Best Practice Guide
Human factors in High-demand situations
for the Process industries

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1 Introduction

Within the EU-funded project PRISM, the focus group on human factors in high-demand situations has drafted a Best Practice Guide on the identification and management of high-demand situations in process control, with the basic question: what measures can be taken to manage or prevent these situations? The guide provides both an introduction to practical theory and demonstrations of solutions, improvements and best practices from related domains, covering the following topics:

- Analysis of cognitive task load
- Work allocation and scheduling
- Cognitive support
- Design support
- Alarm handling
- Training

The guide will be of interest to people from both the process industries concerned with high-demand situations and people working on human factors research in this area.

Approach

During the project it appeared that there is an enormous variety in both the approaches to and in the aspects of human factors related to high demand situations. In order to structure all these issues a framework was developed to show their interrelationships. This framework was used as a base for the two seminars that were organised within this focus group and will be described in this guide. During these seminars relevant issues related to high-demand situations were identified. These issues will be discussed in this guide. However, this guide will follow an approach of practical guidance instead of ‘academic press’. It is meant to guide the reader through the issues by showing practical examples, rather than prescribing rules about what to do or not.

2 Background

Inadequate management of high demand situations can lead to major accidents. Chernobyl (1986) and Texaco, Milford Haven (1994), see below, are dreadful examples of what the consequences can be. In some cases the accidents can be ascribed to technical failures, like unsound material. However, more often critical situations require different organisation, resources, skills and tools. These requirements are not always met, resulting in sub-optimal task performance.

Chernobyl (1986)

The explosion and fire of the Chernobyl Nuclear reactor in 1986 was possibly the world’s worst man made disaster. Whilst subsequent studies have shown deficiencies in the design of the reactors, it is clear that management and operational failings made the major contribution to the disaster. The incident started during a planned shut-down of the unit. In order to carry-out a number of tests it was decided to run the reactor at very low power levels for short period of time. This required the over-riding of a number of trips since operation in this region was known to be unstable. However the operating team felt confident to operate in this region. Unfortunately
unstable operation developed beyond the control of the operators and the one of the units exploded causing damage to other units.

Current reactor designs prevent operators from over-riding the most critical trips.

Milford Haven (1994)
Another example is the explosion at the Texaco Refinery in Millford Haven in July 1994. The series of events that lead to this explosion can be traced to a severe electrical storm prior to 09:00, which caused plant disturbances and affected a number of production units. During the following 4 to 5 hours a fire on one of the units was dealt with, parts of the refinery were shut down and attempts were made to bring all units back on-line. Eventually a combination of failures resulted in a knock-out drum on a flare line being overfilled and the failure of the flare line with the release of 20 tonnes of flammable hydrocarbons. This material ignited, causing a major explosion. In its report into the incident (ref1 &2) the HSE identified important human factors issues as well as failures in safety management systems, plant design and construction. The human factors issues included:

- Limitations in the display systems of the Distributed Control System, which made it difficult for the operators to form a clear overview of the state of the whole unit.
- The operators were further hindered by the alarm systems with a total of 2040 alarms, 87% of which were rated as high priority.
- In the 10 minutes prior to the explosion a key alarm, indicating that the knock-out drum was overfilled, was submerged amongst a total of 275 alarms which had to be dealt with by the operators (an average of one alarm every 2 seconds).
- In fact the operating team had been dealing with alarms at a very high rate since the initial lightening strike, 4 hours earlier.

In other work domains, such as defence, public safety, process control and transport, the need to improve the deployment of human knowledge and capacities is also increasing. Whereas safety requirements increase (due to both company and general public policies), fewer personnel may be expected to carry-out the same tasks by concentration of work in one central control room and further automation. For example, fewer personnel will have to manage high-demand situations and supervise complex automated systems in future ships of the Royal Netherlands Navy. Tasks that were allocated to separate people are currently being combined into new, enriched jobs (e.g. adding platform supervision to navigation tasks on a ship’s bridge). In addition to selection and training, adequate (dynamic) task allocation and computer support can help to realise the required human performance level. The current work provides guidance for defining and refining task allocations and designing support functions that extend human knowledge and capacities in high demand situations. The guidance is based on recent research in the field of Human-Computer Interaction (HCI) and the notion that you need both a model of the environment (the domain) and the cognitive processes involved to enhance the design of human-computer work. We can make effective use of theories of cognitive processing if we also have validated theories or descriptions of the world on which cognition operates including the interactions (Green, 1998). When we have an adequate description of the environment in which cognition operates, then a human viewed as a behaving
system might prove to be quite simple. Or as Simon (1981) stated: “The apparent complexity of human behaviour over time is largely a reflection of the complexity of the environment in which a person finds himself”. However, you still need some cognitive theory, as simple as it may be, to distinguish the environmental components that affect human cognitive task performance. Such a theory should not purely focus on task performance at the micro-level with validation restricted to isolated laboratory tasks as common in basic (experimental) psychological research. The validation of the models should incorporate essential interactions with the real-world environment in which the tasks are performed at the level of real-world operational requirements. Such descriptions enable statements on human task performance by accounting adequately for how context and actions are coupled and mutually dependent (cf. Hollnagel, 1998). Unfortunately, there is not one context-independent, comprehensive theory on human cognition that can be applied for a complete and do-able analysis of complex work demands and it will not be present in the near future. For example, detailed specifications of cognitive processes such as the unified theories of Newell (1990) and the multiple-resource model of Wickens (1992) insufficiently address the dynamic task demands on human-problem solving in a naval operational centre. The solution is not to wait till such a theory has been developed, but to develop limited or practical theories that apply to the specific domain or environmental description that is part of it (cf. Green, 1990). Such a theory should include accepted features of cognition such as limited processing capacity, be validated in the context of a specific domain and possibly group of task performers, and provide predictions of the task performance within this domain (cf. the Simple Model of Cognition, Hollnagel, 1998).

As in the domains described above, in the process industries human operators are working in complex, dynamic environments. Describing the environmental together with comprehensive cognitive factors can help to envision the high-demand situations and find possible solutions to prevent uncontrollable situations that get out of hand. Therefore, the lessons learned in these domains can be applied to the domain of process control as well. Besides that, a practical and applicable theory is most relevant for SME’s, since most often they don’t have the resources to do extensive research themselves.

3 Framework

The core of the Best Practice Guide is a practical theory of cognitive task load and computer support for process-control tasks. The theory has been integrated in a cognitive engineering framework consisting of the specification and assessment of computer-supported work (Figure 1). According to this framework, assessments guide the iterative HCI-refinement process (including possible adjustments of operational requirements), and provide empirical data for improving the theory and its quantification in a specific application area (e.g., a “mental load standard” for railway traffic control; Neerinx & Griffioen, 1996).
Figure 1: Addressing human-factors knowledge and environmental constraints in an iterative system development process.

According to the framework of Figure 1, first, we will summarise the theory on cognitive task load, covering a model of cognitive task load and functional requirements as a basis for general cognitive support principles (Chapter 4).

Subsequently, in Chapter 5 we exemplify the application of the theory on the basis of “best practices” from example domains (the “Technological Design Space”, according to Figure 1). We show that the theory and method can be applied, both in an early system development stage for the assessment of task-allocations and on the user-interface level for the application of support principles. Furthermore, available tools & techniques for the application of the framework are listed in Chapter 6.

Finally, after covering some safety culture and organizational issues in the management of high-demand situations in Chapter 7, in Chapter 8 conclusions will be drawn on the “transfer” of the method to guide an iterative process of human task and interface design from the example best practice domains to the process control environment.

4 High-demand situations: Practical Theory

In process control, under normal conditions plant personnel may have the required work organisation, resources, skills and tools to perform their tasks effectively and efficiently. However, unforeseen combinations of critical events can cause a fundamental change of requirements for the organisation, resources, skills and tools. In practice, the requirements for managing such high-demanding situations are not always met leading to sub-optimal task performances, possibly resulting in serious calamities. In our view, work designs and practices should explicitly show their capability to handle high-demand situations. It should be noted
that we define “high-demand” as the mapping of environmental and task requirements on the human capacities that are available to fulfil these requirements.

