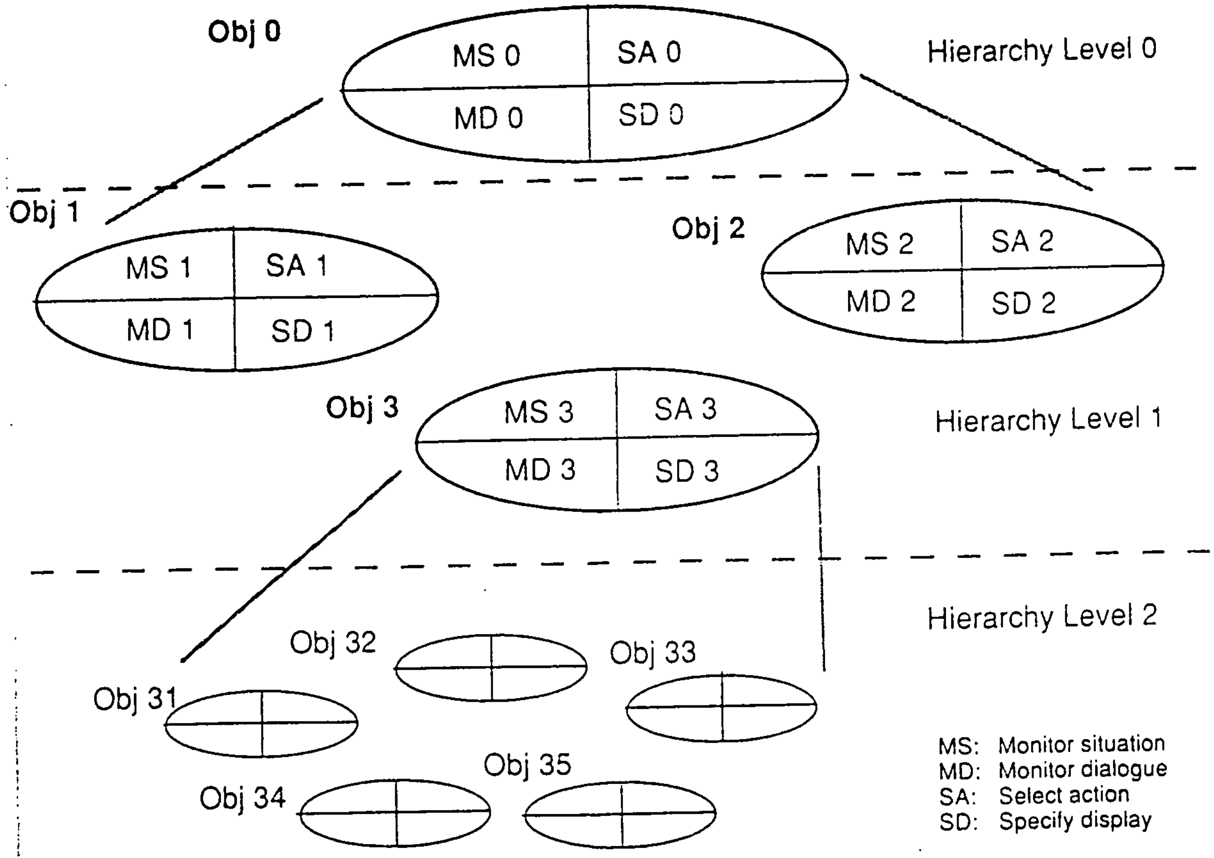

Figure 9.7: Principle of the object hierarchy

A prerequisite for constructing this object-oriented KBUA model is a thorough identification of the functional model, i.e., all relevant events and initiated functions, and the analysis of those functions and their affiliated information/action requirements. These items can be identified by an analysis which starts with the mission of the system and its planned operations. But the analysis should be performed anyhow when designing and prototyping human-machine interfaces (Beevis, 1992). The above described functional and object-oriented KBUA models serve as conceptual frameworks for the analysis in the problem domain. They already contain all classes of mentioned sub-objects with their necessary properties and methods. Additionally, the object-oriented model resulting from the analysis represents a design description of the KBUA as basis for its implementation.

9.5 THE PROTOTYPING APPROACH

A prototyping approach will be applied in developing the human-machine interface of the PWO and using it as a demonstrator. This approach supports the trend in developing computer applications to shift power from specially trained programmers to domain experts and users. This trend will also force development organizations to bring users into system design as early as possible and finally accept prototyping as a legitimate technique.

Prototyping is the construction of a (software) product by iterative design, whereby a user interface is included from the beginning and in most cases a simulator of a controlled or monitored system is involved. The prototyping approach does not mean building and testing a prototype and thereafter creating a new system with another language and another hardware system according to this prototype. Here, the prototype itself becomes the system. Prototyping is an iterative and incremental approach to the construction of systems.

The requirements for many military systems are not clear at the beginning. That is especially true for the design of user interfaces. In the prototyping approach one can start with a very simple design, e.g., with an existing design, let it be evaluated by military users, and augment from time to time in an iterative manner with a better version adapted to new requirements. In this way the user can be involved in very early design stages and the role of the user is implicit. Therefore, the system will be better accepted by users and most requirements are better understood by them. The prototyping approach that we apply starts with a relatively simple mission and a very simple function model reacting to only a few events.

We started our approach by describing a multi-threat situation in an anti-air warfare (AAW) mission of a ship and identifying relevant mission events and functions of the principle warfare officer. The identified mission functions are basic data for designing the function hierarchy. The conditions of relevant mission events specify the rules of the "Monitor situation" procedures of each function. Further, information/action requirements have been identified for each function as a basis of the "Specify display" component. These data are used for developing display layouts with the illustration and designing tool MACROMIND™. The layouts have been and will be discussed with experienced users for acceptance and improvements. By decomposing those layouts into their elementary units it was possible to identify required display and dialogue elements of the display manager.

The object-oriented KBUA model is independent of a specific computer language or implementation system. For realizing the interface demonstrator we installed the model on a DEC-VAX™ station with the expert system shell SMART ELEMENTS™. Other components of the demonstrator are two pixel-oriented screens with pointing devices and a keyboard. The model is implemented with those object-oriented features and rules that SMART ELEMENTS™ offers. The graphical output and dialogue features of SMART ELEMENTS™ are used as an interactive graphical interface.

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This paper presents basic requirements for cockpit systems in favor of improved man-machine interaction. Often times labelled with "Human-Centered Automation" or "Human/Machine Function Allocation". Human-centered automation in its true sense is enhancing flight safety and mission effectivity. The time has come that fututr cockpit systems no longer will be designed on a vague basis of specifications to achieve human-centered automation. The advances in technology provide the necessary means to systematically reflect requirements for human-centered automation into clear-cut specifications for cockpit systems. Machine functions are to be incorporated which not only render support for planning and plan execution as emphasized in the past. Instead, main empnasis should be placed on autonomous machine sitation assessment in parallel to the cre's situation assessment activity which leads to better machine understanding of what the real needs to the crew are. The Cockpit Assistant System CASSY was developed on the basis of these requirements. It is described in this paper.

CHAPTER 10

HUMAN-CENTERED COCKPIT DESIGN THROUGH THE KNOWLEDGE-BASED COCKPIT ASSISTANT SYSTEM CASSY

R. Onken

10.1 INTRODUCTION

Regardless, whether the application is civil or military, the objective of a flight mission is the accomplishment of that mission without loss in life or equipment. Thus, flight safety apparently is of paramount concern. Each accident, which has happened by whatever deplorable cause, is one unnecessary accident too much.

Investigations on accidents in civil aviation and their causes provide ample evidence of the fact that erratic human behaviour is the main contributing factor in about 75% of all accidents. It can be claimed that these human failures are caused by some kind of overcharge, either clearly realized or not even noticed as such until it is too late. In this context, overcharge is considered as describing the situation when potential resulting human failure is imminent because of inherent human deficiencies in his sensory, cognitive and effectory capabilities and performance. Along with the continuous increase of automation in the aircraft cockpit new types of latent overcharge-prone situations arise, in particular with respect to failures in situation awareness, based on cognitive limitations. Recent accidents of highly automated civil transport aircraft, which gained great public attention, were making evident this particular trend.

The potential hazard of overtaxing the cockpit crew in certain flight situations calls for even more automation, which I explicitly want to support, too, as the reasonable way to proceed. Automation should not be blamed as such for potential overtaxing of the crew. However, the question of *how to automate* is to be raised. The way automation has been pushed forward in the past has to be scrutinized.

Automation was advancing by respecting certain principles of the human role, which should not be changed, by no means, and a certain scheme of *function allocation* to the crew on one side and technical components, the machine, on the other side. Figure 10.1 illustrates the functions allocated to the aircraft systems at the time being as opposed to those which the crew is trained to perfom. There are those functions (usually not considered as allocated ones), which are permanently turned on like the basic cockpit instrumentation and actuator machinery for power amplification, and there are those functions, which are activated by the crew and thereby allocated in order to carry out certain tasks in place of the crew.

Function allocation is not such an easy task as it might appear at the first glance. Major driving factors for the assignment of functions or part functions to be allocated to the machine in one or the other way are the potential of reduction of crew workload, to let the machine do what it can do better, and demonstration of technical feasibility. Technical feasibility often times seemed to be sufficient reason for automating certain functions in whatever type of allocation, hoping for some kind of overall system improvement and crew workload reduction. To let the machine do what it can do better might lead accidentally to allocations of certain functions to the machine, of which part functions could be carried out much better by the crew than by the machine. In Billings (1991) this is expressed by:

"While it clearly makes sense to apportion to the man and the system respectively those aspects of the task that each does best, there are no infallible rules to define these proficiencies".

Obviously, the principle of function allocation as it is deployed so far might lead to problems. This is true in particular for automated functions, which are not thoroughly scrutinized with regard to their impact on the overall mission performance. There is a steadily increasing number of permanently activated machine functions the pilot has to keep track of and at the same time there are increasing numbers of options of deployable machine functions at the disposal of the crew. This might become very complex to keep under control in view of the fact that at the same time the crew should be ready to take over all part functions at any time which are not covered by any machine.

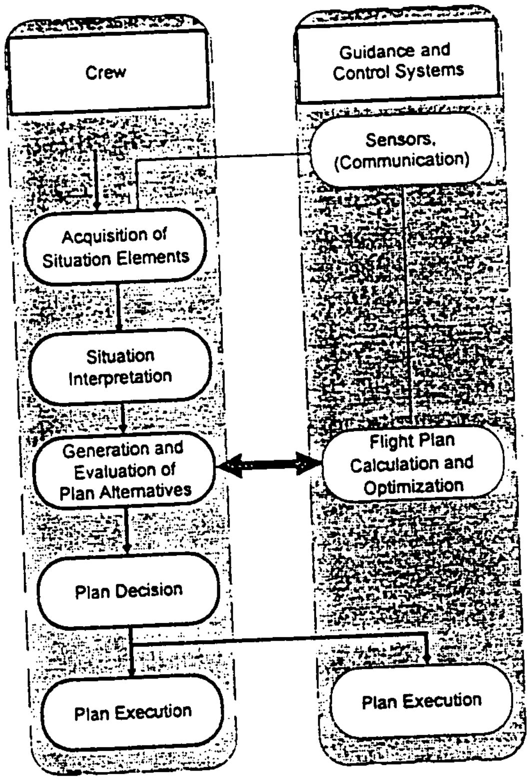

Figure 10.1: Flight guidance and control today

This results in two evident concerns with regard to function allocations to the machine in present operational systems:

1. Permanently allocated functions are often event-driven and working in the background. Resulting changes in constraints for maneuverability and pertinent consequences might not be aware to the crew and might lead to overtaxing in crew situation assessment.
2. Functions intentionally turned on by the crew might unexpectedly demand for too much attention by the crew because of complex handling.

Consequently, it is not surprising that increased automation with no well-established way of function allocation in order to avoid the pitfalls mentioned above implies increased potential of new types of crew overtaxing and resulting human failures, i.e. mission hazards. Dealing in the most efficient way with the short resources of human attention is paramount. Therefore, new ways of automation have to be established in terms of top down structuring of infallible requirements. On the basis of these requirements machine functions can be specified, which really serve the mission accomplishment. To describe this in some more detail is the main purpose of this paper.

10.2 THE FLIGHT MANAGEMENT SYSTEM:

In a US investigation on aspects of the interaction between human and machine in the cockpit (Wise et al., 1993) some of the problems with the flight management system (FMS) were highlighted. Other investigations came to similar results.

The FMS receives information about the actual flight, including data about the destination, the flight plan to the destination with way points and altitudes, weather information and weight of load. When these informations are keyed into the system by the crew, which can become a significant interactive effort, the FMS program can be initialised. From then on the aircraft can fly autonomously unless no changes of inputs have to be keyed in because of unexpected encounters in the overall flight situation. The conclusion of the investigation was that the pilots run into difficulties in time-critical situations with unforeseen constraint impacts like new ATC instructions. For these situations there is not sufficient time for the necessary inputs and the interpretation of computational results as delivered by the FMS. These are the situations when the pilots might be left on their own (Wiener, 1989; Amalberti & Deblon, 1992; Sarter & Woods, 1993) with questions like:

- what is it doing?
- why did it do that?
- what will it do next? or
- how did it ever get in that mode?

Thus, the FMS is usually turned off just at situations when the pilots starvingly look for assistance (Heldt, 1993). These obvious deficiencies clearly indicate that some of the motivations for cockpit automation for the sake of flight safety came somewhat out of sight. Therefore, it is time, now, to reconsider the basic requirements for machine support in the cockpit, in particular regarding situation assesssment tasks of the crew including sensory and information processing functions.

10.3 BASIC REQUIREMENTS FOR COCKPIT AUTOMATION

There are a great number of well-formulated requirements at hand for human-machine interaction in the cockpit, including those for 'human-centered automation' (Billings, 1991). However, in order to merge future automation into what is really wanted with regard to human-centered automation, it should be possible to assess *how much* certain individual requirements from the long list of existing ones contribute to the design goals, in particular when trade-offs are necessary for any reason. Therefore, a top down structure of as few as possible basic requirements is needed which will be described in the following, easing the engineering task of converting the requirements into a technical product.

In order to resolve this problem, we ask at first, what is, in general terms, to be achieved by automation? What is the objective of automating pilot functions? This can be answered very promptly by the following general statement: Overtaxing of the cockpit crew, as defined earlier, is to be avoided. That means that the demands from the cockpit crew have to be kept on a normal level for all situations and situation-dependent tasks, subject to certain task categories in the domains of flight control, navigation, communication and system handling like:

- situation assessment,
- planning and decision making and
- plan execution

For these task categories the following priority list in terms of a hierarchy of two levels of basic requirements can be established (Onken, 1993). These requirements are essentially equivalent to the requirements for human-centered automation as stated in (Billings, 1991), but structured differently in favor of the engineering point of view with respect of mechanisation. They can be formulated as stated in the following:

1. To avoid overcharge of the crew in situation assessment, the top requirement

   BASIC REQUIREMENT (1) should be met, i.e.:

Within the presentation of the full picture of the flight situation it must be ensured that the attention of the cockpit crew is guided towards the objectively most urgent task or subtask of that situation.

2. In order to avoid or decrease overcharge of the crew in planning/decision making and plan execution, as a *subordinate* requirement

   BASIC REQUIREMENT (2) can be formulated:

If basic requirement (1) is met, and if there still comes up a situation with overtaxing of the cockpit crew (in planning or plan execution), then this situation has to be transferred - by use of technical aids - into a situation which can be handled by the crew in a normal manner.

This particular top down formulation of requirements for human-centered automation distinctly makes clear that whatever technical specifications are made for systems in support for the cockpit crew, they are questionable if the specification for the situation assessment capability of the support system (Basic requirement (1)), including the assessment of the crew's situation, is too neglectful and sloppy. How can the support system work on directing the crew's attention, if it cannot assess the global situation on its own? If the system is not able to understand the underlying situation, it might work on the basis of wrong assumptions! Thus, if the specification fails with regard to basic requirement (1), this cannot be compensated by whatever automated support designed to comply with requirement (2) only.

Unfortunately, this inadequacy by disregarding basic requirement (1) usually was the case in the past, essentially because the technical means were not available for comprehensive situation assessment by the machine. Prevention of overtaxing concerning situation assessment was not worked into the specification in the systematic manner as it is suggested by basic requirement (1).

Basic requirement (1), in fact, compulsorily leads to the full set of specifications which in turn can be used to verify human-centered automation design.

10.4 HOW TO APPLY THE BASIC REQUIREMENTS FOR SYSTEM DEVELOPMENT

Obviously, according to basic requirement (1), there is the *main issue to carefully specify the situation assessment part of the machine* functions. The picture of the flight situation as generated by the machine should cover all aspects which are also to be considered as situational aspects by the cockpit crew. Moreover, it would be most desirable, if the machine picture would be even more comprehensive and more accurate. This is already feasible today in certain aspects. In principle, thereby compliance with basic requirement (1) can be accomplished with the technology at hand today.

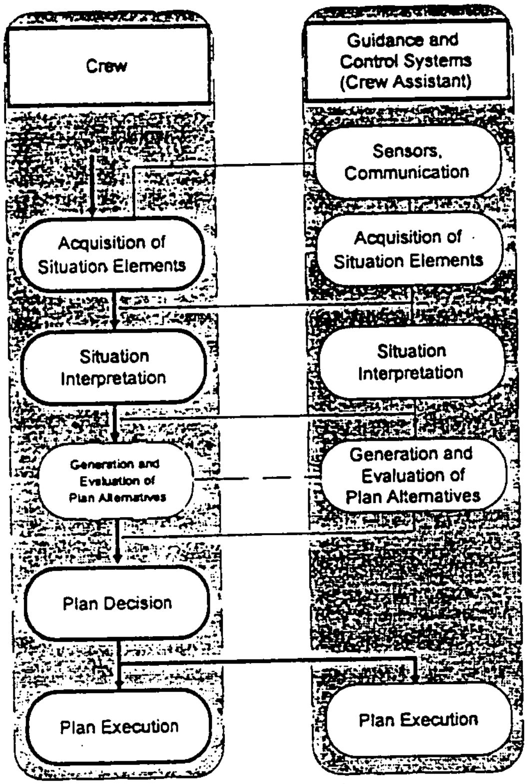

Figure 10.2: Flight guidance and control upcoming

In essence, the capability of situation assessment is to be incorporated in terms of corresponding functions in the machine part of the human-machine system in parallel to those of the cockpit crew (figure 10.2). In addition, the machine part is monitoring the cockpit crew, thereby having the full picture including the crew situation. This is the basis for cooperative automation in order that the cockpit crew's attention can be guided towards the objectively most urgent task or subtask of the actual situation.

It becomes evident at this point that instead of allocating functions either on the machine side or the crew side once and for all times, all functions necessary to fly the aircraft are not only inherent crew functions but also functions which the machine should be capable to perform. All of them are operative in parallel unless effector actions are to be executed. Thus, there is no conflict with the principle that it is generally up to the crew to make the final decision about whether to accept action recommendations of the machine or to follow their own ideas. We call this the situation-dependent function sharing of human and machine as partners.

Partnership means that the capabilities of the partners are similar, but not necessarily identical. Partnership demands for effective dialogue. According to basic requirement (1), the presentation of the full picture of the situation has to be shaped in a way that the crew's attention is guided by the presentation only if necessary. In addition, the crew should also be able to talk to the machine partner like the crew communicates among each other.

Therefore, the key specifications for the development of new generations of cockpit automation, in summary, concern both

- comprehensive machine knowledge of the actual flight situation and
- efficient communication between crew and machine, based on situation knowledge and new dialogue technology

How can the machine knowledge about the actual flight situation be established in order to meet these specifications? Both advanced techniques for structured knowledge representation and information processing based on advanced sensor technology (e.g. voice recognition and computer vision) allow for generating the knowledge base which includes about all static and dynamic situation elements the cockpit crew may be aware of and possibly even more than that. The task-related situation elements are concerned as well as the elements pertinent to the main players like the world surrounding the aircraft, the aircraft itself and, probably most important, the cockpit crew.

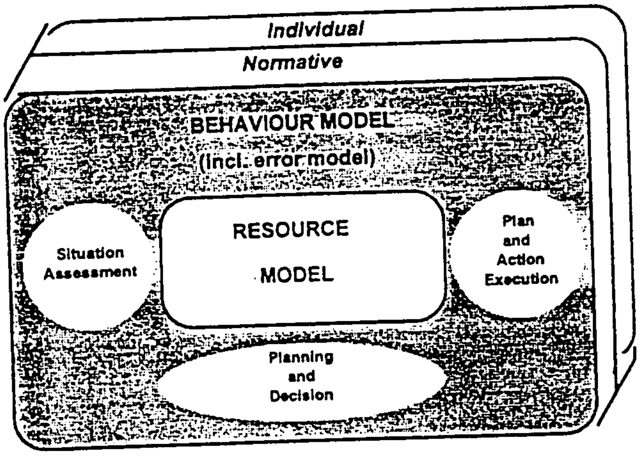

Figure 10.3: Model of cockpit crew

The knowledge about the cockpit crew is crucial. Objective knowledge about the crew can be of paramount value. On the one hand, the machine might have a better picture of the pilot's status than the pilot himself, in particular in situations of imminent overtaxing. On the other hand, machine knowledge about the crew is the basis for crew-adapted assistance. The machine cannot assist in an efficient way, if it does not sufficiently understand the cockpit crew's activities and corresponding needs. In its most advanced elaboration the knowledge about the cockpit crew comprises models of the physical and mental resources as well as behavioural models (see Figure 10.3). Thereby, the crew behaviour for situation assessment, planning and plan execution is to be modelled for normative behaviour as well as individual behaviour. The knowledge about the crew member's individual behaviour has to be learned on-line by the machine. Modelling of the error behaviour is another important behavioural aspect to be covered. Crew action modelling should not be confined to activities with hands and feet, also eye and head motion as well as voice activity contain important information, also with regard to efficient communication management between machine and crew.

In summary, Sections 10.3 and 10.4 have outlined the main guidelines, in little depth though, which are to be followed as closely as possible in order to warrant human-centered automation. These guidelines can easily be formulated as system design specifications. There are already examples of successful developments like those described in Strohal and Onken (1994), which have proven that the transfer of the basic requirements into system concepts and realisation can be successfully accomplished the way it is described.

10.5 THE COCKPIT ASSISTANT SYSTEM *CASSY*

With the following description of the Cockpit Assistant System CASSY (Gerlach & Onken, 1992), we would like to present an example how to design to comply with the discussed ideas. CASSY was developed at the *Universität der Bundeswehr München* (UniBwM) in cooperation with *DASA-Dornier.*

In the previous, the important part of electronic situation understanding for successful machine support spointed out. A system can only understand a situation if it has the appropriate knowledge of the problem space it works in. Since CASSY is limited to civil aviation, its knowledge base comprises the elements of figure 10.4.

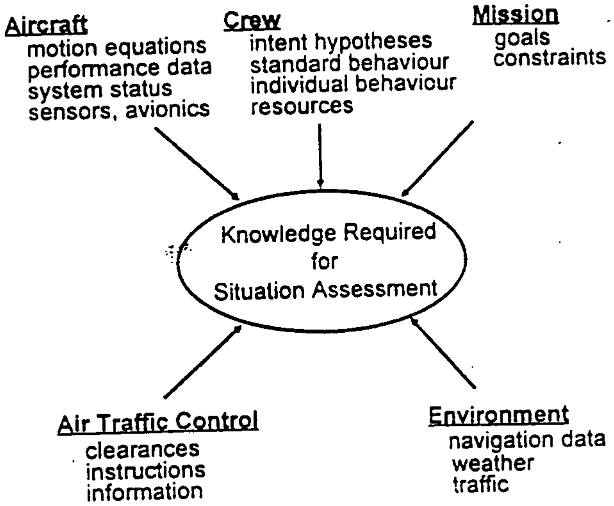

Figure 4

Figure 10.4: Knowledge base of CASSY

This knowledge base is characterized by static knowledge, e.g. a normative model of cockpit crew behaviour or knowledge of the used aircraft, and dynamic knowledge referring to in-flight changing circumstances caused by instructions from air traffic control (ATC) or environmental influences. Stored in a central situation representation, this knowledge serves as a global picture of the current situation.

In order to gather dynamic knowledge and to transmit its conclusions the assistant system is placed in the flight deck. CASSY has interfaces to the flight crew, to the aircraft, and to ATC (Figure 10.5). The interfaces ensure that all knowledge sources are available for the task specific modules of the system.

The **Automatic Flight Planning** module (AFP) generates a complete global flight plan (Prevot & Onken, 1993). On the basis of its knowledge of mission goal, ATC instructions, aircraft systems status, and environmental data an optimized 3D/4D trajectory flight plan is calculated. The flight plan, or several plans, is presented as a recommendation which the crew accepts or modifies. Once a flight plan is chosen it serves as a knowledge source for other CASSY modules. The AFP recognizes conflicts which may occur during the flight, e.g. due to changing environmental conditions or system failure, and appropriate replanning is initiated. If necessary, this replanning process includes the evaluation and selection of alternate airports. Since the module has access to ATC instructions, radar vectors are incorporated in the flight plan autonomously and the system estimates the probable flight path ahead.

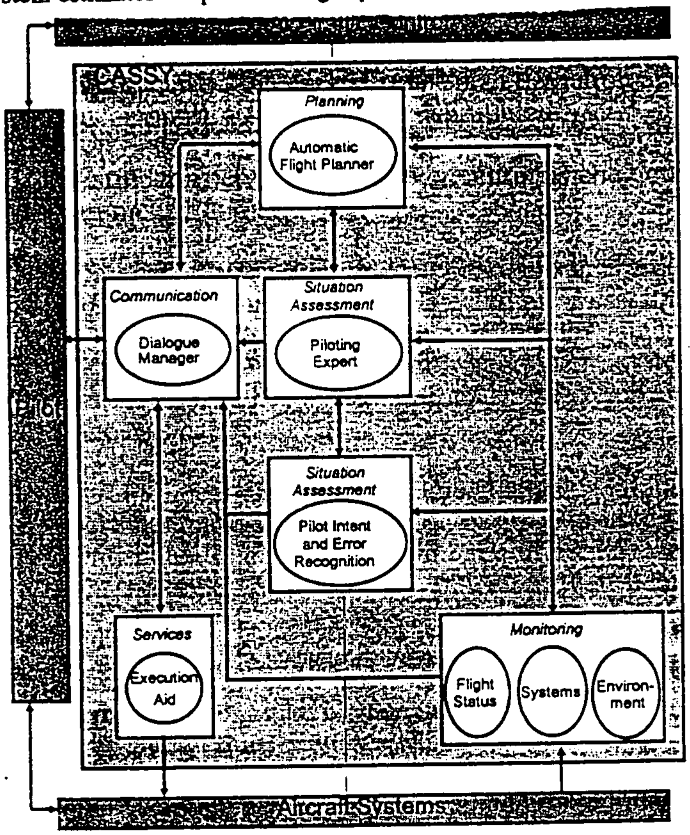

Figure 10.5: The Cockpit Assistant System (CASSY)

The presentation of the resulting situation-dependent flight plan to the crew serves directly requirement as discussed in Section 10.3, it provides evidence for necessary flight plan changes. The extensive aid in decision-making and time consuming flight plan calculations supports the second requirement.

The Module **Piloting Expert** (PE) uses the valid flight plan to generate necessary crew actions. It is responsible for processing a crew model on normative and individual crew behaviour (Ruckdeschel & Onken, 1994). The normative model describes the deterministic pilot behaviour as it is published in pilot handbooks and air traffic regulations. The model refers to flight guidance procedures concerning altitude, speed, course and heading, but also to aircraft systems management. Given the flight plan and a pointer on the current leg, provided by the Monitor of Flight Status, the system determines the appropriate normative values and tolerances on aircraft systems and flight status data. Using the individual model, determined from an adaptive component, these data are adjusted to individual preferences.

The crew model as used to generate necessary expected crew actions, is absolutely vital to meet requirement 1. It enables the system to identify the most important actions on the basis of the underlying situation and to interpret the observed crew behaviour.

The expected crew actions are compared with the actual behaviour of the crew in the module **Pilot Intent and Error Recognition** (PIER) (Wittig & Onken, 1993). The crew actions are derived indirectly by interpreting the aircraft data. If given tolerances are violated, the crew will be informed by hints and warnings and the detected mistake is pointed out to the pilots. In the case the crew deviates intentionally from the flight plan, the module checks if this fits to one of a given set of hypotheses for allowed intents which are also part of the crew model. These hypotheses represent behaviour patterns of pilots in certain cases, e.g. tasks to be done when commencing a missed approach procedure or to deviate from the flight plan to avoid a thunderstorm ahead. When an intentional flight plan deviation and the respective hypothesis is recognized, appropriate support, e.g. replanning, is initiated.

The monitoring of the pilots' actions and the distinction between error and intentional behaviour in extraordinary situations serves both basic requirement 1 and 2. Additional monitoring modules are needed to enable the system to recognize and interprete current situations. The **Monitor of Flight Status** provides the present flight state and progress. It is also able to report the achievements of subgoals of the flight.

The **Monitor of Environment** gathers information of the surrounding traffic, e.g. from TCAS and of weather conditions, and incorporates a detailed navigational data base of the surrounding area. The health status of aircraft systems are monitored by the **Monitor of Systems** like a diagnosis system.

Obviously, the monitoring systems are essential to meet the first requirement as their outputs are an important part of the full picture of the present situation. Since their output is also used to adjust the flight plan to the situation, they contribute to meet the second requirement, too. Additionally, the continous observation of flight progress, environment, and aircraft systems supports the crew on tedious or boring but tasks.

Communication plays an important role in CASSY. The kind of information to be transmitted in either direction varies with respect to the different modules (figure 10.6). The information flow from CASSY to the crew and vice versa is controlled by the module **Dialogue Manager** (Gerlach & Onken, 1993). The many different kinds of messages require a processing in order to use an appropriate display device and to present the message at the right time. As output devices both a graphic/alphanumeric colour display and a speech synthesizer are used. Short warnings and hints are used to make the crew aware of a necessary and expected action and are transmitted verbally using the speech synthesizer. An additional alphanumeric line is fixed on the graphic display to facilitate perception of difficult verbal messages. More complex information, e.g. the valid flight plan, is depicted on a moving map on the graphic display.

Another important feature of the DM is that since the tolerances and danger boundaries are given in the crew model and the necessary actions are inferred, a priority ranking of the output message is evaluated and the most important message is issued with priority.

The input information flow is established by use of speech recognition in addition to conventional input mechanisms. In order to improve speech recognition performance, almost the complete knowledge of CASSY is used to provide situation dependent syntaxes. Thus, the complexity of the overall language model is reduced significantly. Not only the pilot's inputs must be considered but also the inputs from ATC. The data link, indicated in figure 10.6, is not available to date. Discrimination of ATC instruction from pilot input is achieved by picking up the pilot's verbal acknowledgement of the ATC controller's instructions. The use of speech input and output devices also reflects the idea of a human-electronic cooperative crew and of cooperation of partners.

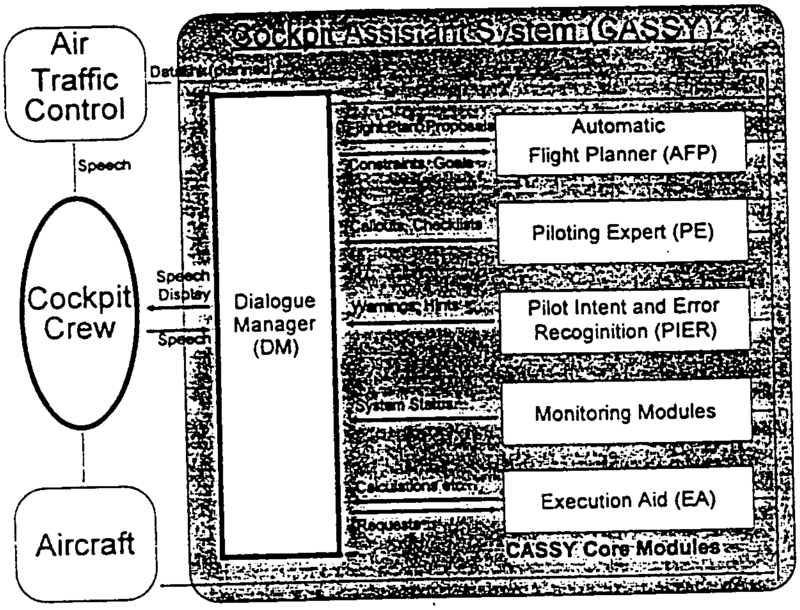

Figure 10.6: Information flow in CASSY

In figures 10.5 and 10.6 an additional module is shown which is called Execution Aid (EA). In this module several functions are realized which can be called up by the crew. Aircraft settings, navigational calculations and data base inquiries are carried out. These functions are similar to available automated functions in today's aircrafts and are mainly designed to meet requirement 2. For the pilots, the main difference is the use of speech input which facilitates the use of these services.

10.6 RESULTS OF THE FLIGHT TESTS

In June 94, CASSY was expered to an eleven hours flight test trials in Braunschweig, Germany.

The modules of CASSY have been implemented on an off-the-shelf *Silicon Graphics Indigo* workstation using the programming language *C*. A *Marconi MR8* PC card was used as speaker dependent, continous speech recognition system. A *DECTalk* speech synthesizer served as speech output device using three different voices enabling the pilot to discriminate between the various messages. The components were connected using serial lines and ethernet.

The system was integrated into the test aircraft *ATTAS* (Advanced Technologies and Testing Aircraft) of the *Deutsche Forschungsanstalt für Luft- und Raumfahrt* (DLR) in Braunschweig. The aircraft is well equipped for flight guidance experiments as it is possible to operate the aircraft via a single seat, experimental cockpit located in the cabin. An ethernet connection to the CASSY workstation was used to simulate an avionic bus system as aircraft interface in either direction. As ATC interface both approaches were tested a simulated ATC data link and the pilot's acknowledgement of ATC instructions.

The test flights comprised instrument flights from the regional airport Braunschweig to the international airports of Frankfurt, Hamburg and Hannover at which a missed approach procedure was conducted before returning back to Braunschweig.

The experiments proved CASSY's functions from take-off to landing throughout the complete flight. Speech recognition performed well in the aircraft as the surrounding noise was primarily engine noise which did not change much during flight. The recognition rates were similar to those achieved in the more quiet simulator environment at the University in Munich where CASSY was developped and tested before.

One important aspect of the tests was to prove the system in the high density air traffic control of German airports which could not be tested in the scope of simulator test runs. During the trials, any given ATC instruction could be processed and integrated into the flight plan by CASSY. Compared to available flight management systems the autonomous integration of ATC radar vectors proved to be faster and did not lead to distracting information input.

On the basis of the flight plan the correct expected pilot actions were generated and pilot errors, provoked or non-provoked, were detected and the appropriate warnings were issued. Wrong warnings occured infrequently and were uncritical in any case.

Two pilots were flying with CASSY in the test aircraft. Additional pilots from Lufthansa German Airlines were participating to observe the tests and to take part as a second pilot aside the test pilot.

CASSY was well accepted by the pilots throughout the trials. In particular, the pilots appreciated the autonomous flight plan functions of CASSY. Warnings and hints were considered justified and corrective system inputs were made. Speech input was generally used when complex inputs were to be made, e.g. frequency settings which could be made using the simple name of the station instead of its difficult frequency.

10.7 CONCLUSION

The time has come that future cockpit systems no longer will be designed on a vague basis of specifications. The advances in technology have brought about means to systematically reflect requirements for human-centered automation into clear-cut specifications for cockpit systems.

Machine functions will be incorporated which not only render support for planning and plan execution as empasized in the past. Instead, main emphasis will be placed on autonomous machine situation assessment in parallel to the crew's situation assessment activity which leads to better machine understanding of what the real needs of the crew are and consequently to more efficient support for the sake of flight safety as well as mission effectivity.

The Cockpit Assistant System CASSY is an example of how a pilot support system could look like for the sake of human-centered automation. It is designed to meet the basic requirements for cockpit systems as they were stated in this paper. The successful flight test trials with this system shows that a new generation of cockpit automation can be introduced for higher standards in flight safety and mission effectivity. There are already examples of successful developments, which have proven that the way of design guideline implementation as described in this paper systematically lead to the desired system performance.

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As the availability of manpower for military systems is reduced, as well as budgets to support fielded systems, more attention is being given to the need to reduce manning levels in future systems as compared with existing systems.The major approach to reducing manning is to reallocate functions to automated performance which were previously conducted manually, thereby reducing the workload on human operators, and reducing the number of personnel required. In this strategy, the emphasis is on a redetermination of the role of man in the system. An approach at role of man determination, conducted for the purpose of reducing system manning with respect to the existing system, is designated "REARM" for Reverse Engineering Allocation of function methodology for Reduced Manning. REARM incorporates several of the tools available in the Carlow International HSI IDEA (Integrated Decision/Engineering Aid) system.

CHAPTER 11

REVERSE ENGINEERING ALLOCATION OF FUNCTION METHODOLOGY FOR REDUCED MANNING (REARM)

T.B. Malone

11.1 BACKGROUND

The Navy combatant ship constitutes one of the most complex weapon systems in a country's defense arsenal. It is a multi-personnel system conducting multi-operations (air, shore bombardment, warfare operations, search and rescue, etc.), in multi-warfare environments (AAW, ASW, ASUW, EW and strike), as an independent combatant, a member of a squadron, or an element of a battle force. The ship systems employed in the fleet today, and being designed for the fleet tomorrow, make severe demands on the readiness, performance effectiveness and physical capabilities of personnel who must operate and maintain them. These systems are complex, highly sophisticated, and extremely demanding of the sensory, motor and cognitive skills and decision-making capabilities of system personnel.

The operational environment of the next generation of combatant ships will impose extreme information loads on the humans responsible for managing, operating, maintaining and supporting shipboard systems. The variety and interactive complexity of systems, equipment and personnel in the ship environment, coupled with requirements for rapid planning, scheduling and deployment of mission elements within a dynamic, unpredictable threat environment, will converge to impose an untenable workload on the human operator. Cognitive workload will continue to be particularly high for ship personnel due to a variety of interdependent elements, including increases in the number and rate of decisions, as well as increases in complexity and quantity of data that must be processed in order to make those decisions. Traditionally, such increases in workload have been compensated for by commensurate increases in manning; however, current and projected budgetary constraints coupled with demographic data projecting a continuing reduction of military-aged males over the next 20 years reduce the feasibility of this solution. The requirement to reduce manning levels as compared with predecessor systems is becoming a fact of life for military systems in general. Projected DoD and MOD budgets demonstrate a definite trend to reduce the numbers of personnel available to human emerging military systems.

In addressing the issue of performing system functions with fewer human operators and maintainers as compared with existing systems, the function allocation strategy is not simply to assign functions to automated or manual performance on the basis of differential capabilities and capacities of the two, as exemplified in the Fitts' List approach. Rather, the strategy is to automate functions to the extent required to enable the required reduction in manning, with attendant provisions for decision aiding, task simplification, and design in conformity with human engineering standards to ensure adequate levels of human performance.

In dealing with human-computer systems it is also important to realize that the issue is not so much defining the allocation of system functions or tasks to human or machine performance as establishing th e role of human in the system. In a human-machine system where both components are equally competent to perform individual functions and tasks, the design issue is to determine the role of the human vs automation in the performance of each function or task. The emphasis on the role of human in the system acknowledges the fact that the human has some role in every system function or task. In some cases that role may encompass actual performance of the function or task.

It is also important to realize that an assigned role for human performance may change with changes in operational conditions. Thus a task optimally performed by a human under certain conditions of workload, time constraints, or task priority, may be more optimally automated under other conditions. It is also important to keep in mind that automating a function or task does not logically mean that the human does not have a role, that he or she has effectively been designed out of the system for that specific function of task. Rather, in an automated function or task, the role of the human is that of a manager, monitor, decision maker, system integrator, or backup performer.

Historically, the most frequently applied method to reduce manning has been to automate operator tasks, thereby reducing operator workload and manning requirements. Human Systems Integration (HSI) generally attempts to reduce manning levels through automating specific tasks and establishing the potential for reallocation of human tasks to automation, or redistribution of human tasks to other humans. High driver tasks are investigated to determine the potential for reallocating the task or task sequence to automated performance or to another operator. Analyses are conducted to assess the effect of reallocation of tasks on individual operator workload and on the potential for manning reduction. Techniques to reduce manning levels through training have also focused on redistribution of tasks among crew members. High driver tasks are examined to determine the potential for cross training and organic, onboard training.

Attempts to reduce manning levels through consolidation of operating positions have been only marginally successful. This lack of success has resulted from two main obstacles: 1) specialized skills and knowledge required for different operating positions preclude simple cross-training, and 2) task performance for existing positions may involve critical activities which are parallel in time. Recent advances in the fields of artificial intelligence and HSI afford the capability to overcome these obstacles by providing on-line decision aiding, by enhancing cross-training through organic training, and by allowing some measure of operators' specialized skills and knowledge to reside in the computer. This approach, which involves what are typically termed expert systems, has met with considerable success in both commercial and government applications.

The underlying rationale of the HSI strategy for manning reduction involves the application of HSI techniques to reduce the physical and cognitive workloads imposed on ship personnel, permitting redistribution of workload among automation and human performance, and among crewmembers, consolidation of existing operating positions, simplification of operator tasks, and reduction of overall ship's manning levels. Application of HSI technology to reduce manning has only been addressed formally in recent years. The potential for reducing manning through improved task simplification and improved human-machine interface design has been demonstrated in a number of studies.

The critical issue in the HSI reduction of manning then is the relationship between manning and workload. The basis for predicting manning requirements must be the workload associated with the roles of humans in system operations. The problem, for the HSI specialist, lies in the measurement of workload. Workload measures and methods being sought involve human sensory, psychomotor and cognitive capacities and the demands placed on these by operator tasks inherent in the design of ship systems. While workload measures in the area of physical work, muscular exertion and physical fatigue are certainly of interest, the greatest uncertainty lies in the area of defining workload in tasks which do not require much physical effort but, rath er, load the operator in terms of perceptual, cognitive and decision making skills.

An obvious difficulty in measurement of these capabilities and of the demands created by system tasks is that the capabilities and the inferred workload are not observable. What is observable, however, and which ultimately contributes to or degrades total system performance is operator task performance in terms of response speed and accuracy. The time taken to respond to stimulus events and the quantitative and/or qualitative accuracy of the response are measurable, at least in principle, and will influence total system performance.

Workload (or overload) is an intervening variable which must be inferred from observable performance. It is presumed, despite the elusive and indirect nature of the workload concept, that workload does exist and that the workload level imposed by a system task or sequence of tasks will influence task behavior.

11.2 REQUIREMENTS

The process by which functions/tasks which are candidates for automation can be identified is through the determination of the required role of the human in the system. The classical method for determining the role of the human in a complex system involves allocation of functions or tasks to human or machine (automated) performance. Function/task allocations can be either static or dynamic. Static allocations identify which functions or tasks should be allocated to human performance vs machine performance based on an assessment of the requirements associated with the function/task and the unique capabilities and limitations of the human and machine. Static allocations are usually made on the basis of lists (Fitts' Lists) which compare the relative capabilities and limitations of human and machine performance in specific dimensions.

Dynamic allocations make the assumption that the optimum allocation strategy can change with operational conditions, workloads, and mission priorities. According to Rouse (1977) a dynamic approach allocates a particular task to the decision maker (man or machine) which has the resources available at the moment for performing the task. Rouse (1981) identified the advantages of a dynamic approach as compared with a static approach as: improved utilization of system resources; less variability of the human's workload; and providing the human with improved knowledge of the overall system. Revesman and Greenstein (1983) recommended an approach wherein the human and computer work on tasks in parallel with the computer selecting actions so as to minimize interference with the human. Here the human is not forced to change planned actions and he or she retains the primary role in the system. This implementation requires that the computer must make predictions about the human's actions and must, therefore, have a model of the human in terms of the actions he/she will take at a point in time and under certain circumstances. The computer would use this model of human decision making to predict the human's actions and to select other actions which do not replicate or interfere with the human's actions.

According to Woods (1985) the role of the human has shifted with increased control automation and developments in computational technologies. The shift is away from perceptual-motor skills needed for direct manual control to cognitive skills such as those required to support such roles as monitor, planner, and fault manager. The key to effective application of computational technology is to conceive, model, design, and evaluate the joint human-machine cognitive system. The configuration or organization of the human and machine components is a critical determinant of the performance of the system as a whole. This means using computational technology to aid the user in the process of reaching a decision, not to make or recommend solutions. If joint cognitive system design is to be effective, we need models and data that describe the critical factors for overall system performance (Woods, 1985).

11.3 METHODOLOGY

The major requirement imposed by the HSI initiative is that considerations for the human in the system, including manning levels, will influence system design. In order to influence design the consideration of HSI requirements, again including manning, must begin early in the system development process. In order to have the maximum impact on design decisions, HSI requirements should be addressed prior to milestone 0, while mission needs are being determined, manning constraints are being specified, and alternate approaches are being considered. The most effective technique of addressing HSI issues early in the development process is to focus on the assessment of lessons learned in baseline comparison systems or predecessor systems. Lessons learned include problems identified in baseline comparison systems which should be avoided in the emerging system, and positive aspects of the baseline system which should be considered in the new system. Through the reengineering process, operations and tasks in existing systems which impose heavy workloads on humans can be identified, and requirements for alternative allocations can be specified. A second technique for addressing human requirements and considerations early in system development is through the use of computer simulation to model human performance in system missions and operations.