The current chapter provides a framework to analyse these issues within their context. First, a model for cognitive task load is described that can be used for the design and redesign of cognitive tasks and computer support in complex, real-time, task environments. Subsequently, a model is presented that describes generic functions and information transfer within the process-control domain. Further, we will argue that the integration of both these two models, in combination with a scenario-based context assessment, will help to identify potential high-demand situations. Finally, based on this approach, a framework that distinguishes a small set of user-interface and cognitive-support functions with specific high-level design principles will be presented.

4.1 Cognitive Task Load

Neerincx et al. (2001) distinguish three load factors that have a substantial effect on task performance and mental effort.

The first classical load factor, percentage time occupied, has been used to assess workload in practice for time-line assessments. Such assessments are often based on the notion that people should not be occupied more than 70 to 80 percent of the total time available (Beevis, 1992). To a certain extent operators can deal with time pressure by increasing their effort. However, at a certain point time is too short to perform all the tasks properly and people will have to adjust their work strategies. First, they can focus on a limited data set ignoring part of it (Maule & Mackie, 1990). An inevitable result is that the quality of decisions decreases. A related strategy adjustment is the concentration on negative information (Ben-Zur & Breznitz, 1981; Edland, 1985). More attention is paid to the reduction of threats and risks than on the chance these might occur.

To address the cognitive task demands, the load model incorporates the Skill-Rule-Knowledge framework of Rasmussen (1986) as an indication of the level of information processing.

- At the skill-based level, information is processed automatically resulting in actions that place little if any cognitive demands on the individual.
- At the rule-based level, input information triggers routine solutions (i.e. procedures with rules of the type ‘if <event/state> then <actions>’) resulting into efficient problem solving in terms of required cognitive capacities.
- At the knowledge-based level, based on input information the problem is analysed and particular solution(s) are planned, to deal with new situations. This type of information processing can involve a heavy load on the limited capacity of working memory.

Uncertainty is an important aspect of unfamiliar situations, i.e. when information is incomplete, conflicting, unreliable, unclear or unknown. The operator has to use knowledge and experience to translate the limited information into a sensible diagnosis. The gaps in knowledge can result in biases in the thinking process of the operator. Possible cognitive biases are:

- Confirmation bias (Wason & Johnson-Laird, 1972). The operator will make an assumption of what is going on, based on prior knowledge and experience. Information
that confirms this assumption will be selected, while contrary information will be neglected.

- **Inferences** (Pennington & Hastie, 1993). People tend to create a story of the situation that is as complete, consistent and plausible as possible. When information is incomplete, people will fill in the information in such a way that the story stays in tact.

- **Framing** (Tversky & Kahneman, 1981). Decisions are influenced by the way the problem is presented. When the same problem is presented in different ways, other decisions will be made.

To address the demands of attention shifts, the model distinguishes *task-set switching* as a third load factor in the performance of process-control tasks. Complex task situations frequently consist of several different tasks, with different goals. These tasks call on different sources of human knowledge and capacities and refer to different objects in the environment. We use the term task set to denote the human resources and environmental objects with the momentary states, which are involved in the task performance. An example of a task set would be managing the propulsion of a ship, or the weapon and sensor systems of a frigate. Switching entails a change of applicable task knowledge on the operating and environment level.

The combination of the three load factors determines the cognitive task load: the load is high when the percentage time occupied, the level of information processing (i.e. the percentage knowledge-based actions) and the number of task-set switches are high. Figure 2 presents a 3-dimensional “load” space in which human activities can be projected with regions indicating the cognitive demands that the activity imposes on the operator.

![Figure 2: Schematic representation of the task load model](image)

The green spot (middle) represents the area in which task load matches the operator’s mental capacity in a certain task setting. In the red (top) area task load is too high. The orange (bottom) area represents the area in which performance is sub-optimal due to underload. The load factors represent task demands that affect human operator performance and effort (i.e. it is *not* a definition of the operator cognitive state). In practice, operator activities will not cover all possible regions in the cube of Figure 2. A higher level of information processing may cause the time occupied to increase. Also a larger amount of task-set switches may cause the time occupied to increase because the costs of these switches are so severe that the operator needs more time to
execute the task. The cognitive task load analysis aims at a cube that is “empty” for the critical regions such as distinguished below. For remaining critical situations, it aims at empowering the operators so that they can meet the specific demands.

It should be noted that the effects of cognitive task load depend on the concerning task duration (see Table 1). In general, the negative effects of under- and overload increase in time. Under-load will only appear after a certain work period, whereas (momentary) overload can appear at every moment. When task load remains high for a longer period, carry-over effects can appear reducing the available resources or capacities for the required human information processing (Rouse, 1988).

Table 1: Overview of four negative effects of cognitive task demands for a certain task period.

<table>
<thead>
<tr>
<th>Task Performance Period</th>
<th>Short (&lt;5min)</th>
<th>Medium (5-20min)</th>
<th>Long (&gt;20min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time occupied Low</td>
<td>no problem</td>
<td></td>
<td>Under-load</td>
</tr>
<tr>
<td>Info processing Low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task switches Low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(E.g. monitoring traffic cameras during night)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time occupied High</td>
<td>no problem</td>
<td></td>
<td>Vigilance</td>
</tr>
<tr>
<td>Info processing Low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task switches Low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(E.g. monitoring traffic cameras during rush hour)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time occupied High</td>
<td></td>
<td>Cognitive lock-up</td>
<td></td>
</tr>
<tr>
<td>Info processing All</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task switches High</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(E.g. solving more problems at once, while continuing normal task)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time occupied High</td>
<td></td>
<td></td>
<td>Overload</td>
</tr>
<tr>
<td>Info processing High</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task switches High</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(E.g. solving complex problems while continuing normal task)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In situations of “combined” high load, the following bottlenecks can appear (see also Figure 3):

- People are inclined to use a heuristics strategy in problem solving under high load. ‘Rules of thumb’ are used to decide what decision to make, instead of comparing all possible alternatives. This strategy saves a lot of time, and is also used when there is no time constraint. However, it doesn’t guarantee that the best alternative will be executed.
- When task-set switches are required under continuous task performance, cognitive lock-up might occur: the tendency of people to focus on single faults, ignoring the other subsystems to be controlled (Moray & Rotenberg, 1989). Because the operator is too much occupied
with, for example, a disturbance, the monitoring task might be neglected. New disturbances are not detected and may lead to dangerous situations. People become committed to their choice to perform a specific task (Boehne & Paese, 2000) and have the tendency to execute tasks sequentially (Kerstholt & Passenier, 2000).

- **Vigilance**, performing continuous skill-based tasks like monitoring, is problematic for operators. Performance decrease can already occur after 10 minutes when an operator has to monitor a process continuously but hardly has to act (Levine et al., 1973; Parasuraman, 1986). Vigilance can result in stress due to the specific task demands (i.e. the requirement to continuously pay attention on the task) and boredom that appears with highly repetitive, homogeneous stimuli. Consequently, the only viable strategy to reduce stress in vigilance, at present, appears to be giving the freedom to stop when people become bored (Scerbo, 2001).

![Figure 3: The three dimensional model of cognitive task load with four general problem regions.](image)

### 4.2 Functional Requirements

From a functional viewpoint, activities within the control room can be hierarchically ordered into three different task levels: the **planning level**, the **monitoring level** and the **execution level** (Passenier & van Delft, 1996).

- At the highest level plans are made to be executed in order to achieve the goals that are set before production. These plans are based on different factors, like supply and demand in the market, or the plant capacities.
During execution, monitoring takes place at the intermediate level. The planned situation is compared with the actual situation. When deviations are present adjustments may have to be made at the planning level.

At the control (execution) level, deviations between planned and actual state variables are compensated on the basis of local feedback control loops.

Activities on the execution level and some on the monitoring level are becoming more and more automated. This means that operator tasks are shifting from specific controlling activities to more general supervisory activities. At the same time, the operator will be exposed to an increased amount of data, with a possibility of having to deal with more and more ‘false alarms’. More effort has to be spent on translating these data into relevant information. Because of this shift from human activities from the execution level to monitoring and planning level, in the following the emphasis is put on the two highest task levels.