HSI approach to influencing system design early in system acquisition, with special emphasis on reduction of manning in the emerging system, addresses the issue of establishing the optimum role of the human in a four step process: 1) identifying candidate roles of the human; 2) identifying specific requirements attendant to these roles for specific scenarios; 3) modelling human performance as expected in the selected set of assigned roles for the scenarios; and 4) assessing the alternative role-of-human concepts in terms of effectiveness, affordability, and risk reduction.

1) identifying candidate human roles.

In identifying the candidate roles of the human in the system, the emphasis, from a reduced manning perspective, is to automate tasks which are currently performed manually. Identifying manpower determination lessons learned in baseline comparison systems involves assessing the adequacy of the allocation of functions to human or machine performance in these systems, and identification of where human functions and tasks can be reallocated to automated performance. This assessment requires a reverse engineering of the function allocation approach underlying the design concept implemented in the baseline or existing system. Through the reverse engineering technique the rationale for allocation decisions can be made explicit and opportunities for alternate allocations can be explored. Alternative role of the human concepts involve alternate approaches to automation, providing decision aiding to reduce human workload, and improved design of human-machine interfaces to simplify tasks and reduce workloads.

2) identifying specific requirements attendant to candidate human roles.

The requirements associated with specific function allocation/role of human concepts include task requirements (information, performance capabilities, decision and support requirements, task sequencing, and time dimensions of tasks), human knowledge/skill requirements, and requirements for containing human errors. These requirements are generated for specific mission scenarios which represent configurations of mission objectives, threat and own force deployment, system conditions of readiness, and special conditions (environmental, operational, and tactical).

3) modelling human performance.
For the task sequences and attendant requirements associated with specific mission scenarios, human performance must be modeled to identify potential problem areas. The modelling process is two-fold .

First, a task performance model is developed through application of task analysis. When task sequences and requirements are sufficiently understood, a task network simulation is conducted to assess the impact of the function allocation/role of human approach on human performance and workload.

4) assessing the alternative role-of-human concepts.
The HSI assessment of function allocation/role of human concepts will include an assessment of technology requirements associated with the concept, and, for individual concepts, assessment of effectiveness, affordability and risk. The technology assessment will focus on the extent to which technology advancements are needed to support implementation of a specific concept. The assessment of concept effectiveness will address the extent to which the concept meets system requirements and will enhance system operability, usability, maintainability, supportability, survivability, and safety.

The assessment of concept affordability will determine the extent to which life cycle resource requirements are met for operational manpower, maintenance manning, training, personnel non-availability due to accident, expected human error rates, expected time to repair, supportability, and expected system downtime. The assessment of alternative function allocation/role of human concepts in terms of risks involves a determination of critical factors that will have a significant impact on, and have risks for, readiness, life cycle costs, schedule, performance, or design. These include such items as: tasks, task sequences, and task complexity; environments and environmental controls; equipment design features; maintenance requirements; information requirements; manning requirements and associated workloads; personnel skill levels and training requirements; and potential existence of health and safety hazards.

11.4 REARM

The need is for a methodology which enables the assessment of the allocation of functions approach which is inherent in an existing system through a reverse engineering technique. This methodology should be automated to the maximum extent and should provide for effective interfacing with a simulation methodology to enable the determination of the effects of specific function allocation schemes on workloads, and consequently on manning levels.

One methodology for integrating the human into a complex system was developed by Carlow International for the US Army Human Research and Engineering Directorate, (USAHRED), the Naval Sea Systems Command (NAVSEA), and Space and Naval Warfare Systems Command (SPAWAR). This approach is designated the HSI IDEA (Integrated Decision/Engineering Aid)(Malone et al., 1992). A subset of the IDEA tools directed at determination of roles of human in a system to support reduced manning has been designated "REARM" for Reverse Engineering Allocation of function methodology for Reduced Manning. REARM incorporates several of the tools available in the IDEA system, including the IDEA Lessons Learned Database (IDEAL), the Role of Man Analysis (ROMAN) tool, the NETWORK graphic task network tool, the IDEA Task Analysis tool (I-TASK), the IDEA task network simulation tool SIMWAM, and the IDEA HSI assessment tool ASSESS. The REARM methodology is directed at describing, through reverse engineering, the allocation of function strategy evident in an existing system, and the problems and positive aspects associated with the strategy. The relationships among the IDEA tools under REARM are depicted in Figure 11.1.

In the IDEA methodology the existing system is described in the Lessons Learned Database (IDEAL) and the implemented roles of the human are developed through application of an automated tool designated the Role of Man Analysis (ROMAN) Tool. The IDEAL provides techniques to acquire, analyze, classify, prioritize, and store lessons learned data describing problems and positive aspects of the function allocation scheme inherent in the existing system.

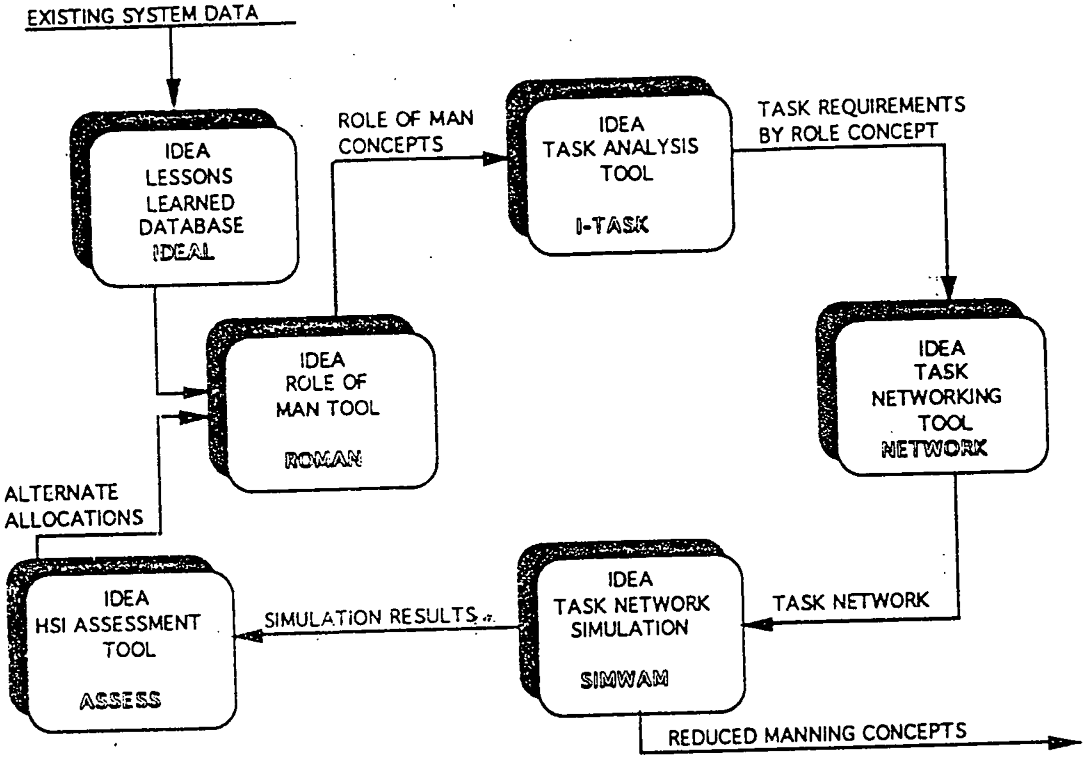

Figure 11.1: Relationships of idea tools in function allocation/role of human determination for reduced manning

ROMAN provides the analyst with the capability to import a set of functions or tasks and to assign roles to human performance and automation in the performance of each function and task. As each function/task is presented to the analyst, a decision is required as to which component (human or machine) should be the performer of the function or task. Where an assignment cannot be readily made, the analyst selects a consultation capability from the tool, and the tool presents a series of questions where the analyst is asked to scale some dimension of the task, operational conditions and environment, user capabilities, and mission priorities, and, based on analyst responses, the tool recommends that the task be assigned to human or machine performance. In each case where an assignment of task performance has been made, the analyst is asked to identify the role of the human, and the role of the machine in the performance of the task.

The assigned roles for each task are then exported to the IDEA automated task analysis tool (I-TASK) where specific requirements for task performance are identified for each task, under the specific allocation strategy and role assignments. I-TASK comprises a data bank of issues and concerns for human performance of system tasks as affected by the selected roles of the human and the machine in the completion of the tasks. For tasks which are cognitive in nature, by reason of the task itself or the assigned role of the human in the performance of the task, the task data are exported to an IDEA Cognitive Task Analysis Tool (I-COG) for a refined analysis addressing the cognitive aspects of required human performance, and the resultant task data are then imported back into the I-TASK Tool.

The results of the task analysis are then exported to the NETWORK IDEA tool which describes task sequences in a graphic flowchart format, with task descriptions available in text format. The task descriptions maintained in the NETWORK tool comprise a subset of the requirements derived for each task in the Task Analysis Tool. These task descriptions include specification of the performer of the task, the tasks which must precede the specific task, and the tasks which are dependent on the specific task, the designation of th e role of the human in task performance if other than performer, the estimated time required for task completion, and the process va-riables associated with performance of the task. Process variables include factors that have a bearing on task performance and which can vary for any simulation exercise. Process variables typically include capabilities or readiness of aircraft systems, operational/environmental conditions, mission data, and threat characteristics.

The NETWORK data are then exported to the IDEA simulation tool, SIMWAM (Simulation for Workload Assessment and Modelling) for exercising the task sequence as specified in the NETWORK tool. SIMWAM is an interactive, microprocessor-based simulation of human performance and workload.

NETWORK is a tool which runs on the Apple Macintosh computer, taking advantage of the Macintosh graphics capabilities and user interface to allow the analyst to draw a task network. A set of drawing tools is provided to generate, locate, and connect task boxes. A task box can be named and then opened to produce a set of dialog windows. These allow the analyst to input particulars about a given task including such things as the operator(s) qualified to perform the task, the priority of the task, conditions which must be met before the task can be started, and parameters which specify the probability distribution of completion time for the task.

Once a task network has been defined, it can be exported to SIMWAM for simulation of the task network, exported to the task analysis tool, or exported to any of the Macintosh graphics applications for documentation purposes.

The objective of SIMWAM is to provide an analysis of a network of tasks which comprise the basis for determination of crew workloads, individual workloads and personnel performance problems. SIMWAM is a task network simulation tool which can execute a network model previously defined by NETWORK. During a SIMWAM run, tasks are called when prior tasks are completed. If sufficient operators are available for a called task, then it will be started. Input data which describe a task include a list of qualified operators and the number of these required to perform the task. In attempting to start a task, SIMWAM will assign capable operators who are currently idle. SIMWAM can also interrupt lower priority tasks in process to obtain operators for higher priority tasks. Operators are not necessarily human operators but could be any resource entity.

When a task is ready to start, SIMWAM draws a random sample from the probability distribution of duration for the task. While the task is in process, operator time is accumulated on the task. When the task is completed, it can call other tasks. If the call is probabilistic, then one task out of several will be called depending on specified probabilities. Human error, equipment failure, or a hit or miss following weapon firing are events which could be accommodated by probabilistic tasks calls. A task can also call one or more tasks deterministically when a fixed sequence of tasks exists. Task calls can also be made conditional on events or variable values by means of user-written subroutines. This capability ensures that virtually any logical conditions for the start of a task can be accommodated. For example, tasks required to process objects in a queue could be called only if there is one or more object(s) in the queue. As SIMWAM executes a network model it tracks mission time, task completions, task start and end times, time spent per task per operator, and operator utilization. At the end of a simulated mission, these data can be printed. At the end of a simulation run involving a number of missions, the means and standard deviations of mission data over the number of missions run can be printed.

SIMWAM consists of a set of related programs which permit the analyst to: create and maintain a data base of task requirements; execute the task network; print performance data following the network execution; and modify the task data to evaluate alternate concepts. Some of the features of SIMWAM which provide the resources for the analyst to model an existing or conceptual system include: predecessor relationships between tasks; calls for execution of other tasks on task completion; specification of the operator(s) qualified on each task; task interruption in case of operator assignment conflicts; task priorities which control operator assignment; and monte carlo sampling of task durations and task calls.

As the network is executed, statistics are stored permitting the following printouts to be obtained: sequence of events showing task times and operators; summary of task completions and operator time on each task; matrix of the time spent on each task for each operator; and summary of active and idle times for each operator.

The interactive nature of SIMWAM allows the analyst to evaluate alternate system design or modification concepts involving manpower reduction, cross-training, automation, task modification, or function allocation. SIMWAM has been used in several military applications to identify the potential for reducing system workloads and manning levels.

The results of the simulation exercise, in terms of workload and expected human performance problems, are then provided to the HSI Assessment Tool. This tool will support an assessment of alternative role-of-man concepts in terms of affordability, risk reduction, and expected effectiveness. The affordability assessment will address the extent to which affordability objectives are achieved with the alternative approach. Affordability objectives from an HSI perspective should address the cost risks identified for each alternative. The objectives should include reduced acquisition costs and reduced life cycle costs. Reduced acquisition costs include cost reductions through HFE/MPT/safety and health integration, and reduced need to redesign. Reduced life cycle costs are achieved through reduced: manning, training time, pipelines, needs for new training facilities, accident rates, human error rates, time to repair, supportability requirements, system downtime, personnel non-availability.

The HSI Risk Assessment will address cost, schedule, and design risks associated with the role-of-man concept. Current human system cost drivers, MPT drivers, human performance, and safety high drivers will be identified for each concept, and tradeoff decisions will be identified. Critical Human System Factors will be identified in design alternatives that will have a significant impact on readiness, life cycle costs, schedule, or performance. These include: tasks, task sequences, task complexity; environments and environmental controls; equipment design features; maintenance requirements; information requirements; user-computer interface features; manning requirements; workloads; personnel skill levels; training requirements; and health and safety hazards. Subsystems or component associated with each role-of-man concept will be evaluated for high or moderate risks.

The assessment of the effectiveness of each role-of-man concept begins with an analysis of outstanding HSI issues and concerns from each HSI domain. The relative criticality of identified issues/concerns will be established. Finally, recommendations concerning the changes which could be made to a concept to improve its effectiveness will be formulated.

The result of the application of the HSI Assessment Tool will be the results of assessments, and the recommended changes to a role-of-man concept which changes are then fed back to the ROMAN tool for analysis and evaluation.

11.5 APPLICATIONS

The techniques and tools described above have been implemented in several HSI attempts to reduce system manning in Navy systems.

1. Reduction of Manning in Carrier (CV) Air Management
A study conducted for NAVSEA by Carlow Inte rnational, (Kirkpatrick et al., 1984) involved the application of decision aiding techniques in the form of automated status boards, to reduce the manning levels of CV aircraft management systems. This effort also resulted in the development of the workload simulation tool SIMWAM, for measurement of the impact of human engineering design changes on system manning.

The CV aircraft management system includes 35 operators. A scenario for exercise of this system was developed with emphasis on the variables affecting human performance for a sequence involving 12 aircraft launches and 13 recoveries.

A SIMWAM simulation was conducted for a scenario currently implemented in the fleet. After tasks, sequences and times to perform were verified in a ship visit (USS Constellation) the simulation was completed for the baseline condition. The sequences inherent in the network of tasks were then adjusted to reflect changes due to the introduction of automated status boards (ASTABs) as decision-aiding devices, and a second simulation run was completed with the ASTAB aids in place. The complete array of tasks performed by all operators was analyzed prior to conducting the second SIMWAM run with ASTAB's included.

A comparison was made for the operator's active times with and without ASTABs. The results of this comparison indicate that four operator positions could be eliminated due to the reduction in workload following introduction of the ASTAB aid. Results also indicate that 25 of the remaining 31 operators were able to accomplish assigned aircraft management tasks in less time with the ASTAB than without it. This finding is statistically significant at beyond the .001 level. In terms of the magnitude of the time change from run 1 (without ASTAB) to run 2 (with ASTAB) it was found that, on the average, operators completed assigned tasks in run 2 in 20.6% less time as compared with run 1.

2. Reduction of Manning in New Attack Submarine Ship Control
Carlow International also recently conducted an effort for the Naval Sea Systems Command to reduce manning levels for the New Attack Submarine (NAS) ship control system. The thrust of this task was two-fold: a) to apply HSI methods and data to the resolution of the issue of operator capability to conduct ship control tasks under representative scenarios with two operators as compared with four operators in the baseline SEAWOLF system; and b) to determine operator workloads associated with the reduced manning.

A description of the baseline system (SEAWOLF) ship control system was developed including: the roles and responsibilities of the 4 operators and other operators involved in system operations (e.g. OOD); the allocation of control function and authority to human control, semi-automated control, or full- automated control; the workstations provided each operator, and the human-machine interface features associated with each workstation; and time estimates or constraints associated with specific tasks and task sequences.

NAS normal and contingency missions, conditions, and operations were identified which were used in scenarios in the assessment of alternative automation concepts. A task sequence was developed for the baseline system for selected scenarios using the IDEA NETWORK tool. Parameters associated with each operator task were identified based on inputs from subject matter experts. Parameters include maximum and minimum time to perform tasks, task dependencies, and the effects of continuous operations on performance.

Workloads associated with SEAWOLF operators for each scenario were assessed using SIMWAM. Operators include those performing functions of helm/planes watch, ballast control, Diving Officer of the Watch, Chief of the Watch, and OOD.

Feasible alternative approaches for reduced manning ship control were then identified using the concepts already developed in the description of alternate ship control system design approaches. The roles of humans in the alternate automation concepts were determined using the IDEA Role of Man Tool. Task sequences for each ship control station automation concept were established for selected scenarios for the two ship control operators and all other personnel involved in ship control activities (e.g. the OOD) and levels of specific task parameters were identified using IDEA NETWORK. Workload and performance assessments for each alternative concept were conducted using IDEA SIMWAM. Feasible concepts were evaluated using the IDEA HSI Assessment Tool to conduct assessments of a) alternative concept effectiveness (ope rability, usability, maintainability, safety/survivability, and supportability); and b) risk potential associated with each concept, including design risks, cost risks, schedule risks, and technology risks.

3. Reduction of Manning in Advanced Sealift Ships

Finally, Carlow International is currently supporting the Naval Sea Systems Command (SEA 03D7) in the application of IDEA tools to reduce manning and improve the HSI aspects of Fast Sealift ships. A major contributor to the overall effectiveness of Sealift ships, systems, and missions is the performance and readiness of the Sealift ship crew. The HSI initiative is directed toward addressing personnel requirements in Sealift ship design. The driving objective of HSI is to *influence design* with personnel requirements and considerations. This is achieved through an approach that ensures, as described above, that personnel considerations are addressed early in system development, that emphasizes attention to the role of the human vs automation in system operation and maintenance, and that requires the use of simulation to model human performance and workload.

Ancillary objectives of HSI as applied to the Sealift program are: a) reduced manning as compared with baseline comparison systems; b) improved readiness of Sealift ships due to reduced skills, reduced workloads, and task simplification; c) improved reliability of Sealift ships and ship systems due to an emphasis on software and a reduction of human error rates; d) improved personnel availability and survivability due to reduced hazards and accidents; e) enhanced system and equipment availability through reductions in time to repair; and f) enhanced system affordability, resulting from the reductions in manpower support costs, training costs, costs of systems unavailability, costs of human errors, and costs of accidents.

Activities to be accomplished in the effort include developing a lessons learned data base; tracking HSI issues in existing Sealift ships; identifying roles of humans and automation in selected Sealift mission scenarios; conducting function and task analyses for selected roles of man; identifying alternate approaches to reducing manning levels in specific Sealift systems; determining requirements to modify licensing procedures; determining training requirements; conducting HSI assessments; and conducting HSI and reliability analyses.

The specific requirements and constraints to be addressed in the application of HSI technology to the Future Technology Variant Fast Sea lift ship acquisition include the following:

- high reliability equipment, which will result in a reduced need for a human backup capability, and at the same time will reduce the maintenance burden, and the workload imposed on maintenance personnel;
- training pipelines which will assure ready availability of trained personnel in the numbers and timeframe required while minimizing the time to complete training;
- reduced shipboard manning levels which address reduction of workload through automation of tasks currently performed manually, and moving to shore establishments activities currently performed on-board, as well as application of HSI technology such as decision support systems, job performance aids, task simplification techniques, and on-line intelligent tutoring;
- reduced skills required to perform tasks in a reduced manning environment, through application of HSI technology such as decision support systems, job performance aids, task simplification techniques, and on-line intelligent tutoring;
- personnel career progression and advancement;
- integration and consolidation of rates and ratings which will result from reduced manning;
- emphasis on influencing design based on a ship, system and equipment design philosophy which envisions the role of the human as decision maker, systems manager, and overall supervisor while the role of the machine encompasses that of worker;
- focused on total ship as well as ship system and equipment acquisition, as opposed to ship system/equipment acquisition alone;
- emphasis on user acceptance, with the designation "user" encompassing the military organization responsible for Sealift operations, the commercial ship owner/operator, and the on-board human operator and maintainer;
- integration of HSI technology into ship and system acquisition through implementation of a standardized and formalized HSI process which is itself an application of the systems engineering approach.

HSI application to the Sealift Future Technology Variant program will be accomplished over a three year period. The products of the effort which will be available at the end of the three year period, are as follows:

1) HSI Issues and Constraints for the Sealift Program;
2) reduced manning ship operational procedures;
3) results of HSI technology, effectiveness, affordability, and risk assessments;
4) training requirements in terms of existing licensing procedures;
5) reduced manning concepts for electric, propulsion, auxiliary machinery, ship control, and ship services such as food service. Existing Sealift ships require manning levels of 30 to 40. The goal in HSI application is to reduce the manning levels to 12-15, for a manning reduction of up to 70%;
6) ergonomic design of integrated consoles for single operators for electric/propulsion, auxiliaries and ship control;
7) innovative messing, inventory control, and stowage concepts;
8) strategies to effect revised U.S. Coast Guard (USCG) regulations and requirements to revise USCG regulations and to accommodate Union requirements;
9) curriculum changes required, and model curriculum for reduced manning ships;
10) final requirements to revise USCG regulations
11) validation of reduced manning and manpower determination processes and tools.

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Function allocation as any other human factors technique shows a wide field of yet unanswered questions. However, partial answers do exist and can be useful to system design, provided that they are compatible with a project managment logic. The paper describes how human factors can be managed in a project, thus offering a guideline. The main steps are the definition of a project strategy, definition, conception and evaluation. The need is expressed for simulation techniques of tasks/function allocations configurations.

CHAPTER 12

MANAGEMENT OF FUNCTION ALLOCATION DURING PROJECT DEVELOPMENT

P. Aymar

12.1 INTRODUCTION

Function allocation is a proven software development methodology. However transposing it to hardware or Man-Machine Interfaces (MMI) development is not as easy as one would expect. If a computer memory can be infinite, and stand multiplication of modules, the real world is finite; a workstation has a limited number of slots and obviously a human has limited number of finger, arms and cognitive abilities as well. This contribution aims to give few hints to explore how the concept of function allocation transcripts to Human Factors (HF), using the management as a guideline.

Project management is a process that ensures that at its end, there will be delivered a satisfying technique within acceptable cost and delays.
It relies on 4 main steps:

- Definition of a strategy based on risk management consideration
- Specification of what has to be done
- Conception
- Control of the conception process and products

The main management tools are the functional specification, the technical specification, the evaluation program.

For all these steps, the first phases of the program are crucial (10 % of the money spent, 90% of the choices are committed). At these stages, the only representation of the project available are some futuristic concepts used to raise the money, the functional description and occasionally some mock-ups. The functional description is the only one to have a contractual pertinence. Being "Functional" has thus a special importance because it forms the basis for a common language and the evaluation of the deliveries; it includes all the declension of the word such as function allocation.

12.2 A PROJECT STRATEGY

The project manager's task is *to handle* risks which may come from management, technique, operation, etc. Risk management is a discipline by itself with its own experts, however, for Human Factors considerations the basic answers are amongst:

- Level of detail of the specification
- Methods and tools mandated
- Control level and communication support
- Co-ordination/co-operation of project actors.

The last item is the most crucial. Paradoxically, it is human factors people who suffer most of this HF side-effect. A strategy can be to set up HF databases providing a common and validated view of the project. "*Fiches Operateurs*" and "*Fiches Equipement*" are used in this purpose in France. Nevertheless, it is necessary to have a common understanding of *HF objectives.*

A formulation can be to make the system and its various subsystems usable; for instance, if we consider a ship, it has to be usable by:

the Navy	through	- Human resources management - Training
the Crew and work teams	through	- Organisation of collective activities - Communications - Habitability and living Conditions
Individual Operators	through	- Operability of systems - Work Conditions

The *knowledge* required by these can be summarised by the MANPRINT domains:

- Human Factors Engineering
- Manpower
- Personnel
- Training
- System Safety
- Health Hazards
- Basic Methods.

MANPRINT suggests a way to implement HF by organising the debate around use activity of the systems (the HOW), because it is where technical people and HF people meets. Different point of view exist in a program, the problem is to organise their co-operation. For instance, on a C3I system:

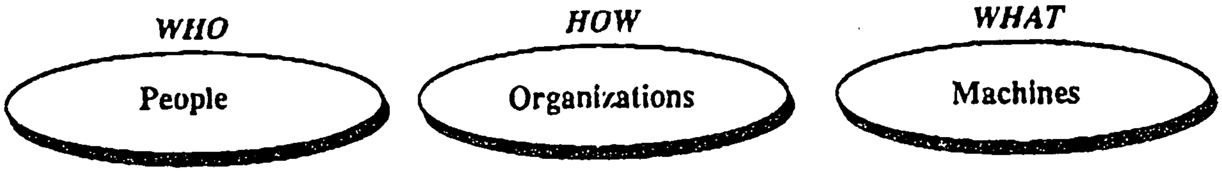

Figure 12.1: Views in a system development program

Architect	think about	- Technical objects (hardware)
Programmers	think about	- Functional objects (software)
Users	think about	- Opering/ Operable objects (liveware)

An implementation program that would allow these actors to communicate can be structured in the following manner:

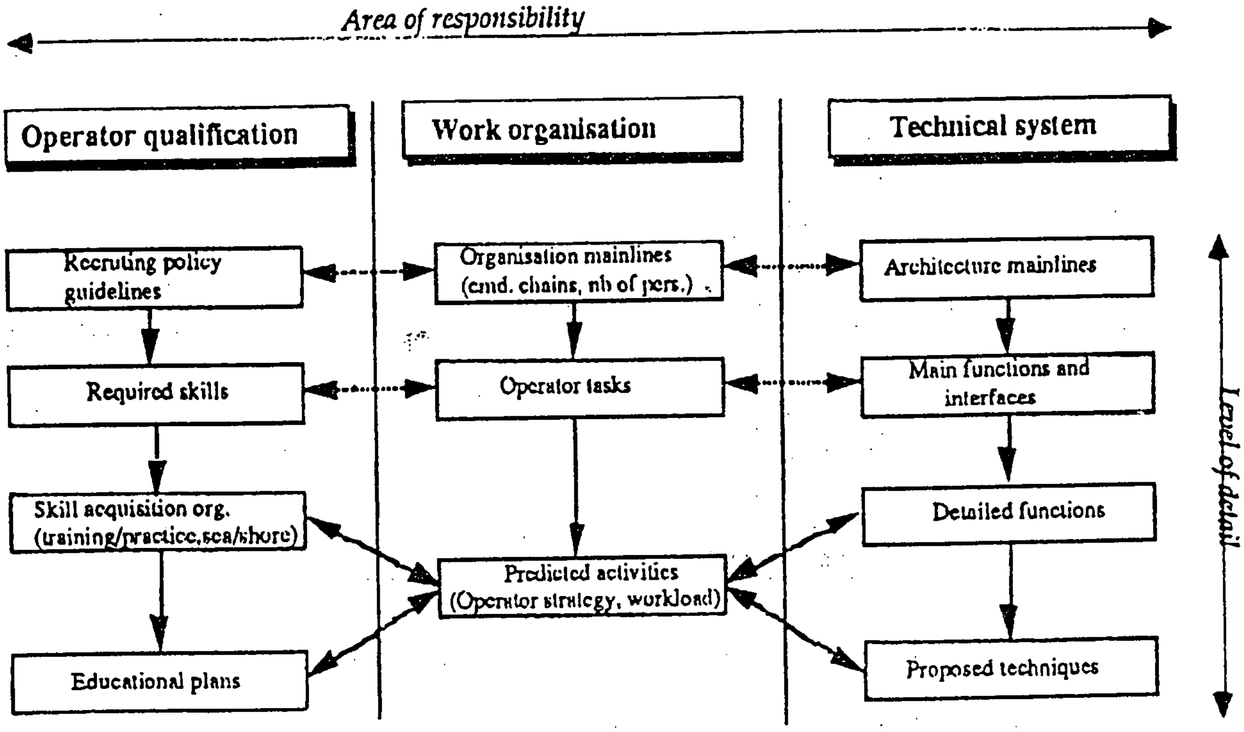

Figure 12.2: Communication between areas of responsibility

- a horizontal arrow represents the communication and control process (consistency checks for instance)
- a vertical arrow represents the application of methods and tools.

The HF expert of the project manager would then ensure the execution of the program, providing expert advice centred on the work activity.

12.3 SPECIFICATION

As every one knows a specification can be functional or technical. Its process corresponds to the elaboration of information and concepts. These concepts being ultimately precised, as mandatory or information, to a contractor. In a top-down approach, that is underlying the "Functional way", it is necessary to compile information from various sources which may include results of analysis of current systems, mock-ups, prototypes, prospective or equivalent systems. This task and activity synthesis helps to organise a negotiation between operator and technique on the field of the work organisation.

Example of argument:
Man rep': "I prefer to keep the old system because the are *trained to use it*"
Technique rep': "Yes, but as you can see *operation* are much simpler with this system so you need less people"
Man rep': "I understand, it would fit us better if you *transfer this task* to the operator, so that we are sure he won't lose his know-how" ...

The synthesis process could be illustrated as:

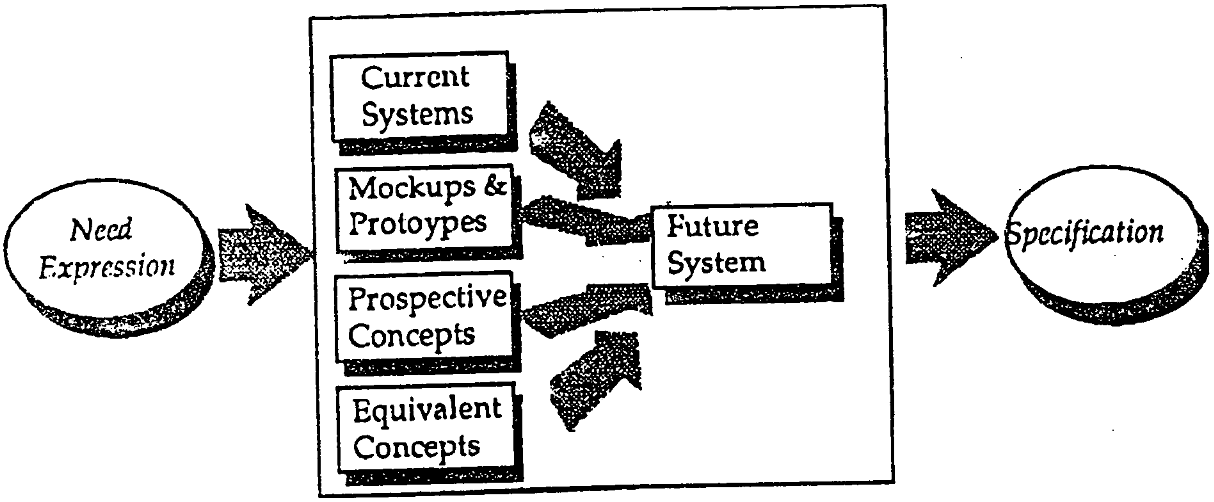

Figure 12.3: The synthesis process from need to specification

In major projects, such as building a ship, there are many subcontractors, specification is not only a system description, it is also underlying the allocation contract with all its constraints: evaluation, design responsibilities and money...These contract sharing consideration are quite often dominant, because they take into account the industrial know-how and market reality (which has always had a strong meaning in NATO countries...). However, these contract allocation always have a strong impact on either the function allocation or the integration. In both cases these choices are not consequence free for the future operator. They will sometime influence the homogeneity of his MMIs, but also the organisation that supports him or her. This include training, career management, selection, ranks and grouping, ... The process of function allocation takes more and more into account the consequences of choices on the operability of the future system. Distributed models (Micro Saint, ...) help to take these criteria into account. However, it should also help to integrate a wider span of HF criteria such as the know-how acquisition and why not job satisfaction and personal achievement.

12.4 CONCEPTION

The conception is usually the obscure phase of structured top-down approaches such as those induced by Functional Analysis. Innovation is not consistent with FA which meets, at this stage, an intrinsic difficulty: the next step should be to allocate functions to the design objects. But which objects? There is a need to iterate with a bottom-up approach where candidate objects would be selected. The selection of objects would be more accurate, while the functional chunks would become bigger and more structured. So far so good, and this is globally the schemes used by my fellow engineers. However, this process tends to forget the synergetic/antisynergetic properties of systems and the possible benefits of redundancies. There is a constant need all along the project to:

- organise a structuration of the function
- evaluate the impact on the integrated system of conception choices.

Analysis methodologies flourish (object oriented, Petri, semantic, cognitive,...), they offer alternative perspectives of the system: what am I used for? In what state am I? What am I doing? What information do I use?

They help to structure the system functions, according to the reference chosen. At the other end, prototypes and integration platforms help to represent the function, its technique and user, in their working environment.

12.5 EVALUATION

The evaluation process takes place all along the project. Evaluation grids exists, there are quite a few in the literature. Every Human Factor expert has his own, depending from his origin: nuclear, C3I, aircraft,... The job of the manager is to define the grid most appropriate to his system, and his quality and risk management objectives. Then he needs to implement an *evaluation* plan that will help him to control the work and deliveries of his subcontractors. Basic investigation methodology imply conformance to standards, operability checks, and user trials. An example of grid for evaluation of warship systems may be:

- Operability
  - MMI devices
  - Workstation facilities
  - Help devices
- Teamwork
  - Operator role
  - Workload
  - Communication
- Work conditions
  - Layout
  - Environment
  - Hygiene
  - Security
- Human resources requirement
  - Number
  - Selection
  - Training

The evaluation should apply at all states of development of the system. The more physical the matter to evaluate is, the less integrated, the later in the project, the better. User trials on prototypes aim to address most of these problems; however when nothing exists yet, the only thing to evaluate is the clustering of functions and the pertinence of technical solution considered in regard of overall performances. Modelisation of distributed system when it is carried out with enough methodological and experimental care, is a way to validate those virtual systems. The function allocation itself should be evaluated, including all its implication on the operation of the system. This may include Human Machine interaction, redundancies of task and allocation of task among operators. This should take into account extern datas such as use scenarios, performance and reliability of imposed concepts of equipment and organisation.

12.6 CONCLUSION

Function allocation is more than a design feature, it is a major concern to the management. It should be:

- a specification tool,
- a basis for contract allocation and evaluation,
- a communication and dialogue tool among project actors.

It can also be a design tool prolonging the top-down approach to the definition of the physical or visual subsystems of the MMI. the function allocation must also be reliable, and methodologies should include evaluation and performance indicators.

With the adequate support and management tools such as HF plans and supervision, a project manager is able to integrate Human factors in his course of work. Function allocation would then play an important part in this process, provided that its alternative make the function allocation alternatives need to make clear the consequences on the future activity. The challenge is of course to include human engineering preoccupation such as the operability and the habitability of the system, it is crucial and technique such as models, CAD/CAM and full scale mock-ups offer a fair support. However there is also a need for a wider span of Human Factors consideration such as the teamwork, and the integration in the users organisation (Navy in the case of ships). This last one offer the toughest challenge but also the most rewarding; it shall open the door of rationality and cost-effectiveness to know-how acquisition, job satisfaction and personal achievements.

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14. Abstract:
It is well known that humans do certain tasks better than machines and that machines do other tasks better than humans. However, in systems design, allocation of tasks between human and machine is not straightforward. Tools and heuristics exist, but more robust function allocation tools are needed. MAN-SEVAL is such a tool that is used to model operator performance and then allow funciton allocation trade offs. The U.S. Navy is using such technology to understand function allocation and workload relationship in tactical display design. Traditional engineering approaches often involve automating functions without regard to human factors and the operator's performance limits. In this paper a series of function allocation trade off studies based on a human engineering analysis of operator performance are discussed. Results are presented in the context of operator workload and reference to display design solutions are made.

CHAPTER 13

FUNCTION ALLOCATION TRADE OFFS: A WORKLOAD DESIGN METHODOLOGY

M.L. Swartz and D.F. Wallace

13.1 INTRODUCTION

Deciding how to allocate control of system functions for real time, highly automated tactical environments that enable operators to perform optimally is essential to good human engineered design. The NATO Sea Sparrow Missile System (NSSMS) is being redesigned to accommodate its integration into the Ship Self Defense Program. The NSSMS is already highly automated with a semi-automatic modes of operation for certain tactical situations. However, the current design was not human engineered to take into account operator performance requirements. To that end, we looked at human performance criteria and function allocation trade offs in the NSSMS so that the redesigned Human System Interface would 1) follow human engineering design principles and 2) support optimal operator performance.

In the current design, NSSMS operators are faced with a host of tasks, each competing for attention during a mission. Two task conditions present workload problems for operators: electronic countermeasures (ECM) and LOCAL (manual) control of target acquisition functions. In an ECM environment workload is increased by imposing additional processing demands on operators (e.g., monitoring an ECM scan for targets). LOCAL control functions are engaged in infrequently, but their impact on operator performance is high. This mode of operation in the current NSSMS design requires that operators manually control certain tasks (e.g., target search). LOCAL control under ECM conditions further compounds this workload placing the greatest demands on operators. Some functions that are not currently automated should be; others need to remain under operator control. This scenario presented the basis of our workload-based function allocation trade offs.

13.1.2 NSSMS Functions and Operator Control

NSSMS radar sensors locate a target, automatically track it, and guide the missile to the target location when it is fired. The system is operated by two individuals. The Firing Officer's Console (FOC) operator is responsible for supervising tracks, missile management, and launcher assignment data. The Radar Set Console (RSC) operator also supervises some dynamic processes, and is responsible for most ECM and LOCAL control tasks. Automatic computer control of NSSMS processes operates at high data rates to efficiently and accurately carry out specific system functions while the operators monitor these processes. The assumption for these "system supervisors" is that they sample the relevant information at a sufficient rate to make an appropriate intervention decision. The problem for the human operator, however, is two-fold. First, we know from human information processing theory that humans have limited resource capacity for the amount and type of information they can process. Second, operators can introduce noise into a system's closed-loop feedback system if information is not sampled at adequate rates (Moray, 1986) or simply the wrong information is processed.

For example, the RSC operator monitors system status data and assigned tracks during target tracking. As he supervises system processes, he may have to make a decision and interrupt the system control loop, such as in the case when target priorities change. In mission critical situations, we can say his workload for these tasks is high. Under ECM conditions, workload will increase even more. Often the RSC operator needs to assume manual control so that electronic counter countermeasures (ECCM) can be taken.

The operator's strategies for handling high workload may affect his supervisory performance. He may not monitor processes effectively, he may decide to change task order, or even drop nonessential tasks.

An intuitive design solution for these potential errors may be to reallocate the tasks and monitored information more equitably between the two operational stations (RSC and FOC). However, this solution cannot be accomplished adequately within the constraints of the existing system, nor without analyzing the supervisory control aspects and their related information processing requirements for both NSSMS operators. The reallocation of tasks is not straightforward (Sheridan, 1988). It must be based on sound human engineering principles for supervisory control paradigms and be integrated within the system engineering design for the NSSMS. Incremental function reallocation trade offs will provide an understanding of how workload is distributed across tasks and between operators when taking control of the autonomous control loops in NSSMS. This incremental analysis will also provide preliminary assessment of manning level requirements for the system as part of Ship Self Defense when certain functions become automated that currently are not.

13.1.3 Multiple Resource Theory and Workload

Multiple resource theory (Wickens, 1986) provides a framework for describing the various resource channels that NSSMS operators utilize to perform mission tasks, and a means for assessing the total load upon the operator at any one time. This theory states that attention processing resources are limited and must be allocated among all tasks performed by an individual. As workload increases, this limited capacity pool of resources may no longer be able to provide the attention and processing needs for the task(s). Each resource channel (auditory-visual-cognitive-psychomotor) is viewed as a distinct processing system, such that an individual can be fully "loaded" when he utilizes the full capacity of one channel (e.g., listening to a Doppler shift signature -- auditory) and still be able to undertake an additional load on other channels (e.g., reading range rate on the display -- visual & cognitive) without performance decrement on either task.

Capacity limits for each channel can be defined by the number of "bits" of information that can be processed in any one of the four resource channels. This limit of 7 +/- 2 bits of information is well known in the experimental psychology community. Function allocation trade offs based on an analysis of these capacity limits will enable us to design console displays that present information in ways that best support the operator and his/her cognitive capabilities.

We approached this display design problem by conducting a detailed analysis of operator performance that included 1) an assessment of operator task requirements and workload, 2) a trade off analysis of system functions to reallocate tasks among the appropriate number and type of operators, including automation, and 3) a design guideline report describing the necessary input devices and information displays to support NSSMS operators as supervisory controllers of system processes. This paper presents the results from task items 1 and 2.

13.2 STUDY DESIGN

We developed exemplar mission scenarios to identify realistic naval threats for ECM and LOCAL control conditions. We video-recorded these simulated scenarios with actual NSSMS operators at two Navy sites for subsequent analysis. Control conditions (no ECM and semi-automatic (no LOCAL) control) were also video-recorded and used as a workload baseline.

13.2.1 Participants

Naval personnel with NSSMS operations and/or training experience were recruited from naval bases in Oxnard, CA and Chesapeake, VA. All participants had received training on NSSMS systems. Some of the participants were NSSMS instructors. The level of NSSMS operator console experience ranged from 1-9 years; operators with actual combat experience were not available.

13.2.2 Apparatus and Materials

Video cameras were used to capture operator performance during this study. All scenarios were generated using the NSSMS training simulator, and run on FOC and RSC consoles and other NSSMS hardware to ensure the validity of our findings. Paper and pencil questionnaires were also employed for the structured interviews. A human performance modelling tool, Workload Analysis Aid (WAA) (Army Research Institute, 1992), was used to run simulations of the modeled NSSMS tasks and to conduct function reallocation tradeoffs between automation and the human operators.

13.2.3 Procedures

Videotaped Scenarios. All operators were informed as to the purposes of the study and provided informed consent to participate in this investigation. Operators were asked to perform a suite of representative NSSMS tactical engagement scenarios including ECM and non-ECM environments, Semi-automatic and LOCAL operations, and prosecution of air and surface targets. All representative scenarios were run in real-time and operator actions were videotaped. The videotapes were time-stamped and specific task times were calculated for each mission scenario.

Operator Interviews. After all scenarios were completed, operators were interviewed to assess the operational models used by the NSSMS operators and clarify any actions performed during the tactical simulation. The interviews were also used to discuss any difficulties operators have had in using the current system, and any suggestions or "wish lists" operators might have had for improvements, features and enhancements to the display and console.

WAA Human Performance Models. Descriptive human performance models for both the FOC and RSC operators were built using the WAA tool. The videotaped scenarios were used to capture the true task performance and to provide task time data. Each function and its constituent tasks were assigned with the appropriate time. NSSMS experts assisted in the verification of these models and time on task to ensure accuracy. Under each major function, tasks and subtasks were listed and organized into either serial or parallel sequencing with other tasks. Where mission-defined branching occurred, appropriate probabilities were assigned for each branch. Performance times and WAA-derived resource channel values were also assigned for each task. Each model was "run" and the workload results analyzed. After a model was built and analyzed, the WAA tool permitted reallocation of tasks between operator and automation within a particular model. This capability was utilized to model performance in a suite of function allocation trade offs.

13.3 RESULTS

Descriptive performance models were run for all study conditions (Semi-automatic versus LOCAL, ECM versus No ECM). These models provide an objective description of task analysis-derived performance and are not to be construed as predictive models of operator behavior. All tasks under each condition were assigned with resource channel values to identify the complexity of a task. Results plotted workload into histograms for each channel's loading per task. WAA also provided task overload summary results for each simulation model. Due to the varied nature of the ECM environment, multiple contingencies, and the fact that some of the activities are classified, we decided to model ECCM tasks within WAA as a continuous function, parallel within the other functions, that can occur at any time for up to the full duration of the coincident function. The ECCM workload values were modeled separately and a composite set of workload weightings derived. We set a limit for each channel at 7 bits to ensure the control of potential workload in the new design.

Each simulation run resulted in a total mission time of 4 minutes 42 seconds, well within the set limits of the defined mission time of 4 minutes 50 seconds (which includes 3 minutes for tuning the missiles).

13.3.1 Overall Workload

Workload during ECM was highest for both operators as predicted The RSC operator had greater workload in both LOCAL control and ECM conditions in general when compared to the other operator. The FOC operator had greater workload during certain functions in both conditions, but this was due to added verbal communication tasks with C^2 personnel and normal state verification of console indicators, not real-time tactical demands incurred in either LOCAL control or ECM. The effects of overall workload for both NSSMS operators are illustrated in Figures 13.1 and 13.2. Here we show a simple additive model that sums the loads across all four channels. If, for example, each processing channel was loaded at 7 bits of information, the operator would be fully loaded at 28 (4 channels X 7 bits). This is not to assume that a value of 28 or less is acceptable, but rather to illustrate that any combined workloads of greater than 28 are excessive and cannot be sustained by an operator for any period of time.