### 4.2.1 Function analysis

In general, four generic functions are fulfilled within the control room.

- In the first place, a ‘picture’ is created about the actual plant state. Sensors provide information about critical parameters that represent the state of the process. Such a picture is called situation awareness (SA). The operator needs the right information to get insight in the actual situation and the situation as it will be in the near future.

- The situation awareness information is used to assess possible disturbances that are or will be present in the process plant. This activity is called disturbance assessment (DA). In some cases these disturbances are directly solved by interfering in the process through standard or rule-based procedures.

- However, in other cases there is no procedure available. The operator (together with others) might have to reconsider the initial plan and create an alternative to prevent damage to the plant and reduce production losses in a decision making (DM) process.

- Finally, the direction and control (DC) function is needed to perform the interventions that are made in the plant process.

The functions are related to different task levels, as described in Table 2. The presence of (potential) automation is shown in the table as well.

<table>
<thead>
<tr>
<th></th>
<th>Situation Awareness</th>
<th>Disturbance Assessment</th>
<th>Decision Making</th>
<th>Direction and Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning level</td>
<td>--</td>
<td>--</td>
<td>H../A</td>
<td>--</td>
</tr>
<tr>
<td>Monitoring level</td>
<td>H/A</td>
<td>H../A</td>
<td>H../A</td>
<td>H../A</td>
</tr>
</tbody>
</table>

Table 2: Relation between functions and task levels. ‘A/H’, automated functions monitored by human supervisors, ‘H/A’, human functions assisted by automatons. ‘H../A’ refers to functions which at present are fulfilled principally by humans, but in the future more and more may be supported by computer aids.
### 4.2.2 Information transfer

The functions SA, DA, DM and DC can be arranged in a two level model, in order to analyse the information transfer (Figure 4). At the primary level, information detected by sensors is used as input for SA. At the DC side, deviations between pre-set values (set points) passed from the secondary level and actual values are directly compensated. Based on lower-level feedback control loops adjustments are made, either automatically or assisted by the operator. At the secondary level, higher-order objectives, determined by the operational goals and criteria for safety and efficiency, are translated into pre-programmed rules for the primary level. Knowledge about the plant and knowledge of the available controllers are used to plan the process activities and settings within a certain timeline, in order to accomplish the pre-set goals (DM). At the same level, the process status is monitored. When there are deviations from the planned state (DA), interventions are made to maintain operational goals, or, when these cannot be achieved with the current plan, the plan has to be reconsidered.

![Figure 4: General process-control functions SA, DA, DM and DC, arranged according to two levels of information transfer](image-url)
4.3 Analysis of High-Demand Situations

The activities within the four functions as described here all have their own characteristics that may, in some cases, lead to high-demand situations. Some of them are described below.

4.3.1 Situation awareness

The operator has to be provided with the right information to create an (internal) picture of the plant state, for which different data sources are available. However, the increasing amount of data, in combination with possible ‘false alarms’ might become too large to process within the available time. Besides that, the operator has to switch between data sets from different parts of the plant. As described in the cognitive task-load framework, switching of task sets may involve an increase of mental load.

Apart from the situation, the operator also has to be aware in which mode the system is (so-called ‘mode awareness’). Working in a different mode than assumed can lead to serious accidents.

An illustration of this is a plane crash near San Francisco with a Boeing 747 of China Airlines. The plane was flying on auto-pilot. Because of an engine disturbance the pilots had to fly on manual. However, they were not aware that the auto-pilot was still switched on. The actions performed by the flight crew were constantly ‘corrected’ by the auto-pilot, which finally resulted in a crash. Had the automatic pilot been switched off, a safe landing would have been no problem with one damaged engine.

4.3.2 Disturbance assessment

The basis of disturbance assessment is mainly a monitoring activity, in which the expected situation has to be compared with the actual situation. Operators, especially the experienced, can often rely on their skills in monitoring the plant, as long as no deviations occur (‘check reading’). Even low-level corrections might be performed on a skill-based level. When disturbances occur, however, information processing has to shift to a higher level. Sometimes rules are used to identify the problem, like “if X occurs on the screen, then there is a problem with Y”. In the worst case, the situation is ‘new’ to the operator. Then the operator has to use the available knowledge about the plant to diagnose the problem. So, occurrence of disturbances may involve a shift to higher processing levels, in which mental load increases. In the meantime, while identifying the disturbance, the monitoring task has to be continued. Switches have to be made between the two tasks, which again may lead to an increase of mental load. Especially when problem identification demands high-level processing, mental load might reach critical levels. (For example, see the Milford Haven incident described earlier)

4.3.3 Decision making

Once a deviation from the planned situation is detected, interventions have to take place in order to maintain the planned operational goals and criteria. Sometimes these can be based on prescribed rules and processes. In that case, actions are taken on a rule-based level. However,
when an uncommon situation occurs, standard procedures will not be available to solve the problem. The operator has to use his experience and knowledge to judge the situation, and maybe consult other information sources, before making an adequate decision on what actions to take. Information processing will shift to the knowledge-based level. Also, because of safety issues or the risk of production loss, time for decision making is often limited. The combination of high-level processing and time pressure may result in a high cognitive task load.

4.3.4 Direction and control

Once a decision is made about the intervention that has to take place, actions to be taken are scheduled and performed according to certain procedures and rules. Operator skills are used for the final execution of the planned actions. However, because of time constraints in emergency situations, actions have to be performed fast, so again mental load may increase.

4.3.5 Switching between secondary and primary level

As discussed earlier, processes at the primary level will become more and more automated, while the operator will be monitoring the process at the secondary level. However, situations may still arise requiring direct operator involvement in the control loop. In that case, task switching has to take place between the primary and secondary level, which implies an increase in mental load.

4.4 Scenario development and assessment

Of course, the list of potentially high-demand situations described before is not exhaustive. An effective technique to generate more critical situations is scenario analysis. Scenarios are stories about people and their activities (Carroll, 2000). These stories illustrate someone’s activities in a particular environment. For example, a traveller wants to know at what time the train leaves to Amsterdam. He starts up his computer in the study room, opens an internet browser and visits the railways web site. He enters the place of departure, the place of arrival and the time he wants to arrive. A list of departure times of trains is presented that arrive around the time he has entered. The traveller scrolls through the list. He finds a train that arrives a bit earlier, but has the shortest travel time.

Scenarios presuppose a certain setting. In the example above, the setting is the study room with a person behind a PC. Within the setting, roles are played by actors. In this scenario only one actor is present, the traveller. In more complex scenarios different actors can be involved, possible interacting with each other. Actors have specific goals. The actor’s main goal in this example is to find a train he can take from his place of departure that arrives in Amsterdam at the time he wants to. To achieve this goal actions have to be taken. In this example the traveller starts up the computer, opens the browser, finds the right web site and enters the data that will give him the departure and arrival times of the train he wants to travel with. In a process control context, the control room could be the setting and the operators the actors. Their goal could be to produce a certain amount of chemicals. The actions that have to be taken are, for example, mixing substances, heating them up and maintain a certain pressure.
The advantage of using scenarios is that in an early (design) stage problems are identified that can occur while working in a specific (technical) environment. Problem issues can be uncovered by describing the scenarios with different settings, actors, goals and actions. In our case, the settings, actors, goals and actions must be translated to the process-control environment.

The challenge is to design future situations that will minimise risk-full high-demands on the human information processes. We propose to make these demands explicit in terms of the cognitive task load and functional processes. Our cognitive load and functional (COLFUN) framework comprises an integrated view on the analysis of situation- and goal-driven task demands, referring to different human-factors methods and enhancement approaches, such as functional decomposition and critical scenario assessments. The next step is to design cognitive support concepts to assist the operator in preventing or to overcome the different possible bottlenecks identified.