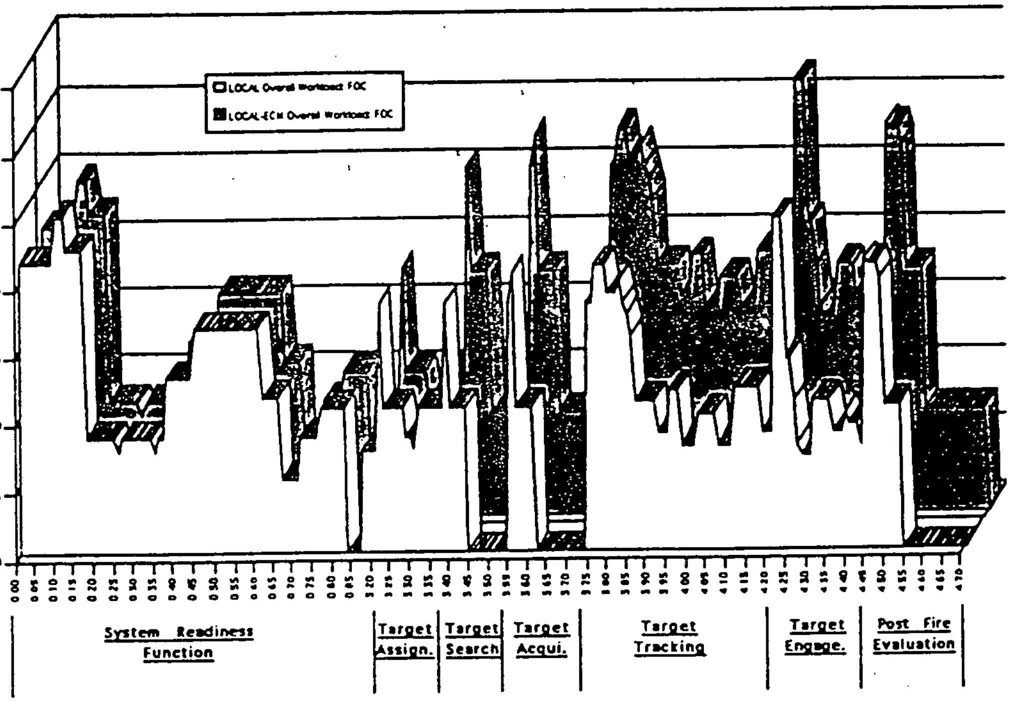

Figure 13.1: FOC workload comparing LOCAL control, no ECM (white area) with LOCAL control, ECM (Gray area). The x axis depicts mission time & system functions; the y axis an additive scale of 'bits of information'. Excessive workload is above 28, a composite of the 4 individual channels assessed.

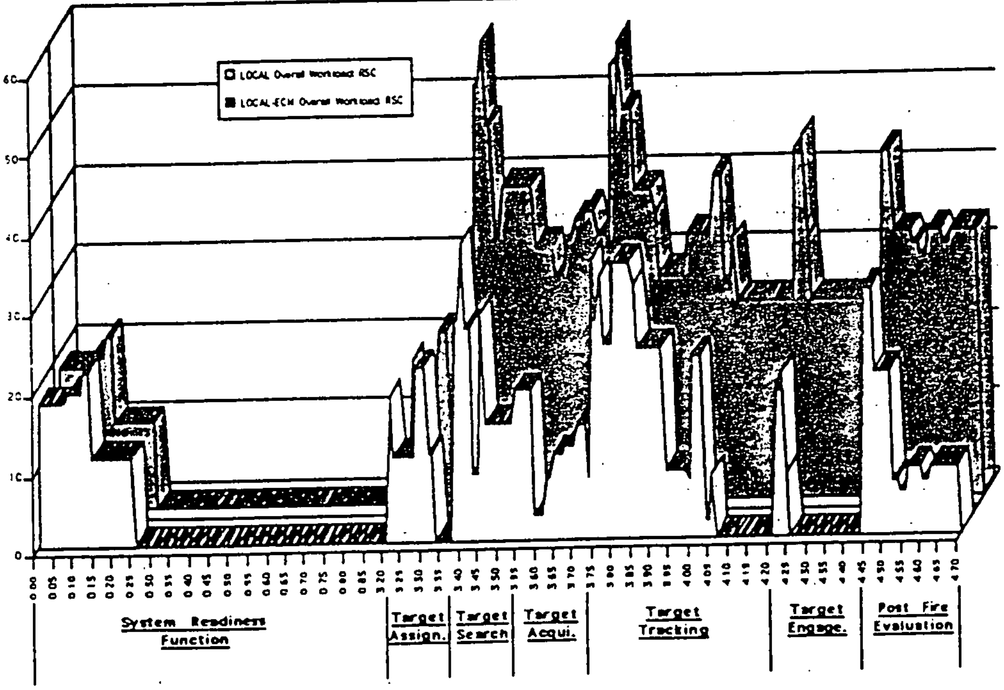

Figure 13.2: RSC workload comparing LOCAL, no ECM (white area) with LOCAL, ECM (Gray area). Same scale as described above.

Research suggests that specific workload channel overloading is not the only factor considered in examining operator performance (Huey & Wickens, 1993). Operators can sometimes cope with heavy workload upon one channel by shifting tasks to other processing resources or eliminating tasks. If all channels are heavily loaded, it can reduce the operator's coping options. Post-experiment interviews revealed that some operators used such coping strategies, but this type of analysis was not pursued further in this research.

13.3.2 Specific Task and Channel Loadings

Next we discuss the specific tasks where high workload occurs and the specific resource channels that are affected for each NSSMS operator. Since the worst-case scenario for workload is when the system is under LOCAL control in an ECM environment, this discussion will focus upon that condition.

An analysis of the FOC operator revealed that the cognitive and visual channels are most often overloaded. Further analysis revealed that the majority of the visual overloads and many of the cognitive overloadings were directly traceable to prescribed observations of system status indicators, as in both System Readiness and Target Engagement tasks. Of the re-maining overload conditions, our analysis showed that many of these were transient "spikes" of increased workload as opposed to a sustained workload over long periods of time. The particular functions with the most sustained workload are: Target Tracking (where missile management decisions are made), Target Engagement (firing of missile), and Post Fire Evaluation (determination of appropriate actions to perform based upon tactical situation, ship's doctrine, and engagement outcome).

The RSC operator revealed a different pattern of workload. Again, the visual and cognitive channels were most often overloaded across tasks, but there was also a substantial psychomotor load that was encountered occasionally during Target Tracking. Even the auditory channel was overloaded during Target Tracking when Doppler audio cues and speech (FOC-RSC communications) were processed simultaneously. As with the FOC operator, visual observation of normal system status indicators contributed to high workload. Unlike the FOC operator, however, the RSC operator is subjected to a more sustained, elevated workload. Some of the specific functions that sustained extreme loading were: Target Search (where many visual and cognitive resources are demanded to identify target video returns), Target Acquisition (psychomotor demands for dual cursor controls, one rotary, one linear), Target Tracking under ECM conditions (visual and cognitive resources demanded to main-taining target return, identify ECM encountered and counter ECM all at the same time), and Post Fire Evaluation (Kill/Survive decisions).

13.3.3 Task Reallocation Trade Offs

Based on the above results, we ran a series of function allocation trade offs using the WAA tool to reallocate selected tasks in the LOCAL control mode between both NSSMS operators with different levels of additional NSSMS automation. Finally, we examined a trade off between a single NSSMS operator and additional NSSMS automation as a first step in identifying appropriate manning levels for NSSMS operation in the new system design.

We ran the function allocation trade offs with the LOCAL control-ECM models because task demands for this condition imposes performance problems for operators during the stress of actual engagement. This was also confirmed in the results presented above. In addition, many LOCAL control and ECM tasks are not currently automated in the existing NSSMS design. Since the visual and cognitive channels were the two that are most highly loaded in these conditions, we were interested in reallocating tasks with those resource requirements. The WAA tool allowed us to reassign tasks and then run the simulations to model the redistributed tasks. Workload histograms were again plotted and threshold levels assessed. In these trade offs, as before, we used 7 bits of information as the maximum allowable limit for any one resource channel at any one time.

In the first trade off we assigned all of the system verification and monitoring tasks across all functions to automation. These visual tasks were unnecessary and accounted for a great deal of the excessive load for both operators. Our design work is looking at display methods that reduce these task demands through more efficient information presentation (Swartz & Wallace, 1994). This trade off showed that overall, both operators' workload was reduced as shown in Figures 13.3 and 13.4. These levels are dramatically lower when compared to workload levels for the baseline allocation of tasks for LOCAL control / ECM conditions shown above in Figures 13.1 and 13.2. The System Readiness function and all constituent tasks in this trade off were below the 7-bit threshold for both operators. The FOC operator experienced a high workload spike in the target acquisition and post fire evaluation functions. The RSC operator's workload began with the target search function as a high, discrete spike and then remained high through the rest of the mission. Consistent with the previous workload results, the visual and cognitive resource channels continued to experience excessive workload despite these automation trade offs. Clearly, more function allocations to automation are needed to reduce the load to more manageable levels.

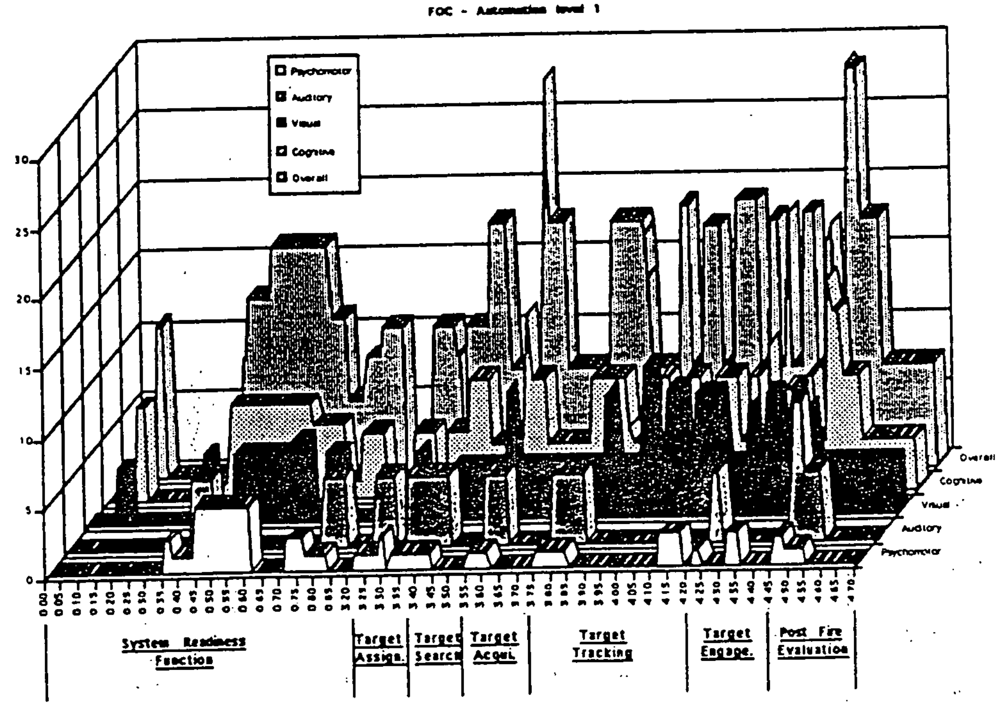

Figure 13.3: Channel workload levels for the FOC operator when a minimal function allocation trade off is used. Excessive workload is reflected where workload exceeds 7 (bits) on the individual channels, or 28 overall.

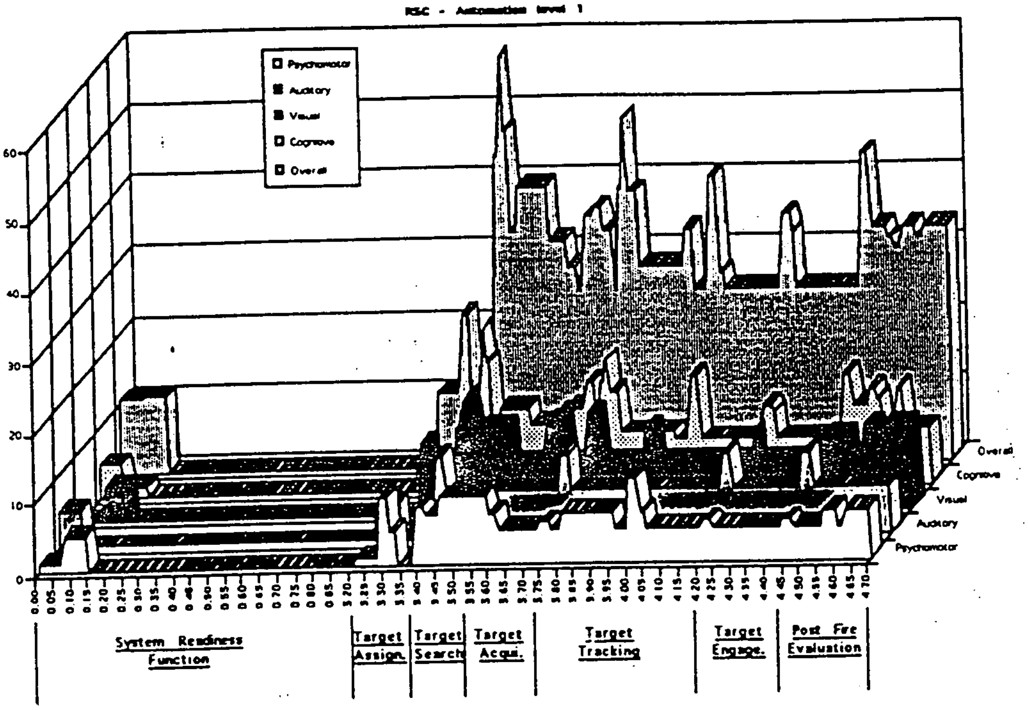

Figure 13.4: Channel workload levels for the RSC operator when a minimal function allocation trade off is used. Excessive workload is reflected where workload exceeds 7 (bits) on the individual channels, or 28 overall

Under the next function reallocation trade off, we included increased automation of additional tasks for both operators based on some of the workload reduction techniques we were developing for the new console displays. Examples include: 1) converting target data observations, mental conversions and calculations from three separate display indicators to a single graphical display that automatically provides a synthesized result, and 2) a redesign of more complex selection and motor tasks (e.g. determination and transfer of track to a target launched weapon, or integration of bearing and range rate controls into a unified multi-degree of freedom input device). These display solutions for the new NSSMS console design are described further elsewhere (Swartz & Wallace, 1994).

The results of the simulation run showed a dramatic drop in workload for the FOC operator (See Figure 13.5). At this increased level of automation, his maximum workload falls below the 7-bit threshold. The RSC operator's high workload drops about half of the original workload we observed (Compare Figure 13.6 with Figure 13.2) and is less than that incurred in the first trade off (Figure 13.4), but he still experiences excessive load in the last four system functions. These are the most critical functions the operator must perform. Consistent with previous results, the cognitive and visual channels are still heavily loaded.

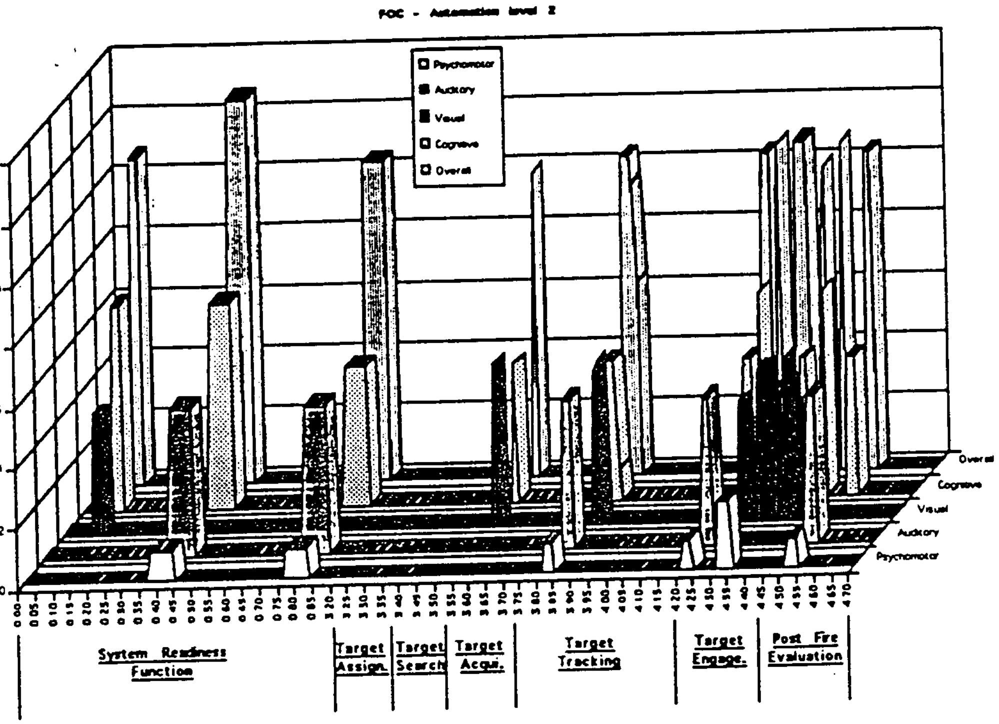

Figure 13.5: Channel workload levels for the FOC operator when a moderate automation trade off analysis is used.

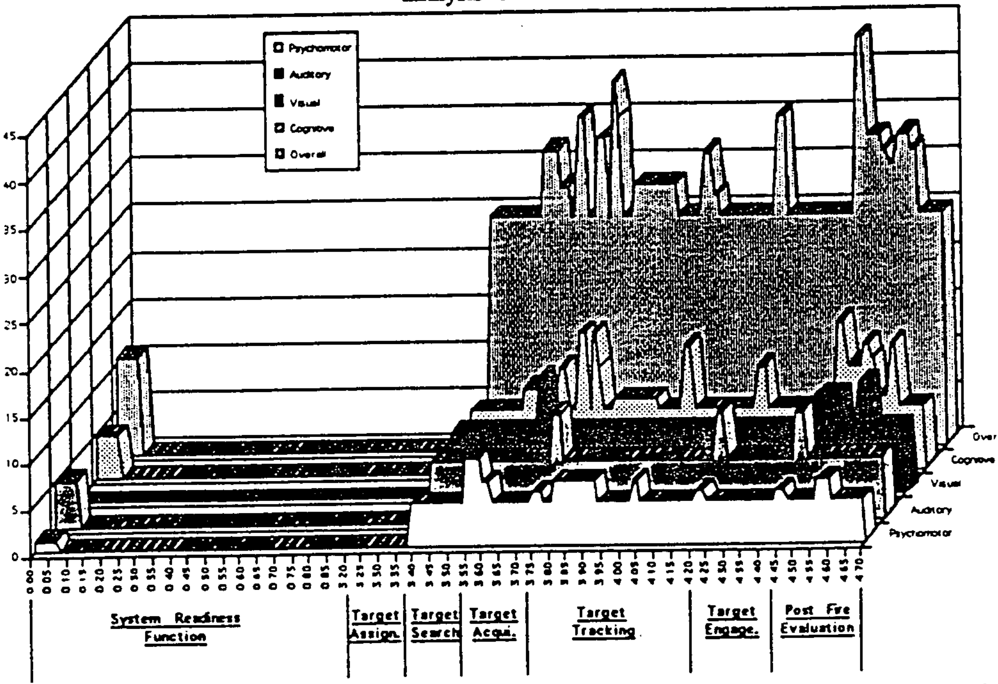

Figure 13.6: Channel workload levels for the RSC operator when a moderate automation trade off analysis is used.

We next looked at the minimum number of personnel required to operate the NSSMS. For this analysis, we examined the impact of allocating all remaining tasks to a single operator to determine if such a design would be feasible. Given the high load for the RSC operator in the second trade off, we had no real expectation of favorable results when the FOC tasks were added to this position. Nevertheless, to uncover those problem areas for a potential single operator, we used the second reallocation scheme as above, and reallocated all operator tasks to a single NSSMS operator and ran the simulation. Some tasks, involving coordination between operators (e.g. FOC to RSC communications) were eliminated inasmuch as they were inappropriate to a single operator system. This analysis was further bounded by an assumption of a single radar, single launcher configuration (Some NSSMS configurations use two launchers and require two operators).

The preliminary WAA analysis indicates that this combination of both operators' functions into a single position does not dramatically increase the workload of a single operator (See Figure 13.7). In fact, the overall workload measure for the single NSSMS operator increases only slightly when compared to the RSC operator in a dual operator configuration with the equivalent amount of automation. However, consistent with all the RSC trade off analyses, excessive workload at this level of automation remains in all functions from Target Tracking through the end of the mission.

13.4 CONCLUSIONS

Results from the task analyses, operator workload simulations, and reallocation trade off studies we conducted consistently identified specific visual processing of system status information and cognitive decision making tasks as high workload areas for both operators. The LOCAL control and ECM conditions, as predicted, imposed the most workload on operators. We determined that many of the high workload tasks involved verification of normal system operations, and could therefore be easily automated.

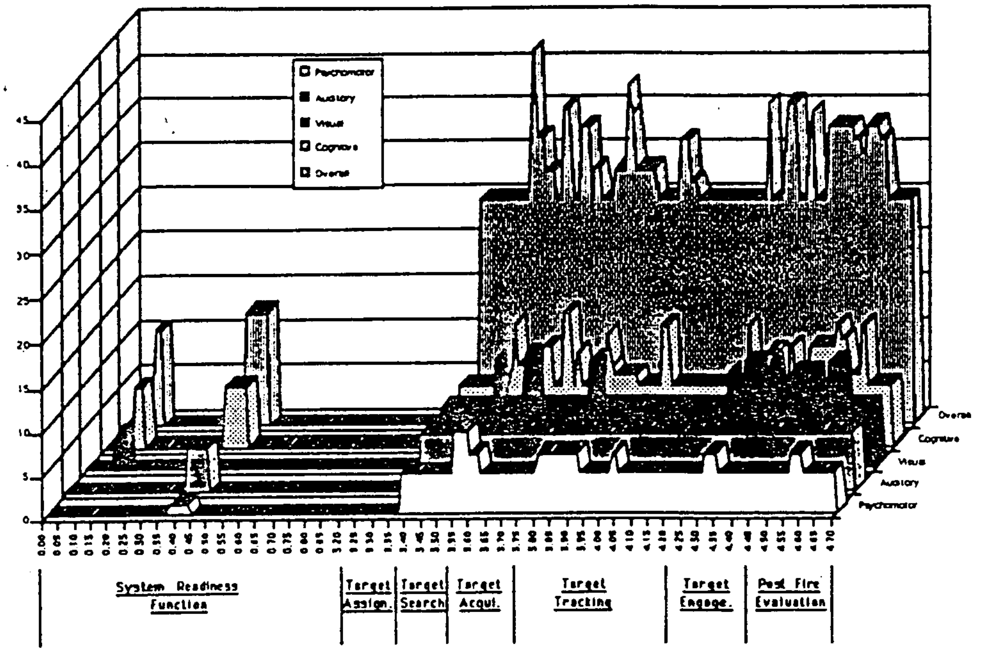

Figure 13.7: Channel workload levels for the single NSSMS operator performing all NSSMS tasks when a moderate automation trade off analysis is used.

The transient spikes of high workload for the FOC indicate that he could be able to temporally distribute some of those tasks associated with sudden spikes over time. This problem can corrected with workload reduction techniques for presenting information on the display. The RSC operator has the highest workload as anticipated even when increased automation was introduced into the operator performance models.

While the workload analysis provided an assessment of specific tasks that continue to impose high workload on NSSMS operators, specifically for the visual and cognitive channels, the task reallocation tradeoff results provided a view of the impact of redistributing tasks upon operator workload. These analyses reinforce the intuitive conclusion that increasing automation can reduce NSSMS workload. More importantly, they identify specific tasks that sustain loading and which processing channels bare the load. This is valuable information for guiding good human engineering of the display interface.

Our task reallocation studies indicate the potential for consolidation of operations to a single operator, but not until more advanced automation is introduced into the system design. A solution to the immediate workload problem for NSSMS operators is to redistribute tasks more appropriately between both positions, and to implement workload reduction techniques for presenting information on the console displays.

13.5 ACKNOWLEDGMENTS

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14. Abstract:

The twin drives of reductions in available manpower and technological advance have combined to produce proposals for vehicle design which use smaller crew numbers. This has also demonstrated the shortcomings in the techniques used for function allocation. This has been graphically demonstrated in the recent task analysis studies of ground reconnaissance performed by Edwards and Streets (1994). In those studies the requirement was to allocate residual function between each crewman, rather than between man and technology. This report documents the difficulties encountered in these tasks, the assumptions that had to be made, and discusses how observations made during data gathering enhance function allocation.

CHAPTER 14

FUNCTION ALLOCATION FOR THE DESIGN OF A RECONNAISSANCE VEHICLE

D.F. Streets and R.J. Edwards

14.1 INTRODUCTION

Beevis (1992) defines function allocation as "The process of deciding how systems functions shall be implemented -by human, by equipment, or by both - and assigning them accordingly." The activity of function allocation is central to any predictive task analysis and yet it is supported by relatively imprecise techniques (e.g. Fitts' lists) which appear to be based upon intuition rather than science. A further problem, and one that is assuming increasing importance is that current techniques do not address team interactions. With the current drive to reduce manning levels in military systems the problem of allocating residual tasks takes on a new significance.

New technology seeks to enhance system effectiveness by removing certain tasks or sub-tasks from the human domain. Technology may, for example, increase data handling, storage and transmission capability but it cannot replace the human function of information interpretation. What technology is achieving is an increase in available free time by performing repetitive and time consuming tasks, leaving the crewman free to concentrate on more intuitive duties. The concept is that free time can be increased to the point where the residual duties of a crewman can be successfully redistributed amongst others, thereby allowing a reduction in crew complement.

Available function allocation techniques fail to address the methods of achieving this re-distribution. At best an *ad hoc* approach may be employed but this fails to address team dynamics, or take account of the nature of the re-allocated tasks. In this paper we report upon observations made during the collection of task analysis data from an active reconnaissance unit which highlights an area which function allocation techniques fail to address. In the second part we demonstrate an iterative function allocation technique and discuss how our in-field observations are being applied, at a relatively low level, to improve human - human function allocation.

14.2 BACKGROUND

The principle function of armoured medium reconnaissance is to provide timely and accurate combat information to higher formations. In the British army the base vehicle for this activity is the Combat Vehicle Reconnaissance (Tracked) (CVR(T)) which has 3 crew, a commander and gunner located in the turret and a driver located in the hull. Compared to the rest of the British Army armoured fleet this is a relatively old vehicle and the aspiration exists to replace the CVR(T) with a significantly enhanced vehicle the Tactical Reconnaissance Armoured Combat Equipment Requirement (TRACER).

The expectation is that the design of TRACER will take full advantage of recent advances in integrated vehicle electronics architecture (vetronics) and military equipment technology. The philosophy behind vetronics is very similar to that governing avionics in high performance aircraft. A central processor connects each system and sub system through a data bus architecture. This allows system integration and enhanced information flow and exchange. It is this potential increase in information processing efficiency that offers scope for reductions in crew workload and, possibly, crew numbers, and has led to the suggestion that TRACER could possibly have a crew complement of two.

The Defence Research Agency Centre for Human Sciences was tasked with performing a series of task analysis activities in support of studies for TRACER. These activities have been reported elsewhere (Edwards & Streets, 1994). In outline the first series of studies were aimed at documenting current reconnaissance practices whilst the second series were predictive studies which specifically addressed surveillance activities based on the best available information on scenarios for future deployment. The information presented in the second series would be used as a design tool for the crew workstations within the vehicle. It was also anticipated that the analysis would indicate areas of crew work overload.

14.3 CURRENT RECONNAISSANCE

The overall crew tasks of CVR(T) are orientated to fulfilling the primary aim of reconnaissance. Within the crew each human has a set of well defined core roles. The main task of the driver, for example, is to move the vehicle tactically using the fastest and safest route and without causing the other crew members undue distress. However, in performing a given mission crew co-operation is paramount, for example, the driver may also be expected to provide route information such as ground conditions, state of bridges, or possible ambush points. The operation of the vehicle depends upon close co-operation between the crew and, in particular, the commander and gunner. The nature of this co-operation will be determined by the scenario and a set of rigidly demarcated procedural rules.

Allocation of current functions amongst the crew was recorded by structured interview of serving crews, discussions with subject matter experts (SMEs), and participation in training exercises (Edwards, 1992). This methodology produced the type of information shown in Table 14.1.

Table 14.1: Function allocation between 3 man crew in CVR(T)

TASK	COMMANDER	GUNNER	DRIVER
SURVEILLANCE	X	x	x
RADIO WATCH	X	x	x
NAVIGATE	X	x	
DRIVE			X
DIRECT DRIVER	X	x	
MAINTENANCE	x	X	X
STOWAGE	x	X	X
START UP DRILLS	X	X	X
COOK	x	X	X
ENCODE / DECODE	X	x	
RANGE CARDS	X	x	x
LOAD GUN	X		
FIRE GUN	x	X	

members primary duties. Following the establishment of a working taxonomy a set of task synthesis rules was derived, these were:

i Crew referred to as commander and co-commander. The commander had sole control of communications flow into and out of the vehicle, the co-commander had sole control of the driving function. These primary crew functions could only be transferred between crew members when the main armament was manned and ready for use.

ii Driving was an autonomous activity with the co-commander having the sole decision over the route and speed at which the vehicle travelled. When driving he made no primary contributioh to any other surveillance duties except route reconnaissance and survey.

iii Unless stated otherwise the co-commander had sole responsibility for off-vehicle duties.

iv The activities of driving or communications could not be combined with engagement.

v The activities of weapon and engagement or weapon management and driving could not be combined. Weapon management is defined as keeping the main weapon in readiness when the vehicle is moving

vi The crewman who made first visual contact with an enemy objective completed the engagement sequence.

These rules were based upon a behavioural premise that no more than 2 dissimilar manual tasks could be performed simultaneously. Cognitive workload could not be accounted for because the performance parameters of the surveillance devices, and possible data handling capabilities of the vetronics were ill-defined. Clearly it is impossible to read text and observe a picture for discrete changes, however it is not known if information exists on the ability to observe a scene for driving and for surveillance purposes, and if there would be any performance decrement.

Table 14.2: "Core" duties for either crewman

Commander	Co-commander
Surveillance	Drive
Communications	Route reconnaissance
Survey	Troop security
Navigation	Survey
Troop security	
Weapon management	
Troop control	

The uppercase refers to a crewman's core task whilst the lowercase refers to a secondary task where that crewman might co-operate with another man, or where he performs systems task. This relatively simplistic presentation of self-selected function allocation provided both the base data for subsequent studies and revealed some of the dynamics of duty allocation within a group.

During the collection of these data it became apparent that task allocation and individual workload in a three-man crew are driven by rank and experience. When the vehicle is in motion the commander will perform all the key functions, such as communications and surveillance. The gunners role is to aid the commander, it is rare for him to perform any command function unaided. It was noted that on many occasions that the commander used the map to mark the route taken and as a record of information flow. It was rare that other crew members saw, or used, the map. Indeed the only tasks that were, generally, not performed by the commander were driving and gunning.

It is these observations that make function allocation in a reconnaissance vehicle so difficult. Models of team work (e.g. METACREW; Plocher, 1989) work to a set of command rules which address how individuals manage work. Task sharing and switching is not addressed, nor are any procedural rules.

When static the roles of surveillance and communication are shared amongst the crew, this is known as the "stag" system. In this case each crewman will take equal turns at each system task, but with the commander having overall control and responsibility. This very tight control ensures that the system operates in an efficient and effective manner, and it is the basis of the military training system for reconnaissance troops.

The rigidity of this system may be gauged from a recent trial in which reconnaissance crewmen were presented with two identical operational crewstations which could be used for either command or driving functions. The concept was that tasks could be switched between each crewman in response to changes in the mission scenario. What was observed was that crew functions were self distributed by rank so that even when the more senior soldier was performing the driving function by choice he also performed the traditional command functions, the second crewman merely provided support. Although this may be viewed as a consequence of the military training system it does highlight a significant problem that current function allocation techniques cannot take account of rank and experience hierarchy. It is well documented that rank and hierarchy are powerful determinants of how systems actually operate; a proper understanding of these dynamics is essential. The consequences of being unable to account for rank and hierarchy in function allocation is illustrated in the next section.

14.4 PREDICTIVE TASK ANALYSIS

The second series of task analysis studies were aimed at characterising the activities associated with surveillance and engagement tasks in a TRACER concept vehicle. A full account may be found in Edwards and Streets (1994).

It was assumed that the crew would be designated as a commander and a co-commander with the gunner's duties being shared between vetronics and remaining crew members. A further assumption was that all tasks would be interchangeable depending upon the nature of the scenario. Appropriate scenarios and outline equipment performance parameters were made available.

As noted above, the gunner's on-vehicle duties which are directed at supporting the commander leave few primary tasks to be performed totally by vetronics. The outcome is that function allocation is primarily between the remaining crew member's primary duties. In order to perform this allocation it would be necessary to produce a set of task synthesis rules which characterised the remaining crew

Table 14.2 shows the core duties that were defined for each crewman from these task synthesis rules, the information gained from our earlier studies was used to enhance this allocation but the possible effects of rank and experience were purposely ignored. Because the task analysis exercise was concerned with surveillance duties the systems tasks such as stowage and maintenance were not considered.

It was unnecessary to undertake function allocation between human and surveillance devices as such systems enhance human performance, they cannot readily replace the man. However, Table 14.3 shows an attempt to allocate other equipment, by function, to the remaining crew. Performance parameters were poor and allocation was based upon the above task synthesis rules. Primary user is defined as that crewman who would have the expectation of being the priority user of that system under all conditions.

Table 14.3: Function allocation between technology and a 2 man crew

Equipment	Primary User	Secondary User
Audio and digital communications	Commander	Co-commander
Battlefield Management System (BMS) Moving	Commander	Co-commander
BMS - Stationary	Equal priority	
Land Navigation System (LNG) for driving	Co-commander	Commander
LNG for information	Commander	Co-Commander
Electronic Map System (EMS)	Commander	Co-Commander

The formal task analysis techniques used were a combination of function flow diagrams (FFDs) and operational sequence diagrams (OSDs). Function Flow Diagrams were chosen as they permitted the representation of information flow and could be altered to show each crewman's activity. The basic outline for each FFD was a preparation phase, a number of activities which had to be completed to fulfil the task, and an either / or statement. This allowed the task to be continually recycled, to be halted, or to progress onto a related activity. Each FFD was divided into 3 parallel flow lines. The central flow line described the functionality of the system task. Systems tasks were given individual reference numbers to allow a degree of ordering. To the left and right, respectively, of the systems flow line were the commander and co-commander flow lines. Text to either side of a systems task box indicated the duties each performed in accomplishing each activity. Concurrent tasks were also indicated by text between each systems task box. Information flow to and from the system, and outside the system (i.e. SHQ), to each crewman could be represented by directional arrows.

A total of fifteen FFDs supporting identified surveillance tasks were derived. An example is shown in Figure 14.1. This approach allowed visualisation of the tasks that each crewman would need to perform and permitted function allocation by default. The principle employed was that a task could only be performed if a crewman was available.

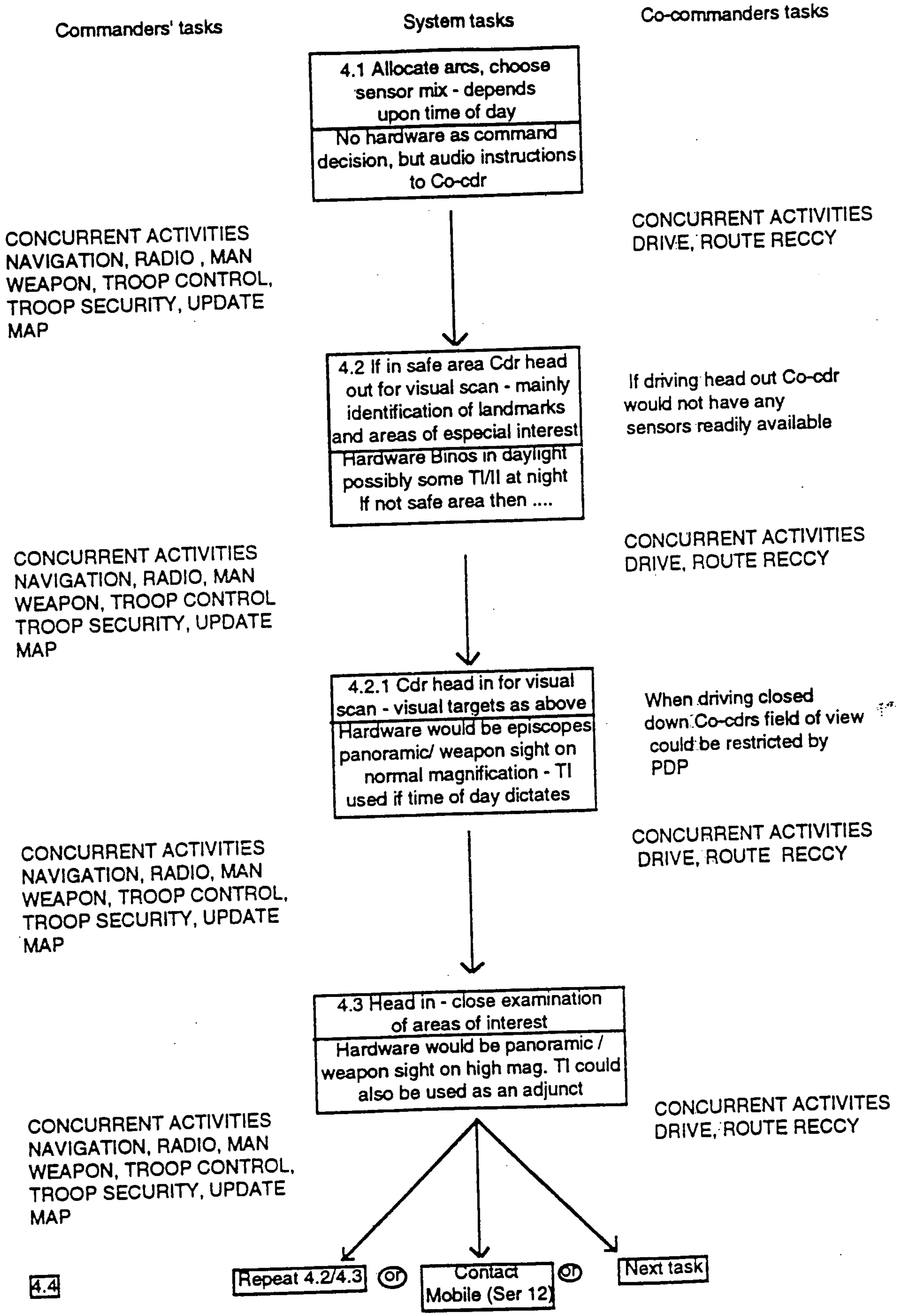

Figure 14.1: Function flow diagram for observation (Mobile).

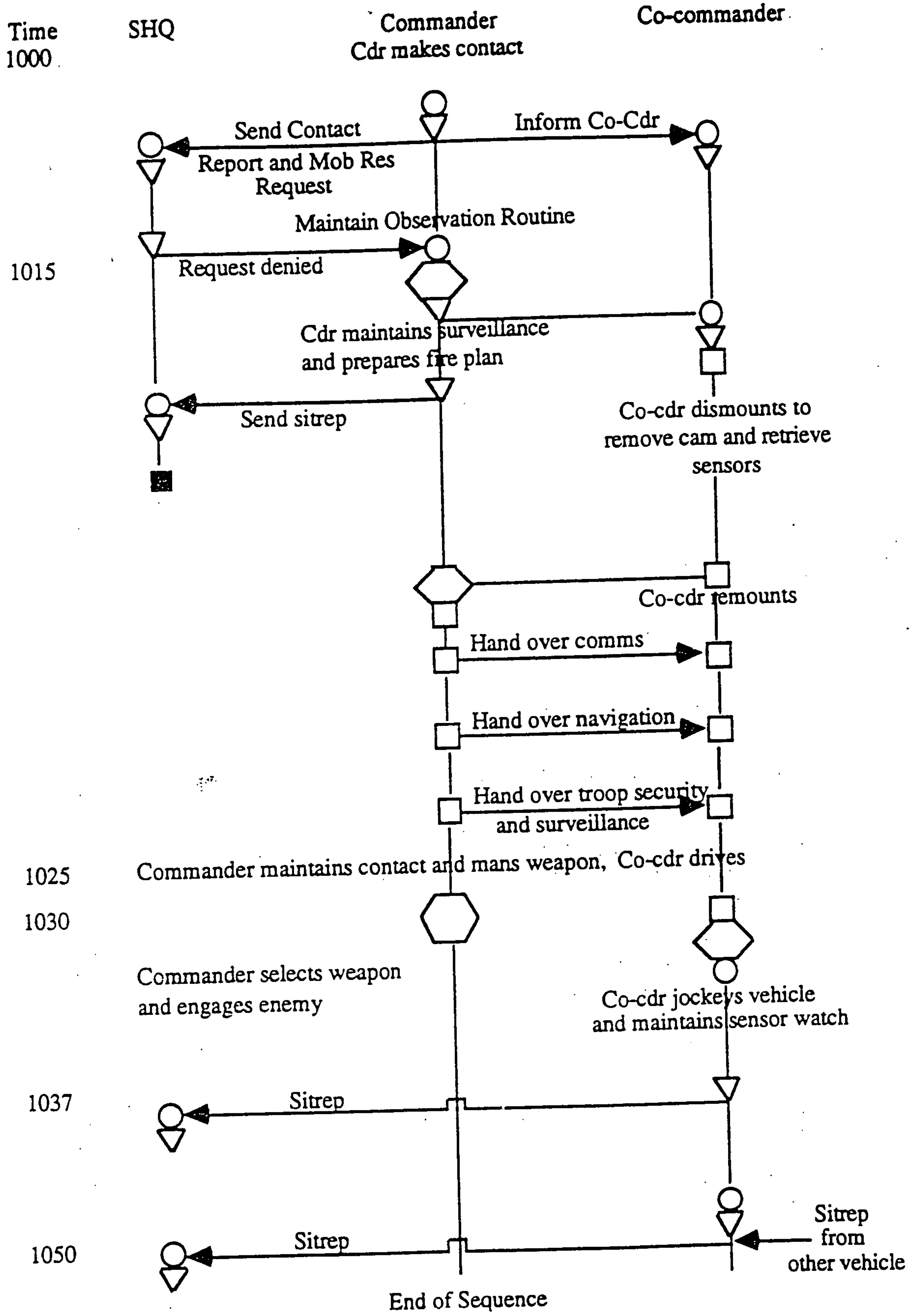

Figure 14.2: Operational sequence diagram for task switching

The output of the FFD served as the data base for the formal task analysis. A review of task analysis methods suggested that the most appropriate technique would be the OSD method as it can represent the flow of information (Beevis, 1992), and show individual activities of teams of workers performing tasks (Laughery & Laughery, 1987). Timeline analysis was rejected because of its imprecision, flow process charts and hierarchical methods were rejected because of their relative complexity, particularly for the representation of multiple and concurrent tasks.

The FFDs represent the performance of single tasks with interactions being shown but not explored, the OSDs were able to visualise these inter-relationships and identify areas of task overload. More significantly they were able to show the extent to which tasks would need to be shared, or switched, to allow 2 men to operate the system. An example is shown in Figure 14.2.

The scenario supporting this OSD is for a static observation made by a single vehicle. Support is denied so the vehicle is required to carry out an engagement sequence unaided. The task synthesis rules (above) have been used as the basis to determine how tasks are shared and switched, the two prime drivers are rules iii to vi which set out primary roles and forbidden task combinations. Reference to Figure 14.3 shows that once the co-commander has prepared the vehicle to move and has remounted there is a staged handover of systems tasks until the commander's sole duty is control of the weapon system. At the end of the engagement sequence there is a staged return of duties.

Although this appears, superficially, to be plausible there are a number of serious faults. At the commencement of the engagement sequence the co-commander may be expected to perform up to 10 tasks or sub-tasks, whilst the commander has a single duty to undertake, but has no direct communication with higher formations. It is hard to imagine that a commander would willingly hand over duties in the manner described, but it is the absence of a function allocation technique that takes account of rank and experience that could lead to this conclusion. Assumptions made from this example could be erroneous and be translated into poor equipment design.

We have re-examined this OSD, and task synthesis rules, in the light of our observations on rank and experience as significant factors in determining function allocation and have arrived at revised conclusions. It is clear that a further task synthesis rule needs to be drawn up, our tentative new working rule at present is.

vii Rank and experience dictate that the commander maintains control of communica-tions to, and from, the vehicle at all times when the vehicle is in motion. When the vehicle is static control may be shared between the crew.

iv Rule iv is rewritten as "The activities of driving cannot be combined with engagement".

The outcome of these rules is that the commander, by retaining the communications task, may maintain control of the vehicle throughout the engagement sequence, with a consequent reduction in the workload on the co-commander. The problem with this iterative approach to function allocation is that a suitable test of validity does not yet exist. Unlike aviation or industrial scenarios where missions are of a finite length, and have clearly defined goals, in military land based systems these conditions are not normally fulfilled. Under such circumstances it is possible that traditional function allocation techniques are inappropriate and that a combination of intimate knowledge of current activities, and the dynamics that control crew performance coupled with an iterative approach are the only valid techniques. It is equally possible that the approach described for land based reconnaissance is only valid for this system.