4.5 Design of Cognitive support

Neerinx & de Greef (1998) propose a model-based design approach that aims at human-computer co-operative problem solving by integrating cognitive support into the user interface. Based on this approach and the load theory, we developed a framework that distinguishes a small set of user-interface and cognitive-support functions with specific high-level design principles. Below, the framework will be presented, as a basis for best practice design in example domains.

4.5.1 Time occupied

There is a trade-off between the benefits of support facilities and the interaction costs. In particular when the time pressure is high and the user has only a small part of his or her cognitive resources available to manage and consult such facilities, the benefits should outweigh the costs substantially. The additional time required for interacting with the support facility should be small compared to the execution time for the primary task. We distinguish four general design principles to reduce the interaction load that apply to the user interface:

- **User adaptation.** The user interface design should take account of both the general characteristics of human perception, information transfer, decision-making and control, and the specific user characteristics with respect to education, knowledge, skills and experience.
- **Goal conformance.** The functions and function structure of the user interface should map, in a one-to-one relation, on users’ goals and corresponding goal sequences. Functions that users don’t need should be hidden for these users.
- **Information needs conformance.** The information that is provided by the user interface should map, in a one-to-one relation, on the information needs that arise from users’ goals. Irrelevant information should not be presented to the users.
- **Use context.** The human-computer interaction should fit to the envisioned use context and/or situation (e.g. a speech interface should not be designed for noisy environments).

4.5.2 Level of information processing
Based on the Skill-Rule-Knowledge-framework of Rasmussen (1986), we distinguish four support functions: rule provision, information handling, problem exploring, and rule checking. Below we will discuss these functions, following the human information processing steps of Figure 5.

**KB** = Knowledge based  
**RB** = Rule based  
**SB** = Skill based

**Figure 5:** Four cognitive support functions at the knowledge-based (KB), rule-based (RB) and skill-based (SB) level. The broken arrows represent “short-cuts” in the human information processing based on training, experience and/or support.

The Rule Provision function provides the normative procedure for solving (a part of) the current problem. Due to training and experience, people develop and retain procedures for efficient task performance (i.e. they apply the rule-based “short-cuts” of Figure 5). Performance deficiencies may arise when the task is performed rarely so that procedures will not be learned or will be forgotten, or when the information does not trigger the corresponding procedure in human memory. For these situations, rule provision aims at supplementing human procedural knowledge. We distinguish four design principles:

- The support function should take the initiative to provide information at the right time. Consequently, the user does not need to know when and how to search for information and does not need to invest in these actions.
- Rule provision should consist of context-specific, procedural task knowledge. The advice is minimal, not more than necessary. Each individual (sub)procedure should however describe a complete problem-solving path to accomplish the (sub)goal.
- The user interface of the rule provision facility should be a well-integrated part of the human-machine dialogue. A minimal and consistent interaction requires little knowledge and contributes to efficient task performance.
- The advice should be provided in such a way that the user remains in the loop of the overall activity by interactive involvement in the process of action executions as part of a task procedure.

An example in a control room context could be that, in case of a fire, the system shows a checklist of procedures that have to be followed during this particular fire. The operator should be warned when critical steps are neglected.
The *Information Handling* support filters and combines information to improve situation awareness, i.e. knowledge of the state of the system and its environment (Endsley, 1995). Due to the increasing availability of information, situation awareness can deteriorate without support. Sensor information should therefore be combined into alarms that are structured according to their function, such as fire control, propulsion and energy supply. Furthermore, Information Handling can support the operator in keeping overview by making the structure of the complete system explicit at a global level and by indicating functional relationships between system components. Taken together, Information Handling support should enhance information acquisition and recall in such a way that situation awareness is optimal for the current task performance. Three *design principles* for this type of support can be formulated:

- An information handling support function should provide an overview of state and process variables, showing the correspondence to system's components (i.e. structure) and the fluctuations in time (history).
- Alarms should be prioritised according to the current situation and provide information about how to (start to) solve the problem. Important alarms should stand out and irrelevant alarms should be hidden.
- The support should enable fast and easy access to the requested information with adequate orientation cues and state explanation. It should correspond to the optimal search strategy for the specific task and situation, i.e., support several accurate information acquisition processes of users.

*Problem Exploring* comes into play when there is not a complete (executable) procedure available to deal with the current alarms and situation. First, the problem and solution space has to be analysed. Subsequently, based on information about the environment (state, process) and information from memory, a procedure must be planned for solving the problem. Based on a mental model (i.e. an internal representation of the system), the person sets local goals, initiates actions to achieve them, observes the extent to which the actions are successful and, if needed, poses new sub-goals to minimise the discrepancy between the present state and the desired state. A problem-exploring function consists of a knowledge-based component that can execute some problem-solving activities such as the generation of hypotheses and the selection of an urgent and most promising one. Another possibility is to provide predictions of future states based on the current user actions (e.g. predictive displays, Wickens, 1992). The benefits of such predictions can be very large for a number of tasks if the “predicted path” is explicitly presented and well integrated into the overall presentation of state information. We distinguish three design principles for Problem Exploring support:

- The user must understand what the support function is doing and why, so that, for example, the user will remain in the loop of task execution.
- The problem-solving process of the support function should be compatible with the user's problem-solving process and enable the involvement of specific user's capabilities.
- For providing predictions of future states, the “predicted path” should be explicitly presented and well integrated into the overall presentation of state information.

*Rule Checking* functions recognise when the human operator has strayed from the normative problem-solving path, and help to reach a more correct task outcome (Silverman, 1992). However, as task difficulty increases, a point will be crossed at which subject-matter experts can no longer be assisted by Rule Checking alone. Thus, under conditions of high task load this kind
of support seems not to be optimal. A further restriction is that the users must have some knowledge to start their task execution. If they do not know which goals to achieve, then they cannot be critiqued. In general, the first three principles that were identified for Rule Provision apply also to Rule Checking.

### 4.5.3 Task-set switching

Task-set switching support should comply with the following design principles:
- For the momentary activity, it should provide an up-to-date overview of the tasks with corresponding actions, including the current status of the activity and the status of each task.
- The current priority of each task should be shown. Changes in priority should be communicated to the users, so that they can keep a correct, up-to-date situation awareness.
- Humans are inclined to focus on the tasks they are working on, neglecting tasks with a possible higher priority (“cognitive lock-up”, see previous sections). The support functions should check if users do obtain the required abstraction from action level to the task and activity level.
5 Best Practice from example domains

In work domains other than the process industries such as defence, space and transport the need for improved deployment of human knowledge and capacities in high-demand situations is increasing. In addition to task allocation and computer support, adequate selection and training can help to realise such improvement.

As stated before, this guide will present principles and process guidance instead of rigid rules. Standards and guidelines are found in Annex 1.

5.1 Analysis of task allocations

5.1.1 Future Ship Bridge operation

Given the current technological developments in the field of marine automation, together with the need for crew reduction, also for the officer of the watch at the future ship bridge a shift in function allocation is to be expected from low-level control functions to higher-level monitoring and planning functions. To investigate the effect of this shift in function allocation on human decision-making behaviour under critical conditions, e.g. when (part of) the automated systems fail because of incidental break-down of important parts of the ship or machinery, an Anglo-Dutch research programme on Human Factors in Bridge Operation’ was initiated. This programme was funded by the Netherlands Foundation for the Co-ordination of Maritime Research (CMO) and SERC, through the Marine Technology Directorate Limited (MTD). Ultimately, insight in the bottle-necks of information processing under such critical conditions provides the opportunity to design interfaces that may help to overcome these limitations of the human information-processing system.

Scenarios
To identify the critical elements in decision making, several experiments have been conducted based on an analysis of system functions and human tasks. For the experiments, a dynamic simulation set-up has been constructed of four subsystems: ‘navigation’ (track-control systems), ‘propulsion’ (diesel engine and transmission), ‘electricity’ (power generation and distribution), and ‘cargo’ (cooling system). In the simulation the subsystems were controlled by automated systems, in which disturbances would occur to be diagnosed and resolved by the subjects, students from maritime curricula who voluntarily participated in the experiments.