14.5 CONCLUDING COMMENTS

This paper has described some of the problems that have been encountered in attempting to perform function allocation between human and human rather than human and machine in a ground based system. At a time when the drive appears to be to reduce manning levels it is essential that new techniques for human-human function allocation be derived. A major factor in determining function allocation in a three man reconnaissance crew is rank and experience, and this assumes greater significance when attempting to allocate functions to a two man crew. Whether this would be such a strong determinant if human - human function allocation were being performed on a reduced crew complement for larger systems (e.g. self propelled guns) remains to be determined. From the evidence outlined in this paper it is suggested that the first steps in deriving techniques must be to clearly define the system, identify the high driver functions and the acceptable departures from hierarchical command structures.

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Function analysis and function allocation are described for a new mine-sweeping system based on remote control of "drones". The critical question for system design was whether one operator on board of a mothership could manage four drones at once, using remote control. The results of a human-in-the-loop simulation revealed under what conditions of automation support the performance of the human-machine system is acceptable or not. A general conclusion of the simulation study is that one of the allocation criteria be to make use of the human mental capacity available, even when the system requires only a fraction of this capacity.

CHAPTER 15

FUNCTION ALLOCATION FOR REMOTELY CONTROLLED MINE-SWEEPERS

L.C. Boer

15.1 INTRODUCTION

The current paper presents some highlights of a function allocation study for the Royal Netherlands Navy. Function allocation was performed together with a function analysis in which the functions were defined that were required to fulfil the system's mission. The focus of analysis was the role of the human operator. Those functions that involved a human operator were analyzed in more detail; functions not involving humans were not further analyzed. Function allocation and function analysis were thus coupled interactively, as shown in Figure 15.1.

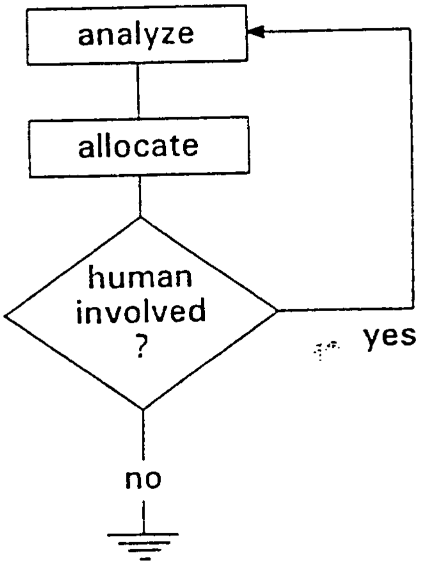

Figure 15.1: The interaction between allocation and analysis of function

The function analysis was hierarchical. At the top level, the complete system was addressed. The system, consisting of four "drone" minesweepers remotely controlled from a mothership, needed two basic functions: mine-sweeping capability and navigation capability. A preliminary consideration of function allocation revealed that the mine-sweeping capability requires no human involvement except for a minor degree of supervision and authorizing start and end of the sweeping action. This function was not analyzed further. Human involvement was foreseen in the function called navigation capability. In a further analysis, a distinction was made between the subfunction *planning*, which provided a plan for how to sweep a designated area, and the subfunction *drone control*, responsible for executing the plan. Both functions require human involvement. The concept of remote control is new for the Royal Netherlands Navy. Thus, the function "drone control" required special attention, as shown in Figure 15.2. Remote control is an attractive design option, because it increases the safety of mine-sweeping and, secondly, promotes manning reduction which is a long-term policy in many NATO countries.

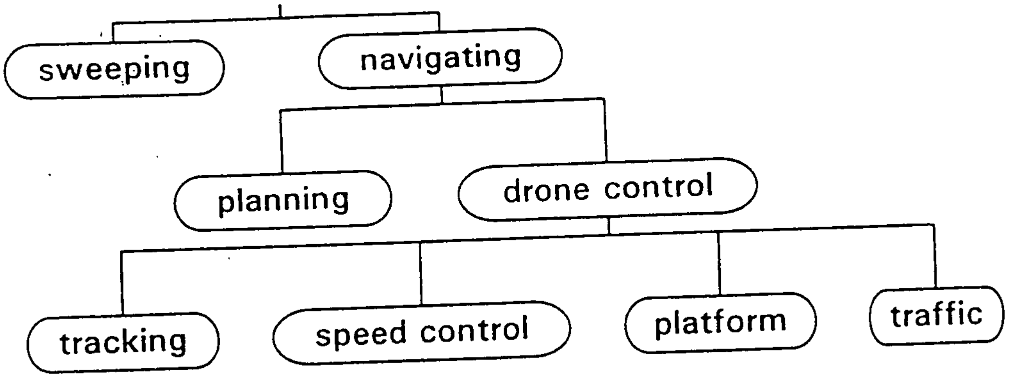

Figure 15.2: Three levels of function analysis. The human operator in the subfunction "drone control" is the focus of the current paper

Tracking is a subfunction concerned with keeping the drones on their designated track. *Speed control* is a subfunction concerned with maintaining the designated speed. *Platform* is concerned with the integrity of the drones and their technical systems. *Traffic* is a concerned with watching out for other vessels and evading if necessary.

Platform and *traffic* take into account particular aspects of the environment. Damage to the drones' platforms is not unlikely considering the possibility of mines exploding in the vicinity of the drones. Other traffic is not unlikely because the system will be designed both for wartime and peace-time operation. In peace time, other traffic cannot be denied access to the to-be-swept area. Operator involvement was deemed necessary because platform and traffic require flexibility and improvisation--things where humans still surpass machines.

A simulation of the drone-control function was set up in order to see whether one operator could control four drones at once, managing the four subfunctions outlined above. In other words, the operator was involved not only in extraordinary situations (platform damage or dangerous traffic), but in continuous tracking as well. One reason to consider a more extensive allocation to the human operator is financial cost. Instead of automating as much as possible, the approach advocated here is to allocate more functions to the human operator if the operator's mental capacity allows for additional activities. This saves automation costs. Moreover, a more satisfying job is created, promoting "human well-being" (Drury, 1994; see also Fitts, 1962). Careful allocation of function can save thus not only money but operator frustration and boredom as well, making the job more challenging.

Two types of simulation can be used for the assessment of system performance and operator workload: fast-time simulation and human-in-the-loop simulation. In fast-time simulation, a computer model of the human operator is part of the simulation. Typical parameters include the time to complete an action, the probability of success, and the mental load on the operator. By running a fast-time simulation many times, indications of average performance of human-machine systems are produced. Fast-time simulations are promising tools, but somewhat risky to use at the current state of knowledge about human factors. The problem is that the human factors discipline has no complete model for operator performance--nevertheless, fast-time simulation requires such a model. In consequence, unsound and questionable assumptions may abound in fast-time simulation. There are also reasonable assumptions, for example, for simple tasks when "time to completion" conveys all the information required, or for tasks that are known into tiny detail such as cockpit tasks, where the time to operate every individual switch is known, as is the probability of error and the mental load factor. The assumptions are weak and debatable when applied to complex tasks and multitask situations. The consequence is pseudo-accuracy. The simulation model produces accurate time-lines of mental workload, but their validity is questionable.

Human-in-the-loop simulation uses a computer model of the system together with a real human operator. The flight simulator is the classical example: a real pilot operating a simulated airplane. Human-in-the-loop simulation requires a "real" interface between human and machine; the development of an interface was part of the project. Fast-time simulations do not require human-machine interfaces.

The advantage of human-in-the-loop simulation is the presence of real humans with real mental capacity which frees us from debatable assumptions.

For these reasons, the present study used a human-in-the-loop simulation. In the simulation, both system performance and operator workload were measured. Performance criteria for operational acceptability were formulated in advance. Attempts towards fast-time simulation based on GOMS principles (Card, Moran & Newell, 1986) are under way, but it is not yet clear whether this is a viable alternative.

15.2 SIMULATION

Apparatus. There were two displays, one for tracking, the other for the remaining tasks. There was a special control panel for tracking and a mouse and the computer keyboard for the other tasks. Figure 15.3 shows the setup.

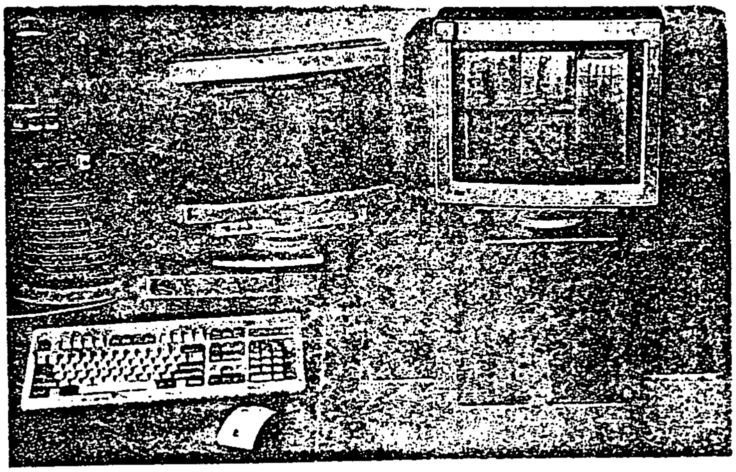

Figure 15.3: The simulation setup. Displays are for platform and watching (left) and tracking (right; see Figure 15.4 for more detail)

Subjects. Eleven young adults participated as paid subjects. On Day 1, they were trained on the tasks; on Day 2, they did the tasks for data collection.

Tasks. The tasks allocated to the subject were (a) tracking, (b) platform, and (c) watching. Speed control was automated--the drones sailed at a constant speed. The tracking task was presented with various degrees of automation support. Control by rudder was the lowest level of automation support; control by a course autopilot the medium level; and course-autopilot control plus presence of a path predictor a level just below full automation. A high quality "radar view" on the first display showed the position of the designated track relative to the individual drone. Figure 15.4 gives an impression of this human-machine interface. For the highest automation level, a line protruding from the drone showed the path prediction for the coming 20 s. The dependent variable was the deviation between the actual path and the designated track.

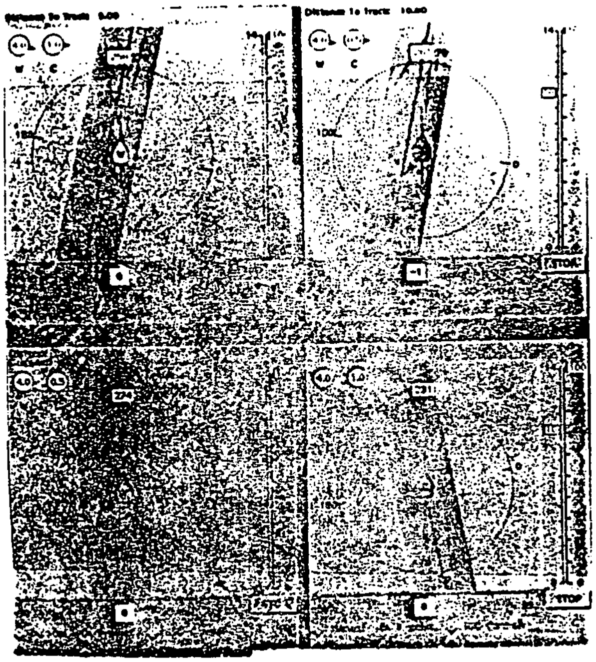

Figure 15.4: The radar view for the tracking task

The sweeping plan contained a number of straight tracks. The scenario specified wind (constant) and current (different for different parts of the area). Both wind and current were at, or close to, the limits considered just acceptable by the Royal Netherlands Navy.

The platform and the watching task uses the second display. They were represented with some abstraction because the details of these tasks were not known at the time of the experiment. The platform task was to react to "alarms" presented every 4 minutes. An acoustic alarm annunciated the alarm. At the same moment, one out of three windows in the upper part of the display was illuminated. The subject had to extinguish the window by clicking. Then, one of the other windows was illuminated, and had to be clicked upon; then another window got illuminated, and had to be clicked upon. After these three actions, a two-number addition was presented. The subject had to enter the solution by using the keypad of the computer. The dependent variables were the number of correct solutions and the time between the alarm and the ENTER command.

The watching task was to monitor arrows appearing every 20 seconds in the lower half of the second display. Subjects had to react by pressing the space bar if an arrow pointed anywhere between East and South. The dependent variable was the number of missed target arrows.

The instruction was to sail the drones over their designated track, to react to platform alarms, and to watch out for target arrows. There were six conditions defined by the three levels of tracking automation and the number of drones under control (2 or 4). The platform and the watching task were the same across the six conditions. Each condition lasted 30 minutes. The order in which the conditions were presented was randomized across subjects.

Mental workload was measured subjectively. Immediately after a condition, the subjects were asked to report their mental effort as a number between 1 (no workload) and 5 (very high workload). These univariate ratings are at least as sensitive as multivariate ratings (Hendy, Hamilton & Landry, 1993). Moreover, univariate ratings are easier to collect and to process.

15.3 RESULTS

Tracking. Figure 15.5 shows the interval around the designated track within which the drones sailed 95% of the time. The figure also shows the standards of operational acceptability. The level of automation is set out along the abscissa. At the extremes, the results are very clear: Tracking performance was unacceptable for the lowest level of automation, rudder control; tracking performance was acceptable for the highest level of automation, course-autopilot control aided by path prediction. These conclusions held irrespective of whether the subject controlled two or four drones (although tracking performance was better when controlling two drones). At the middle level of automation, control by a course autopilot, performance was acceptable depending on the standard applied and the number of drones under control.

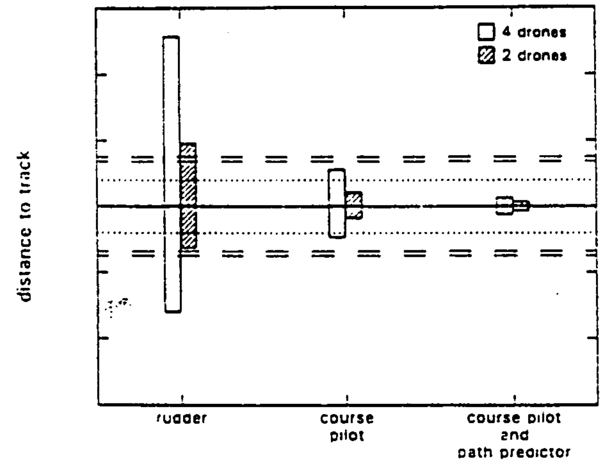

Figure 15.5: Tracking performance as a function of the automation level with number of drones as the parameter. (The dashed lines show the boundaries of operational acceptability.)

Platform and watching. Figure 15.6 shows the performance on the platform and watching task as a function of tracking condition. In either task, performance reflected the difficulty of the tracking task; that is, performance both on the platform and watching task became better when more tracking automation was provided or when the number of drones was reduced from 4 to 2. For either task, performance was acceptable except for the most difficult tracking condition (controlling 4 drones by rudder). For all other conditions, the reaction times to platform alarms and the number of missed target arrows were acceptable. Strict standards were, however, available for the watching task only.

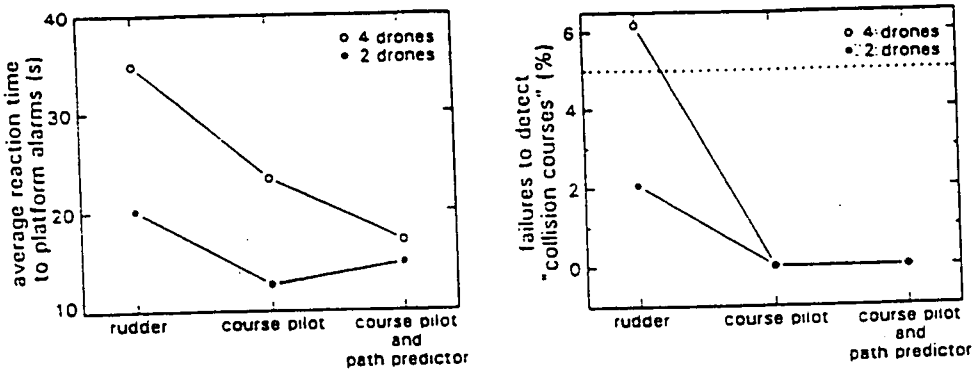

Figure 15.6: Performance on the platform and the watching tasks as a function of the automation of the tracking task with number of drones in the tracking task as the parameter. (The dashed line shows the boundaries of operational acceptability for the watching task.)

Mental workload. Figure 15.7 shows the average level of mental workload reported by the subjects. Mental workload decreased if the level of automation was increased or if the number of drones went down from 4 to 2. Mental workload was close to the maximum for the most difficult condition; mental workload never exceeded the level "slightly above medium" for the other conditions.

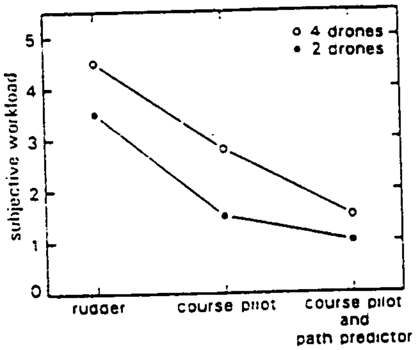

Figure 15.7: Mental workload for the various conditions of the drone-control task

15.4 DISCUSSION

The conclusion of the study is that one operator can do more to the system than just providing intervention in extraordinary situations such as platform damage or collision avoidance. The operators were able to monitor the drones' platforms adequately and to watch out for other traffic; moreover, the operators had sufficient spare capacity to control four drones at once using a course autopilot. The fact that their tracking performance was not always acceptable is probably irrelevant considering that real operators will have more experience and, hence, will meet all operational criteria. The operators expressed the combined level of mental workload when doing these tasks simultaneously as "slightly above medium". When a path predictor was available, tracking performance was excellent, and the operators estimated their workload as low, perhaps too low.

Operator capacity comes in units, not in fractions. At initial allocation, the system may need the fraction, but still gets the unit. The position advocated in the present paper is to use the available operator capacity in the best possible way. It would be unwise to load human operators to the limits of their mental capacity, because this deprives the system of safety margins. It would, however, be equally unwise to *under*use the human operators. Mental capacity is a valuable system resource. Using this resource a little more does not increase the manning level, can save costly automation, and can provide the operator a more satisfying job.

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Au cours de la conception d'un système moderne se pose le problème crucial de savoir qui (tel ou tel membre d'équipage ou tel ou tel automatisme) fait quoi (fonction à remplir). La décision d'attribution des fonctions peut reposer aujourd'hui sur une démarche scientifique. Le Centre Facteurs Humains essaie actuellement de mettre en place une démarche normalisée. Celle-ci repose sur une analyse du besoin puis une analyse fonctionnelle indépendante (dans la mesure du possible) des solutions techniques potentielles. Elle est complétée par une analyse du travail des équipages sur des systèmes actuels proches du système futur. A partir de là il es possible de modéliser informatiquement le déroulement de scénarios types où les activités élémentaires à mettre en jeu dans le système sont représentées. Différents regroupements de ces activités sont effectués pour les faire jouer par un opérateur (humain ou automatique) afin de trouver une solution optimale de répartition des fonctions à remplir. Ce shéma théorique simple est en fait plus complexe à mettre en oeuvre car les activtés humaines à mettre en jeu pour remplir une tâche donnée dépendante fortement de l'interface choisie et donc d'une solution technique pariculière. C'est pourquoi il devient nécessaire de poursuivre la démarche d'optimisation du système pendant la phase de développement du produit. Ceci peut se faire par une validation sur des maquettes fonctionnelles informatisées. Les méthodes utilisées sont: l'analyse des tâches sur les systèmes proches du système futur (ef Hélico), l'analyse du besoin, l'analyse fonctionnelle en cours de développement (ef VAB Reco, SIR) prenant en compte des solutions techniques imposées, la modélisation informatique de scénario (Char, VAB Reco, Hélico) , la modélisation informatique de poste de travail (SIR, Tireur), l'avenir maquettage dynamique informatisé. Pilotage des mannequins des opérateurs par logiciels type MAcrosaint.

CHAPTER 16

ATTRIBUTION DES FONCTIONS DANS LES SYSTEMES TERRESTRES

J.P. Papin and J.Y. Ruisseau

16.1 INTRODUCTION

La conception des systèmes d'armes modernes pose le problème de la répartition des rôles entre l'Homme et le système: qui (opérateur, automate, équipage) fait quoi (fonction à remplir, par exemple). De nos jours, la décision d'attribution des diverses fonctions au sein d'un système peut reposer sur une démarche à caractère sciéntifique. Cette dernière doit cependant être intégrée à la démarche générale de conception, dans un esprit systémique, et donc proposer des solutions, tant sur le plan architectural que celui de l'allocation des fonctions.

Le Centre Facteurs Humains oeuvre actuellement dans ce sens, pour la mise en place d'une démarche normalisée, reposant sur une analyse du besoin, impliquant une analyse fonctionnelle indépendante de solutions techniques probables ou potentielles. Une analyse des tâches sur un système proche du système futur permet d'envisager certaines possibilités pour ce futur système. Ces possibilités peuvent être appréhendées en termes d'activités élémentaires, représentatives de l'activité future probable, et modélisées sous forme de divers scénarios types, répondant au besoin opérationnel.

Des outils informatiques divers permettent actuellement de répondre, au moins en partie, aux problèmes ainsi soulevés, et de proposer ainsi des solutions aux concepteurs répondant au mieux aux contraintes globales, issues tant des aspects opérationnels, que des aspects techniques.

16.2 ANALYSE DU BESOIN

Le premier point à aborder lors de la conception d'un nouveau système concerne l'analyse du besoin. Si elle se réfère, pour l'ergonome, à une pratique connue, puisque l'analyse de la demande est un principe fondamental de l'intervention ergonomique, et la détermine en tant que telle, l'analyse du besoin est parfois moins bien mise en évidence dans le monde des ingénieurs et des opérationnels. Il est du domaine du spécialiste en Facteurs Humains de bien faire percevoir l'importance de cette démarche dans le cas de l'Homme. En effet, l'Homme est à ce jour, et restera encore certainement longtemps, un élément, voire l'élément déterminant majeur, de la mise en oeuvre des systèmes d'armes.

Un exemple de cette démarche peut être identifié dans le cadre du programme VBM (Véhicule Blindé Modulaire), dont la finalité est de procurer à l'armée de terre une famille de véhicules propres à répondre à un ensemble de besoins opérationnels: transport de troupes d'infanterie, poste de commandement, porteur de système d'armes, véhicule d'appui direct, etc...

Dans le cas du VBM, une première analyse du besoin a été basée sur une analyse des contraintes actuelles des véhicules répondant seulement en partie au besoin opérationnel, et sur une analyse des évolutions probables des concepts à moyen terme. De cette analyse, nous avons extrait les axes principaux devant orienter notre réflexion. Ainsi il apparaît que, dans la version VTT, il est difficilement envisageable de séparer les deux fonctions principales du chef de bord: chef d'engin et chef du groupe de combat embarqué. Ceci a une influence marquée sur la conception future du véhicule.

16.3 ANALYSE FONCTIONNELLE

L'analyse du besoin fait apparaître les contraintes principales qui interféreront avec le système et ses performances globales. L'analyse fonctionnelle va permettre de déterminer les fonctions principales que le système doit assurer, comment il doit les assurer, et dans quelles conditions d'environnement elles pourront être assurées. Elle permettra aussi de déterminer, au moins en première approche, quelle pourrait être la répartition des diverses fonctions impliquées entre l'Homme et la Machine. Il s'agit, à ce niveau, de connaître "ce qui doit être fait", et la façon dont "cela doit être fait", pour assurer par la suite une efficacité optimale du système.