Assessment
Based on the analysis and part-task simulation of the automated vessel functions, first, experiments were conducted to identify different elements in the decision-making process and the extent to which these elements can be regarded as critical (Kerstholt & Passenier, 1995a, 1996). The critical elements identified were:

- **lack of system knowledge**, where this knowledge concerns both the relations between causes and symptoms within subsystems and the dependencies between subsystems,
"cognitive lockup", the tendency to concentrate on one sub-goal at a time, ignoring the rest of the system.

Furthermore, the results suggested that people trade-off performance accuracy against effort: they may want to save effort at the expense of sub-optimal task performance. This was demonstrated by the fact that, in the presence of false alarms, the effort subjects spent on resolving real faults was substantially reduced (Figure 6).

![Figure 6: average sampling rates for different subsystems in a process monitoring task, both in the presence and absence of false alarms](image)

Such factors can be considered as 'latent factors': in that they contribute to an increased risk of accidents, but they will not be identified by only analysing behaviour in situations that led to accidents. For designing the human-machine interface this finding implies that information should be readily available, reducing the effort needed to create a mental model of the actual state of the system under control.

Based on the results, two broad categories of support were discerned as a basis for further research: training and interface design.

- Training can contribute to a more efficient information selection process, taking into account the dependencies between subsystems.
- A well designed interface can further improve performance by providing additional insight into the relations between subsystems and into one's own diagnosis behaviour.

Indeed, the results of a subsequent experiment on the influence of training (Kerstholt & Passenier, 1995b) showed the percentage of correct diagnoses within the time constraint to increase from 70%, for subjects who had learned the subsystems in isolation, to 90% for subjects who had received an integrated training. In this integrated training, besides the relations between causes and symptoms within a single subsystem (for instance 'propulsion'), also the dependencies between the subsystems (for instance 'electricity' and 'propulsion') were taken into account.

To further support the decision-making process, by means of the human-machine interface, a decision support system was designed, based on the information-aid concept. Related experimental research on the application of a DSS from the information-aid category to the
diagnosis of unfamiliar system failures, focusing on a ship propulsion system, has shown the percentage of correct diagnoses to increase from 60% to 90% (Raaijmakers & Verduyn, 1993). The information aid in this particular study was based on a relatively simple concept of providing the operator at his discretion with a number of most probable causes of an alarm and indicating the corresponding sensor data to be checked.

For the present study, this concept was generalised for the four main vessel functions, providing the subjects at their request with context-sensitive information from platform handbooks. The resulting integrated DSS set-up allowed subjects to construct hypotheses on failure causes on the basis of global ('overview') information and to selectively test these hypotheses on a local, more detailed level within subsystems.

A final experiment on the evaluation of the on-line decision support set-up, showed the percentage of correct diagnoses to increase from 70% to 90% (Passenier & Kerstholt, 1996). In this experiment, failures were of a complex, combined nature such that solving problems in isolation, characteristic of the 'cognitive lockup' phenomenon, would not yield the required solution of the diagnosis problem.

**Conclusions**

In all, the results of the experimental research described here present a clear picture of human supervisory control behaviour in complex fault-finding situations. Sub-optimal performance could be ascribed to basically two factors: lack of system knowledge and a tendency to concentrate on only one goal at a time, while neglecting the rest of the system under control ('cognitive lockup', see also, for instance, Moray & Rotenberg, 1989; Boer, 1995). To improve task performance in these complex control situations, where the supervision of multiple functions becomes more and more the role of a single human operator, both the results on training and interface design demonstrate the relevance of an integrated approach in supporting the operator. According to this approach, the improved operator insight into the interactions between the main process functions may be used for the guidance of information search at a more local system level, resulting in a more structured, and eventually more effective, problem-solving approach.

### 5.1.2 Integrated Ship Monitoring & Control

Recently, the Royal Netherlands Navy developed the Integrated Monitoring and Control System (IMCS) for a new ship: the Air Defence and Command Frigate. The IMCS is a large and complex system that is used in diverse situations and work settings for supervision and control of the platform systems and damage control. In the first phase of the IMCS development, the high-level system requirements were provided as Government Furnished Information. This section gives a brief overview of the method for cognitive task analysis that was applied to assess these system requirements (for details, see Neerincx et al., 2000).

**Function analysis**

To make the task demands explicit for the IMCS operators, we followed the specification process of Figure 7.
First, we specified the task-set classes. At the top-level, the task decomposition distinguished four platform functions:

- provide survivability,
- provide mobility,
- support hotel functions,
- weapons and sensors.

In the first instance, the task breakdown stopped when all task allocations to the control-centre crew and IMCS could be designated within it. After establishing the jobs as a set of tasks that have to be performed by one person, decomposition continued until the subtask can be mapped on a specific IMCS support function of the Air Defence and Command Frigate or defined as a ‘pure’ human action, so that either the human-computer interaction or an observable human action is specified.

**Scenarios**

Subsequently, we transformed the general task-set specifications into task-set instances and “envisioned” about 40 different scenarios. Two critical scenarios that differed from each other fundamentally were selected for further analysis.

- The first, ‘fire in the galley in harbour’, consists of an ‘unexpected’ calamity with extra complications occurring in a quiet situation and a small crew.
- The second consists of a very severe damage in war-time, comprising a hectic situation that the complete crew must be able to deal with.

The two selected scenarios were transformed into ‘Compound Action Sequences’ (CAS in Figure 7) using the ‘Basic Action Sequences’ (BAS in Figure 7) for handling the events of this scenario.
(see Figure 8 for the ‘fire in gallery’ example). Navy experts estimated for each action the fastest and slowest performance and the level of information processing according to the Skill-Rule-Knowledge-framework. This resulted in two CASs per scenario: one consisted of the fastest performances and the other the slowest. The actual Action Sequences consisted of a number of actors, the action times were presented in them, and the individual BASs were coded separately to get an overview of the number of switches between task sets in an activity.

**Figure 8:** Outline of a Compound Action Sequence (CAS) consisting of 2 Basic Action Sequences (BAS) (i.e. handling of both the fire and the black smoke events).

For scenario 1, the fast CAS lasted about 18 minutes and the slow version about 56 minutes. For scenario 2, the fast CAS lasted about 25 minutes and the slow version about 72 minutes.

**Assessment**

In the first step of the assessment, general patterns and extremes of task load were identified. The percentage time occupied, the percentage knowledge-based actions and the number of task-set switches for each person of the future ship control-centre crew, can be directly derived from the CASs. Differences in the time a person is occupied appeared mainly between scenarios. There was a large variance: between 8% to 70% occupied. Time occupied did not appear to be a cause of overload on its own, because it remained below the critical level of 70-80% (Beevis, 1992). Overall, the tasks of managers and operators showed a large knowledge-based component for which system and process knowledge is required. The work is complex and cognitively demanding for the complete crew. Managers’ tasks comprise primarily planning, supervision, priority determination and co-ordination, while the operators have to assess, diagnose and solve specific technical problems. The future situation in the Air Defence and Command Frigate requires that the operators have knowledge of specific parts of the platform control system and tasks they are involved in. In the Cognitive Task Analysis method, a task set is defined as a BAS for a specific event. For example, when the same BAS appears more than once in a CAS, they are viewed as different task sets, because they apply to different events (i.e. different objects in the environment). Task-set switching proved to appear rather often. In particular, for manager 1, the number of task-set switching showed to be high in the fast scenario 2: 54 switches in an hour (i.e. 54 times per hour)
a switch every 67 seconds). The number of switches increased in scenario 2 when action times were longer, because the operational requirements were more difficult to satisfy in this condition. In the second step of the assessment, situations of momentary overload were identified. The CASs show the action times of each person and the interrelationships between the actions: the critical path. Often, more than one person is on the critical path, so that sub-optimal performance of one person at a specific moment will often have a major effect upon the overall SSC-crew performance. Therefore, it is of utmost importance to detect possible peak loads for all persons. Compared to the general load, for momentary peak loads the time scale of occurrences of almost continuous knowledge-based actions with a lot of switches is much shorter (between 5 and 15 minutes) and the load limit is higher. For example, the momentary load of operator 2 in the fast condition of scenario 2 proved to be relatively high. In a period of five minutes, he should have to switch every 20-second to a new task set that comprises almost always a knowledge-based action. It can be expected that he will not be able to fulfil these task demands and, because he is on the critical path, this will have an impact on the overall crew performance. Further, in this period the operator performs 19 interactions with the IMCS. For this specific action sequence of operator 2, it is very important that the dialogue with the IMCS is as efficient as possible, i.e., the user interface structure should map very well on this sequence.

Conclusions
The assessment of the four CASs showed possible risks for overload that are mainly caused by the composite of measures on time occupied, percentage of knowledge-based actions and the number of task-set switches. Because cognitive load was described in terms of task and interface characteristics, recommendations could be formulated for task allocation and interface design to diminish these risks. The IMCS specification for the future Air Defence and Command Frigate should be improved by describing a general coherent user interface structure and establishing the dialogue principles for its components. In particular, the interface should enable efficient task-set switching and may even provide support to keep track of task sets that ‘run in the background’ and to return to these task sets. It should be noted that the IMCS requirements specification defines a number of individual support components from sensor-fusion and filtering mechanisms to damage control advice functions. Each function will probably have a positive effect on the local task performance. However, an overview on the interrelationships and the combined effects of these functions is lacking. For example, a general “high-level” user interface structure is lacking and the management of the support functions can be a load factor in itself (i.e., the control of the envisioned information presentations). To establish support for the managers of the crew, to diminish peak loads and to prevent human biases such as cognitive lock-up, the combined effects and integration of the support in the overall task performance should be defined explicitly. Human-centred development of interactive systems requires an iterative design process in which cognitive engineers provide the required human factors input in terms of guidelines, user interface concepts, methods and facilities (cf. ISO 13407). Because the IMCS-development had already been started and the development process defined, it was difficult to bring these insights into this process.

5.1.3 Traffic Monitoring & Control

Rypkema et al. (2002) assessed a design of the control room for supervising traffic in the future “Westerschelde tunnel”, with a length of more than six kilometres currently the longest motor-
traffic tunnel in The Netherlands. The tunnel has two separate tubes, each tube containing two driving lanes. For evacuation purposes the tubes are connected by corridors (the distance between corridors is 250 m). The tunnel is expected to be fully operational at the end of 2003. A monitoring and control system (TUBES) was developed for operating the tunnel, containing 94 cameras, 20 monitors, various sensors and different systems to control the tunnel like traffic lights, speed reduction signs and barriers. The initial plan was to assign the control tasks to one operator. However, there were concerns if one operator would be able to perform all these tasks. The framework described above was applied to find an answer to this question.

**Function analysis**

First, an inventory of operator tasks was made based on the four generic functions SA, DA, DM and DC of the process control model introduced in Section 4.2. On the primary level these were mainly tasks that are related to the monitoring and control system TUBES. Tasks like watching monitors, camera selection, monitoring sensors and communication systems were analysed within the SA function, while tasks related to control systems like speed signs, traffic lights and barriers were described within the DC function. On the secondary level the higher order tasks were analysed. A distinction was made between threats and incidents. Incidents are events that are caused (intentionally or not) by road-users which obstruct the traffic flow and bring themselves or other road-users in danger. Threats are situations, in or around the tunnel, that could bring road-users into danger or lead to incidents. Tasks concerning the identification of threats and incidents were analysed within the DA function. Decision tasks about the plans and actions to deal with threats and incidents were identified within the DM function.

**Scenarios**

The scenario design was based on three variables: frequency, severity and expected mental effort. Frequency expressed how often a scenario occurs. Highly frequent scenarios occurred more than once a week, low frequent scenarios less than once a month. Severity expressed the number of casualties within a scenario. Severe scenarios contained heavy injuries or deaths, while non-severe didn’t have any casualties at all. The expected mental effort was defined by domain experts during an interview. Some scenarios were expected to cause a high mental effort, others weren’t. For every scenario the operator tasks identified during the function analysis were placed in chronological order according to the subscribed procedures (see Fig. 9 for an example sequence diagram). Tasks were divided into five task-sets: regular monitoring task; monitoring and controlling situation in tunnel, communication with parties concerned with emergency response and unexpected tasks not directly related to the handling of the situation (for example, a telephone call from the media).

**Assessment**

The average percentage time occupied, complexity and task-set switches were measured to determine the cognitive task load. It appeared that percentage time occupied was high in all the scenarios. Because the monitoring task is a continuous task the time occupied is always 100%. In three scenarios the complexity and the number of task-set switches showed a peak during the period that took place from the start of the incident to the arrival of the emergency response teams arrive. After the teams arrive they become responsible and take over a major part of the tasks. At that moment the operator’s task load decreases to a lower level.
**Conclusions**

The prevention of and the response to tunnel incidents highly depends on the performance of the tunnel operator. However, during critical situations operator task load might become too high for adequate task performance. As a result, incidents may be handled improperly and might escalate. Especially when there is a fire and the operator has to evacuate the people out of the tunnel. The overload was due to the large number of tasks, the task complexity and in some cases the large number of task-set switches. Furthermore, the sudden change from low to high mental load and the operator’s responsibilities play an important role. It was recommended to improve procedures and clustering of tasks. Furthermore, it was recommended to support the operator during incidents by deploying a second person who is able to assist the operator within a short period of time (e.g. someone who is working in the same building). Finally, it was recommended to use a simulator during training and selection, in order to create a dynamic task environment. This can be used for two purposes. Firstly, to train the operators and secondly, to freshen up the tasks that must be performed during critical situations.

**5.1.4 Discussion**

The method for task allocation applied in this section provides a framework for the identification of critical situations through analysis of the functional demands and cognitive load. The cognitive load and the functional model individually have been used more often in the past and have proven their value in several studies (a.o. Passenier & van Delft 1996, Passenier & van Delft 1999, Neerincx & van Besouw 2001). The “Westerschelde tunnel” study shows that combining the two has an added value in the sense that it offers a tool for a structural analysis of operator tasks,
while at the same time the cognitive task load can be measured systematically. Together with the identification of critical situations, the combined framework helps to identify possible solutions:

- **Procedures.** Highly complex knowledge-based tasks can be transformed in less complex rule-based tasks by provision of context-specific procedures and diagnosis guidance.
- **Support systems.** For all four process-control functions, requirements for support functions can be provided (from cameras and sensors to advanced decision support systems).
- **Manning.** Dynamic task allocation can help to handle critical situations (e.g. an (extra) employee could take over some of the operator tasks).
- **Organisation.** The framework may show possible inefficient information transfer processes. For example, the communication between operators and emergency response teams could be inefficient, leading to an enormous amount of communication tasks for the operator.
- **Training.** Operators can be prepared for envisioned critical situations by training and refreshment courses (e.g. in a simulator).

### 5.2 Design of Cognitive support

The previous section showed examples of how to assess the different load factors for a given domain, both in an experimental and task-analytical approach. The present section will focus on the application of a set of corresponding support functions that can reduce the negative effects of each factor on task performance and mental effort, such as described in Section 4.5. Example studies are presented, which focus on decision support for the operator (future integrated ship bridge) and design support for the user interface design team (payload interfaces in the space domain).

#### 5.2.1 Decision support

The research reported here has been partly funded by the EU project ATOMOS IV (Advanced Technology to Optimise Maritime Operational Safety, Intelligent Vessel), and as such is a continuation of earlier work aimed at the development and demonstration of decision-support concepts in the maritime domain.

To exemplify the design method, we will provide small (simplified) task descriptions for four support functions that reduce the negative effects of a specific load factor in an integrated monitoring & control environment (see Table 3):

- An **information handler** that supports task-set integration for keeping overview of the overall system’s state. Based on the system structure and current events, this function provides an overview of alarms and a set of integrated views (i.e., system overviews).
- An **emergency scheduler** that supports task-set switching by providing an overview of prioritised alarms that have to be handled or are being handled, based on the overview of alarms.
- An **emergency scheduler** that supports task-set switching by providing an overview of prioritised alarms that have to be handled or are being handled, based on the overview of alarms.
- A **rule provider** that supports task-set switching by providing the context-specific procedures for each emergency with the current state of each procedure. Context information comprises the state of the objects in the task set, such as the position of the ship (e.g. harbour at open sea), the location of an emergency (e.g. a fire in room 12) and the maintenance data of a machine (e.g. pump X replaced last week). The combination of emergency scheduler and rule
provider provides the action plan for the operator.