Un exemple de cette analyse est matérialisé, là encore, avec le programme VBM. Les missions principales susceptibles d'être confiées à chaque élément de la famille VBM ont été définies, analysées, validées au niveau opérationnel. Chaque fonction nécessaire à l'accomplissement des missions a été identifiée, et les éléments de contrainte propres à chacune de ces fonctions ont été examinés. Ceci a été réalisé pour l'ensemble des besoins exprimés au niveau de la famille de véhicule, ce qui a permis de déterminer avec précision quelles étaient les orientations à prendre pour définir plus précisément le concept. Entre autres, le choix de certaines solutions techniques dérivera directement de cette analyse, que ce soit pour la partie purement système du véhicule (fonctions mobilité, feu, protection) ou la partie qualifiable de plus "humaine" (ergonomie, facteurs humains, etc.). Un exemple de ces choix est celui de la détermination de l'ouvrant arrière du VBM Transport de troupes, pour lequel s'opposaient deux conceptions différentes: l'aspect technique orientait les solutions vers un système de portes à deux battants, alors que l'aspect opérationnel orientait les solutions vers une rampe inclinable. Le bon choix devra privilégier l'aspect opérationnel. A ce jour, sans présager de la solution qui sera définitivement adoptée sur le véhicule, il est clair que l'analyse qui a été effectuée, étayée par des expérimentations sur des maquettes en bois à l'échelle 1 des différents concepts, permet de proposer des orientations précises au concepteur, sur la base d'arguments à la fois techniques et opérationnels.

16.4 ANALYSE DES TACHES SUR UN SYSTEME PROCHE

Un pas plus en avant va concerner l'analyse des tâches, dans le but de déterminer l'activité future probable du ou des opérateurs du système développé. Cette analyse peut être réalisée dans l'absolu, en prenant en compte les résultats directs de l'analyse du besoin et de l'analyse fonctionnelle, mais elle peut aussi être bâtie de manière relative, en prenant appui sur l'analyse de systèmes existants proposant partiellement ou non une réponse au problème posé. En particulier, la connaissance des systèmes équivalents peut être d'une grande utilité dans cette démarche.

Un exemple de cette démarche est issu du programme "Véhicule de Reconnaissance NBC" (VAB Reco NBC), dont la réalisation est effective à ce jour (matériels en cours d'industrialisation). Dans ce cas particulier, l'analyse des tâches a été réalisée au moyen d'un support matériel figurant une partie simplement du futur système, regroupant les composants principaux. Cette analyse a concerné chaque membre d'équipage (quatre, au total), et a permis de mieux organiser l'activité des opérateurs au sein du système. En particulier, certaines contraintes sont apparues dimensionnantes pour le système technique et ont motivé des évolutions profondes dans l'attribution de certaines fonctions à tel ou tel opérateur. Parmi ces éléments dimensionnants, on peut citer la nécessité pour le chef d'engin de disposer d'un écran de contrôle des processus en cours (non identifié lors de l'analyse de besoin et l'analyse fonctionnelle). Ceci a engendré des répercussions importantes sur la conception du système globalement, ainsi que sur la conception du poste de chef d'engin.

Cette même démarche est en cours d'application dans un autre contexte, afin de déterminer les contraintes propres aux systèmes étudiés en matière de sélection (char Leclerc et hélicoptère de combat TIGRE). La réflexion actuellement en cours concernant la sélection et la formation des pilotes des futurs aéronefs TIGRE, par exemple, nous conduit à envisager de manière globale le problème du transfert de compétence. Faut-il convertir des pilotes existants sur le nouveau système, ou former des pilotes "novices" sur le nouveau système? L'analyse des tâches de chacun des deux systèmes (la Gazelle, système ancien, et bien connu, et le TIGRE, système futur, encore à l'état de prototype) a fait ressortir un certain nombre de différences entre les deux systèmes, principalement en raison des différences technologiques présentes entre eux. Il s'avère que la séparation des rôles, pour ne pas dire des fonctions, entre le chef et le pilote, risque d'être beaucoup plus marquée sur le nouveau système que sur l'ancien. Cette spécialisation demandera peut-être des aptitudes différentes à chaque membre d'équipage en fonction de la mission globale à accomplir.

16.5 ANALYSE FONCTIONNELLE RETROGRADE

Ce concept, que nous venons de développer récemment, est un mélange d'analyse du travail et d'analyse fonctionnelle. Cette démarche présente un intérêt lorsqu'il s'agit, par exemple, d'automatiser ou de mécaniser partiellement une tâche effectuée de manière satisfaisante avec des outils manuels mais présentant des risques de santé majeurs.

L'exemple présenté concerne les opérations de dépollution effectuées par les sapeurs du génie. En premier lieu a été effectuée une analyse fine du travail, puis les actions mises en évidence ont été traduites en fonctions "solution". Nous avons recherché ensuite à quelle fonction de niveau supérieure la fonction "solution" appartenait. Ensuite nous avons construit l'arbre des fonctions en remontant le plus possible pour aboutir à une fonction principale. Cette dernière a été ensuite déclinée en fonctions "solution" possibles. A titre d'exemple nous avons trouvé une fonction "solution" balayage à l'aide d'un pinceau, et une autre, palpation du terrain à l'aide d'une pique. Ces deux fonctions ont pour but de détecter, voire de reconnaître une mine dans la terre. La question s'est posée de savoir s'il n'était pas possible d'effectuer cette détection et cette reconnaissance en une seule opération à l'aide d'un outil manipulé à distance. Les travaux en cours nous conduisent à développer un palpeur mécanique à base d'aiguilles et opérable à distance. Il sera possible ainsi de recueillir en une seule action une forme et éventuellement une nature physique d'objet.

Cet exemple montre comment on peut transférer une partie de la construction mentale qu'effectuait le démineur par plusieurs palpations du terrain, voire en mettant à jour l'objet, par la présentation à l'opérateur d'une image donnant directement la forme de l'objet.

16.6 MODELISATION DE SCENARIO

L'analyse des tâches nous permet d'obtenir une vision globale de l'activité des opérateurs au sein d'un système particulier. Il est alors envisageable, lorsqu'on est en mesure de caractériser de manière précise chacune des tâches et les enchaînements entre tâches, d'effectuer au moyen d'outils de simulation appropriés, une modélisation du fonctionnement global du système. Cette modélisation est accessible avec des outils tels que MicroSAINT, que nous utilisons depuis plusieurs années dans ce type de démarche.

Les résultats obtenus nous permettent de valider des choix initiaux d'allocation de fonctions et de répartition de tâches entre l'Homme ou à la Machine, d'ordonnancement des tâches, mais aussi de connaître l'influence des variations des paramètres de certaines tâches (en termes de durée, de type d'enchaînement, de niveau de tâche, etc...) sur la performance globale attendue du système.

Dans le cas du VAB Reco NBC, cette modélisation a permis de valider l'objectif de durée d'une mission unitaire du véhicule, dont les caractéristiques initiales étaient estimées (mais non entièrement étayées sur des données techniques ou opérationnelles connues), et de montrer que des modifications devraient être apportées. En effet, dans les premières simulations effectuées, le taux d'occupation de certains opérateurs était proche de 100%, alors que d'autres avaient un taux d'occupation très limité. Une meilleure répartition des fonctions a permis de diminuer cette différence.

16.7 MODELISATION DES POSTES DE TRAVAIL

Un autre aspect de la modélisation des contraintes liées à l'environnement concerne les aspects géométriques et dimensionnels des postes de travail. Dans cette démarche, plusieurs points peuvent être abordés. Le principal concerne la modélisation géométrique de l'opérateur humain, en tant qu'élément à part entière de la situation de travail dans laquelle il évolue. Cette modélisation permet de déterminer les contraintes anthropométriques, et dimensionnelles, liées à l'homme en fonction de la population spécifique à laquelle il appartient. On peut ainsi extraire des contraires posturales, des contraintes d'atteinte, des contraintes de vision, liées soit à l'anthropométrie des sujets, soit au dimensionnement des postes de travail eux-mêmes. Nous utilisons, dans ce domaine, un logiciel de modélisation humaine (Safework ™) qui autorise la création de mannequins paramétrables à volonté, ainsi que la création (ou l'importation depuis un logiciel de conception assistée par ordinateur) de scènes de travail. Les mannequins ainsi créés peuvent être mis en posture dans leur environnement, de manière simple et intuitive, et il est alors aisé de vérifier ou valider, suivant le cas, la cohérence des solutions techniques proposées. Cette démarche a été appliquée pour différents programmes, tels que le VAB SIR, par exemple, pour lequel une analyse détaillée de l'environnement de travail des opérateurs est en cours. Nous avons montré à cette occasion, les contraintes posturales attachées à la conception du poste de chef d'engin et du poste de l'opérateur radio. Cette analyse permet de préfigurer les concepts qui influent sur l'activité globale des opérateurs, et en fin de compte, sur l'efficacité du système dans son ensemble. Le concepteur, à la suite de cette analyse, a repris certains éléments de conception et recherche actuellement des solutions plus optimisées.

16.8 MAQUETTAGE DYNAMIQUE INFORMATISE

Plus avant encore dans la définition des concepts et dans le processus d'optimisation d'allocation des fonctions au sein d'un système d'armes, la réalité virtuelle nous permet aujourd'hui de simuler "en vraie grandeur" et à moindre coût, des situations complexes dans lesquelles l'opérateur est un élément indissociable des boucles de contrôle. Il est possible de définir un environnement virtuel suffisamment détaillé pour donner un certain réalisme à la simulation ainsi générée, et permettre à l'opérateur d'évoluer dans une configuration proche de ce que sera le futur système. Toutefois, il faut se garder des interprétations hâtives des résultats de telles expérimentations, dans la mesure où l'aspect validation de la situation simulée par rapport à la réalité n'est pas toujours facilement accessible. Il faut aussi tenir compte des problèmes de transfert d'apprentissage dans l'exécution des tâches dans deux mondes différents, le monde virtuel, d'une part, et le monde réel d'autre part.

16.9 PILOTAGE DES MANNEQUINS PAR LOGICIEL (TYPE MICROSAINT)

Enfin, d'autres opérateurs pourraient être incorporés dans les simulations telles que décrites ci-dessus, en envisageant le pilotage de mannequins par des outils de type génération de scénarios. C'est une voie que nous explorons actuellement, avec pour objectif principal, de pouvoir piloter un mannequin de type Safework™, par exemple, avec des données de type comportemental issues de MicroSAINT, par exemple, ou d'autres produits. On peut penser, principalement, à des données sur les mouvements humains, sur les efforts qu'un opérateur peut exercer, sur les contraintes mécaniques liées aux opérateurs dans l'exécution de leurs tâches (en termes de stabilité posturale). Nous accéderions alors à la phase ultime de la simulation, permettant la validation des processus conduisant à l'allocation des fonctions au sein du système en cours d'élaboration, à savoir le jeu, en temps réel, de l'ensemble des situations et comportements permettant d'apprécier le fonctionnement du système, et d'extraire les points forts et les points faibles des solutions de conception retenues. Cela semble encore futuriste à ce jour, mais augure déjà des possibilités offertes par la technique à très court terme.

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Le probème de l'allocation de fonction dans un système complexe et fortement informatisé est au cœur de la réussite du couple homme-machine. C'est un travail à haut risque d'erreurs techniques et financières. En fait il est impossible d'expliciter par des seuls écrits la totalité des contextes d'emploi d'un système. Aussi, dès les phases amont, une méthode associant de manière équilibrée analyse fonctionnelle, retour d'expérience exhaustif, maquettage dynamique représentatif du fonctionnement réel du matériel futur est conseillé. Cette approche doit permettre d'essayer et valider l'allocation de fonction prévue afin d'écrire des spécifications en partie validées par le futur utilisateur.

CHAPTER 17

ALLOCATION DE FONCTIONS ET ERGONOMIE DE GUTENBERG A MCLUHAN

A. Bry

17.1 POSITION DU PROBLEME

Pour effectuer une tâche à un ou plusieurs hommes avec une ou plusieurs machines, le concepteur d'un système opérant est amené à définir en liaison plus ou moins avec l'utilisateur une véritable organisation du travail qui n'a de chance d'être efficiente que si un grand nombre de considérations sont prises en compte (formation des opérateurs, culture de l'institution, connaissance approfondie des contraintes du milieu). Ce qui est en jeu est bien un problème de représentation.

Il s'agit en effet de faire converger un certain nombre de représentations floues et différentes vers une représentation de compromis qui soit acceptable par tous:

- par l'utilisateur: un système répondant globalement à son besoin,
- par le concepteur: un système réalisable techniquement en respectant coûts et délais.

Le problème de la coincidence des représentations doit prendre en compte les multiples sources de malentendu qui pourraient exister entre des partenaires de bonne foi. L'écrit et l'oral ont un rôle irremplaçable dans la phase de conceptualisation du besoin mais appraissent insuffisants pour sa réalisation pratique car ils peuvent faire omettre un grand nombre de sous-fonctions et surtout ils permettent une trop grande liberté de représentation (même la puissance évocatrice d'un Shakespeare paraît peu pertinente pour la construction d'une maison...).

Aussi apparaît-il capital d'utiliser d'autres moyens de représentation moins discutables et faisant moins appel à l'imagination pour figurer réellement ce qui sera le futur produit. C'est à cette réflexion somme toute banale que l'on doit le souci déjà ancien de faire des maquettes avant de passer à une réalisation finale lorsque l'enjeu en terme de prix et d'efficacité opérationnelle imposent de limiter les erreurs de conception. Les progrès de l'informatique ont donné de nouveaux soucis à l'homme mais lui ont procuré aussi des moyens devenus bon marché de se représenter un produit futur dans ses fonctions ultimes avec un grand réalisme. Et ce bien avant que la première pierre de l'édifice ait été réellement posée. Globalement cela revient à faire des dessins animés que le système conçu soit en un local opérationnel ou un logiciel même très complexe. Les adultes que nous somme n'en ont pas fini avec ces moyens que l'on croyait réservés à l'enfance, nos histoires sérieuses doivent aussi comporter beaucoup de dessins pour qu'on les comprenne mieux.

17.2 PLACE DES OUTILS DE MAQUETTAGE INFORMATIQUES DANS UNE DEMARCHE D'ALLOCATION DE FONCTIONS

Toute personne exerçant une activité s'approprie, pour peu qu'il s'investisse un peu dans sa tâche, des méthodes de travail qui s'améliorent au cours du temps du fait de l'enrichissement de l'expérience. Cette amélioration est cependant très limitée et consiste plus en une adaptation à d'outils mal adaptés qu'un véritable progrès. Une chose est claire, ce travail sert à remplir un certain nombre de fonctions et sous-fonctions qu'il est possible d'expliciter. La manière dont celles-ci sont réalisées peut également être appréciée sur des critères d'efficacité.

On voit ici apparaître deux prémisses fondamentaux à la réalisation d'un système nouveau. D'une part on doit conceptualiser l'ensemble des fonctions qu'il doit remplir d'autre part on doit avoir une connaissance aigue de la manière dont celles-ci sont effectuées aujourd'hui. Les deux prémisses confrontées aux technologies nouvelles en développement doivent permettre de proposer des modèles nouveaux qu'il faut valider avant leur réalisation: cette validation est capitale car l'opérationnel ne changera pas ses méthodes de travail s'il n'est pas convaincu de la viabilité des alternatives proposées. Enfin le risque technique et financier est tel qu'il faut chercher à le minimiser àtout prix.

Concernant un local opérationnel à haut flux d'informations, une analyse fonctionelle doit permettre de définir précisément la nature des informations et décisions que le système homme-machine doit produire pour accomplir la mission. Le retour d'expérience est utile pour mettre en évidence les insuffisances des systèmes en service du fait du manque d'informations ou d'informations de mauvaise qualité mais aussi et surtout du fait des difficultés d'exploitation liées à la mise en oeuvre d'outils inadaptés ou obsolètes. Parallèlement une veille technologique efficace à propos des performances des senseurs mais aussi des constituants de l'IHM doit mettre à disposition des concepteurs les possibilités d'utilisation d'outils nouveaux qu'il conviendra d'essayer. En fait, dans ces systèmes très informatisés la difficulté n'est pas d'écrire des logiciels mais bien de se faire une idée réelle de besoin afin d'y répondre de manière adéquate.

En général un local opérationnel comprend un certain nombre de postes de travail servis par un certain nombre d'opérateurs accomplissent grossièrement trois types de tâches: tâches de capture de l'information, de synthèse et de décision/action. Le nombre de postes de travail dépend des capacités d'intégration des différents sous-éléments, de la possibilité d'automatisation fiable et de la maîtrise de la conception de la totalité des IHM. Certains sous-systèmes en effet (comme conduite d'armes) sont parfois conçus avec une IHM spécifique inpliquant trop souvent outre des méthodes de travail différentes, la création d'une tâche apparaissant "artificielle". Pour être certain d'obtenir à la fin un ensemble harmonieux, il est capital de viser un haut niveau d'intégration et de standardisation. L'intégration nécessaire permet de diminuer le nombre d'opérateurs en améliorant la performance de la tâche. Une bonne standardisation garantit une unité de représentations et de méthodes de travail permettant une grande fluidité de communication et un travail de group cohérent.

La nécessité d'outils spécifiques en fonction de tâches particulieères doit s'intégrer harmonieusement à la politique de standardisation en s'autorisant des produits particuliers par exemple pour les décideurs. Ces derniers en effet ont un besoin particulier de réflexion et de représentation par plusieurs acteurs . Un haut niveau de convivialité s'avère également nécessaire. Tous ces éléments montrent bien que les situations sont suffisamment complexes, le besoin opérationnel suffisamment original pour devoir être représenté par des moyens réalistes *dans la phase*

Amont. Cette représentation concerne aussi bien les locaux et le hard de IHM, que le SOFT de ces mêmes IHM. Il apparaît ainsi indispensable d'utiliser d'une part la conception assistée par ordinateur ou la représentation virtuelle pour l'aménagement du local lui-même, et d'autre part les générateurs d'interface pour maquetter un interface qui corresponde strictement au besoin de l'utilisateur. Ces documents informatiques forment une expression du besoin auquel les industriels doivent répondre par les mêmes moyens. En commençant aussi "par la fin", l'objectif est d'obtenir un système hautement intégré pour les hommes let les machines dont les produits correspondent réellement à l'attente des utilisateurs. C'est de cette manière qu'à la nécessaire coïncidence entre la représentation de l'utilisateur et celles des concepteurs aura quelque chance d'exister.

CHAPTER 18

DISCUSSION AND CONCLUSIONS

18.1 DISCUSSION

The aim of the workshop was

- to review the need for function allocation
- to review the maturity of available techniques and the need for additional research in the area
- to make recommendations to human factors practitioners.

There was general agreement on the importance of function allocation to the system development process. Some experts were concerned that the term function allocation means different things to different engineering specialties.

Function allocation decisions define the roles, functions and tasks performed by human operators and maintainers. Thus, function allocation is linked to issues of automation and manpower reduction, as well as to questions about human responsibility for the safe and effective operation of a system. It was recognized that function allocation is a design solution which is achieved as part of the creative process in developing a system design. This solution includes expectancies about how the system will perform. The decision about how to balance human factors considerations against political, financial, managerial and performance constraints is complicated by the steadily improving capability of hardware and software. Therefore, expectancies about how the system will perform must be tested, the consequences for the human operator must be evaluated, and the allocation of functions reviewed and revised, if necessary, in a tightly coupled iterative process.

Reviewing the maturity of the techniques, no major development in function allocation was reported at the workshop. Function allocation techniques which were reviewed included: a simple dichotomous choice between human and machine; a two-stage allocation process; iterative modification of function allocations, and; reverse engineering of operator tasks. None of these techniques can deal with all the complexities of system performance.

Most approaches to function allocation described at the workshop focus on the means of evaluating the implications of the allocation decision for system performance and operator workload, in stead of guiding the decision. Methods which are available for evaluating implications of function allocation decisions include fast-time computer simulations of operator tasks and workload, human-in-the-loop simulation, rapid prototyping, and virtual-reality prototyping.

Potentially promising means for improving the function allocation decisions include the use of principles borrowed from computer science for the allocation of functions in software, especially in distributed systems. Other methods might be available from resource allocation principles used in Industrial Engineering and the genetic algorithms being used for problem solving in computer science.

Reviewing what recommendations could be made to practitioners, integrated design teams such as those described in the paper by McDaniel were seen as providing the working climate necessary for the early and effective interchange of data and concepts on the role of the human. Practitioners were advised to select techniques which were understandable by systems engineers and designers. As an adjunct to this, they must use clearly understood, common definitions of missions, functions, tasks and of the goals of function allocation.

The review of potential research topics generated a number of ideas. A high priority was assigned to research leading to the development of a taxonomy of function allocation issues. The goal would be to have available a taxonomy relating the problem domain (type of system, functions, and function allocations), the factors affecting function allocation (political, organizational, technical, financial, etc.), and the techniques which are appropriate to function allocation in that domain. Related to this proposal was that for research to understand the creative aspects of design.

The importance of testing the function allocation decisions was reflected in the priority placed on research into operator workload. This should investigate the validity of current workload prediction techniques, the relationship of workload to system performance, the use of computer simulations of networks of operator tasks and the validity of extrapolating from such predictions to conclusions about system performance.

An equally high priority was given to research related to adaptive allocation of function. Many operational systems involve missions lasting several days, and a single, 'static' allocation of functions was seen to be inappropriate for such systems, as noted in the paper by Edwards and Streets. The function allocation process has to cater to situations when operators may pass responsibility for specific functions from one to the other. The process must also cater to the adaptive allocation of functions between humans and machines. Modelling of the operator to permit function re-allocation based on the machine's model of the operator was seen as an important research topic; decision aiding was another.

Research on the role of the human in systems was also judged important. Several different concepts were proposed during the workshop, ranging from the human being a system component to the system being a means to support human responsibilities. Opinions on decision making ranged from the principle that the human should make all decisions to the principle that there are some decisions which humans should never be permitted to make.

18.2 CONCLUSIONS

No single function allocation technique is available which deals with all the complexity of the issues involved in assigning functions to humans. Therefore, within the iterative design process, function allocation requires its own iterative approach to evaluate and refine the decisions made. Function allocation can be thought of as an independent variable in design, with system performance or operator workload being the dependent variables.

The discussions during the workshop showed clearly that function allocation means different things to different people. More importantly, it means different things to the systems engineers with whom human factors engineers must collaborate.

The workshop papers demonstrated that there is an awareness of human factors engineering issues in systems design and of current HFE techniques which meet the requirements of regulatory documents such as US DoD Directive 5000.2. Judging by the papers, however, there is little research activity devoted to human behaviour in systems operation, or to improving HFE techniques. Panel 8 should sponsor such research.

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