- A diagnosis guide that supports task-set integration for alarm handling. This guide consists of an overview of possible symptom-cause relations between alarms, e.g. ordered by probability. Based on context information, the alarm overview and the system structure, relations between the alarms are proposed, and based on the settled relations, the context information is refined.

Table 3: Four example support functions that reduce the negative effects of each load factor.

<table>
<thead>
<tr>
<th>Load factor</th>
<th>Support type</th>
<th>Support function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time occupied</td>
<td>Information handling</td>
<td>Information handler</td>
</tr>
<tr>
<td>Level of information processing</td>
<td>Rule provision</td>
<td>Rule Provider</td>
</tr>
<tr>
<td></td>
<td>Problem exploring</td>
<td>Diagnosis Guide</td>
</tr>
<tr>
<td>Task-set switching</td>
<td>Task managing</td>
<td>Emergency Scheduler</td>
</tr>
</tbody>
</table>

To evaluate the interactions between interface support type and task load factors, a prototype user interface was constructed, providing the proposed support concepts (Grootjen et al. 2002). Application of the design method proved to be possible for the chosen maritime domain (the bridge of an icebreaker) and resulted in an interface that contains an information handler, a task scheduler, a diagnosis guide and a rule provider. Table 4 gives an overview of all support instantiations and their connection with the support functions.

Table 4: All support instantiations and their connection with the support functions.

<table>
<thead>
<tr>
<th>Support function</th>
<th>Support instantiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information Handler</td>
<td>Ordering alarms in categories</td>
</tr>
<tr>
<td></td>
<td>Process-based (automatic) presentation of required interface component</td>
</tr>
<tr>
<td></td>
<td>Hyperlinks within and between the components</td>
</tr>
<tr>
<td>Rule Provider</td>
<td>Context specific procedural information</td>
</tr>
<tr>
<td></td>
<td>Spatial advice (graphical presentation of ‘routing rules’)</td>
</tr>
<tr>
<td>Diagnostic Guide</td>
<td>Help with diagnostic process</td>
</tr>
<tr>
<td>Task Scheduler</td>
<td>Task overview</td>
</tr>
<tr>
<td></td>
<td>Check mark ability (process state)</td>
</tr>
<tr>
<td></td>
<td>Prioritising alarms</td>
</tr>
</tbody>
</table>

The resulting prototype user interface was evaluated with navy cadets, to study the effects of cognitive support, under high and low task load, on task performance, mental effort and out of the loop effects. In Figure 10 the results are presented, showing the effect of the level of information processing (LIP), task-set switching (TSS) and support on the time dealing with “incorrect” alarms.
Figure 10: Interactions between the level of information processing (LIP), task-set switching (TSS) and support on the time dealing with incorrect alarms. The condition where both load factors are high shows the largest effect of support.

As expected, especially at combined high task loads (high level of information processing together with a high number of task-set switching) the support functions proved to be of great value. Costs on out of the loop effects, like not reacting on an implemented wrong advice and a decrease in understanding of performed actions, could not be found.

5.2.2 Design support

For the European Space Agency (ESA), the cognitive engineering framework has been applied to assist the development teams of payload user-interfaces in the International Space Station, with an emphasis on different usability aspects (Passenier & Neerincx, 1997; Neerincx et al., 2001). It attempts to synchronise the activities of two traditionally separated groups, the operations group involved in procedure development and the software group involved in display development, to realise adequate online procedural operation support (instead of the traditional paper-based support). Usability guidelines were derived according to an iterative development process, starting from more abstract specifications that are assessed (analysis stage) and subsequently refined into more concrete specifications (design stage). In the analysis stage, based on users’ goals and information needs, the system’s functions and information provision are specified (i.e. the task level of the user interface is established). This specification is the basis of the display and procedure components, and their mutual dependencies in the user interface. In the design stage, the control of the functions and the presentation of the information is specified (i.e. the communication level of the user interface is established). Table 5 summarises some high-level HCI guidelines that are ordered in the same hierarchy, and that are further defined and
exemplified in the method’s description. These guidelines should guide the development activities, but can also be used for usability checks.

**Table 5:** A selection of high-level guidelines at the two interface levels

<table>
<thead>
<tr>
<th><strong>Task Level Guidelines</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>User adaptation</strong></td>
</tr>
<tr>
<td>Take account of both the general characteristics of human perception, information transfer, decision-making and control, and the specific user characteristics with respect to education, knowledge, skills and experience.</td>
</tr>
<tr>
<td><strong>Goals conformance</strong></td>
</tr>
<tr>
<td>Map the functions and function structure of the user interface, in a one-to-one relation, on users’ goals and corresponding goal sequences. Hide functions from the user who does not need them.</td>
</tr>
<tr>
<td><strong>Info. needs conformance</strong></td>
</tr>
<tr>
<td>Map the information that is provided by the user interface, in a one-to-one relation, on the information needs that arise from users’ goals. Hide information from the user who does not need it.</td>
</tr>
<tr>
<td><strong>User’s complement</strong></td>
</tr>
<tr>
<td>Provide cognitive support to extend user’s knowledge and capacities when needed.</td>
</tr>
<tr>
<td><strong>Use context</strong></td>
</tr>
<tr>
<td>Attune the human-computer interaction to the envisioned use context and/or situation (such as micro-gravity).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Communication Level Guidelines</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compatibility</strong></td>
</tr>
<tr>
<td>Minimise the amount of information re-coding that will be necessary.</td>
</tr>
<tr>
<td><strong>Consistency</strong></td>
</tr>
<tr>
<td>Minimise the difference in dialogue both within and across various user interfaces.</td>
</tr>
<tr>
<td><strong>Memory</strong></td>
</tr>
<tr>
<td>Minimise the amount of information that the user must maintain in working memory.</td>
</tr>
<tr>
<td><strong>Structure</strong></td>
</tr>
<tr>
<td>Assist the user in developing a representation of the system’s structure so that they can navigate through the interface easily.</td>
</tr>
<tr>
<td><strong>Integration</strong></td>
</tr>
<tr>
<td>Provide an integrated interface in which the different components are attuned to each other according to the current task.</td>
</tr>
<tr>
<td><strong>Feedback</strong></td>
</tr>
<tr>
<td>Provide the user with feedback and error-correction capabilities.</td>
</tr>
<tr>
<td><strong>Interaction load</strong></td>
</tr>
<tr>
<td>Minimise the effort that is required for dialogue actions.</td>
</tr>
</tbody>
</table>

An example application of the cognitive engineering framework resulted in a prototype user interface with the online procedures integrated into the operation display, and with consistent navigation support in procedure and operation interface components. A controlled experiment showed that the integration and the navigation-support enhance the efficiency of payload operations substantially as a first validation of this example interface design (Table 6).

**Table 6:** Summary of the test results on the four usability measures.

<table>
<thead>
<tr>
<th>Measures</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Effectiveness</strong></td>
<td>76 percent of the VCP-tasks was performed correctly.</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>Faster task performance in the integrated than in the non-integrated conditions.</td>
</tr>
<tr>
<td></td>
<td>Fewer payload operations needed for the tasks in the integrated than in the</td>
</tr>
</tbody>
</table>
non-integrated condition. Fewer payload operations needed with navigation support.

Satisfaction Participants were positive on the usability with comments on details.
Learnability With navigation support, the *effectiveness* was worse in the pre-test, but increased over time to the “without level” in the post-test. With navigation support, the *efficiency* was better in the pre-test, but similar to the “without level” in the post-test.

A web-based handbook presents the framework and the example design, providing on-line guidance for the distributed ISS development teams. A user needs’ analysis showed that the handbook concept fits with the usability guidance needs for crew interface development processes, and provided requirements for improving the handbook’s content and accessibility.

![Figure 11: Main menu of the usability handbook](image)

### 5.2.3 Discussion

The investigations described in this section primarily concentrated on the demonstration of human-factors support and design objectives in complex monitoring & control tasks, within the general cognitive engineering framework described in Chapter 4.
In the first place, information transfer to the human operator may be improved by considering some basic cognitive support principles, based on general characteristics of human information processing. Also in the process control domain, at various levels of interface design, many of the problems encountered can be traced back to system designers and system users having a different notion of what is functional for a particular application. Therefore, an important design objective to be considered here is the information presentation and coding to be compatible with user or task concepts and human capacities. Within this scope, the studies have illustrated the role of experimental human-factors research, in demonstrating that information transfer to the human operator indeed can be improved by the human interface, e.g. by facilitating the access to the required diagnostic information in the process control system.

In the second place, besides operator decision support, support of the user-interface design team on general usability aspects is considered to be essential in complex task domains, to achieve a consistent overall design, compatible with different end-user needs and characteristics.

5.3 Design of Training

Naval ships are equipped with a large number of systems with a combat function, varying from sensor systems (radar, sonar) to weapon systems (guns, missile launchers) and communication systems (computers). In order to maintain optimal combat readiness, it is essential that the integrity of these systems is maintained at all times. The Weapon Engineering Service is responsible for this task. The weapon engineers on board carry out periodic preventive maintenance, much like car mechanics do when you bring your car to a garage at certain intervals, as well as corrective maintenance, that is, troubleshooting in case a malfunction occurs. The corrective maintenance task is carried out under high time pressure, particularly under operational conditions. Often, the command team is waiting anxiously for the weapon engineers to find the fault and bring the defective system back to operational status. It is therefore essential that the weapon engineers are well trained and are able to troubleshoot effectively and efficiently.

About ten years ago, complaints started to emerge from the operational Dutch fleet concerning the speed and accuracy of the weapon engineers. At a macro level, a number of reasons could be given for the apparent sub optimal performance of the engineers. First, expert trouble-shooters are in high demand in the civilian world, and a sizable number leave the Navy each year. Second, fewer candidates for the weapon engineering branch are entering the Weapon Engineering School. Whatever the precise reasons, the Royal Netherlands Navy asked TNO Human Factors around 1990 to look at these complaints and come up with possible solutions to the problems. In this process, we have used multiple techniques. In understanding the domain, we have, of course, resorted to documentation analysis and interviews. We firmly believe, however, that what has made this project convincing and successful has been our collection of empirical data. Several techniques were used for behavioural observation.

5.3.1 Observational studies of real-life tasks

As a starting point, it is often very useful to observe experts perform the task they are familiar with. However, added value is provided by introducing a quasi-experimental manipulation, for instance by using experts with different perspectives or backgrounds or areas of expertise, and by
contrasting expert with novice performance. In our radar observation study, for instance, we observed both theory and practice instructors, and experts with varying familiarity with a particular radar system. This study yielded as important insights that possessing theoretical knowledge was not sufficient for good troubleshooting, and that, presumably due to training practices, there was no such thing as “general radar knowledge”.

5.3.2 Use of verbal protocols

We made extensive use of verbal protocols in our observation studies. Analysis of the verbal protocols was greatly facilitated by a generic model for troubleshooting, decomposing the task into the subtasks: ‘formulate problem description’, ‘generate causes’, ‘test’, and ‘evaluate’. We also used the verbal protocols for the assessment of troubleshooting performance by experts.

5.3.3 Controlled experiments

In order to assess whether our proposed training innovation actually had the intended effect, we conducted a number of controlled experiments. These were not laboratory experiments with artificial tasks. Rather, they were experiments under naturalistic conditions with the stimuli (faults) under control. This allowed us to obtain quantitative data on the effectiveness of the different courses we compared. For practical purposes, these data have served us well in convincing others of our approach to innovating training courses.

Interestingly, the most challenging and still ongoing task has been the domain modeling. Troubleshooting as a behavioural activity is more or less the same, regardless of the particular equipment. However, our approach places a lot of emphasis on modeling the equipment at a functional level. This part has also been difficult to convey to the technicians themselves, who tend to confuse functions and design. After having applied the functional decomposition technique to various systems, we have discovered that there is not one model that fits all. Rather, there are, at least, causal models and component models; moreover, the electronic and mechanical parts of a system each require a different approach to modeling. In sum, our experience reflects Simon’s (1981) parable of the ant: the apparent complexity of behaviour is a reflection of the complexity of the environment, not of the human.

5.3.4 Results

Combining the results of the several studies carried out, two conclusions can be drawn about the troubleshooting performance of beginning technicians:

- Beginning technicians lack a systematic approach in troubleshooting, resulting in a lack of goal-directed problem solving, and
- They lack a functional understanding of the equipment they have to maintain.

As a result, several recommendations for the training of “Structured Troubleshooting” have been put forward:
The training of a systematic approach to troubleshooting should be embedded in regular training courses, in such a way that this systematic approach becomes "second nature" for technicians. This is a different approach to the training of troubleshooting than taken by, for example, Kepner and Tregoe (1966). These authors claim it is possible to train a systematic approach to troubleshooting independent from any specific knowledge of equipment. Recent research in cognitive psychology has shown, however, that general strategies are ineffective when trained in isolation, that is, separated from domain-specific knowledge (Singley & Anderson, 1989). We have demonstrated the same in the domain of troubleshooting (Schraagen & Schaafstal, 1996).

The theory incorporated in training courses, and the relation between theory and practice should be geared towards the job, and should be very much fine-tuned to the task that technicians have to fulfil in their daily routine. The training should be geared towards the acquisition of troubleshooting skill, and the necessary knowledge of the equipment should be related to the acquisition of this troubleshooting skill, and should not be isolated.

The knowledge of equipment should be taught at a functional level, not at a component level.

### 5.3.5 Discussion

The practical implications for the training of troubleshooting in technical systems have been the following. Training designed and given according to the principles of Structured Troubleshooting results in an enormous performance improvement. On the basis of this, the Naval Weapon Engineering School has taken this method as the basis for the design of all their courses, resulting in a more practice-oriented and job-oriented training, with less emphasis on the detailed functioning of equipment and its components, but with much more emphasis on the actual skill of troubleshooting. Now that a large number of training courses on a variety of systems have been redesigned according to this method, we have even more convincing results about the validity of the method. Almost all courses that have been redesigned have resulted in good troubleshooting performance and substantial reductions of training time, 30% on average with sometimes reductions up to 60%. During this process of redesign we acted as consultants, and take the experiences we obtained with us for the design of guidelines with respect to the implementation of Structured Troubleshooting. Certain parts of the method are easier to grasp for training designers than others. In general, it takes them time to design functional schemata for systems. This is understandable, since it requires "self-elicitation of knowledge". Second, they are so much used to training design on the basis of available documentation, that learning to think in terms of task analyses, is also difficult. Finally, there are all sorts of (administrative) procedures that should be adapted to fit the new scheme of training design. However, after they have gone through the process of redesign, instructors feel that their students are better trained for the job situation and have better skills.

Structured Troubleshooting is also useful in civilian (process) industry. First of all, Structured Troubleshooting makes the process of troubleshooting explicit. Hence, companies can show their clients how their technicians troubleshoot. Second, technicians can more easily communicate with each other and learn from each other when they record their troubleshooting on the fault isolation form that we have developed as part of Structured Troubleshooting. Finally, Structured Troubleshooting leads to faster and better performance. Ultimately, this saves a lot of money.
6 Tools & Techniques

6.1 Requirements

Technological advances like the ones taking place in the area of integrated monitoring & control will interpose new information handling and display devices between the operator and the rest of the system. Those developments may lead to an increase of both the amount of information presented to the operator and the information “density” per area of the human-machine interface. At the same time, as stated earlier, progress in “automation” has driven the functions performed by humans increasingly towards monitoring, supervising and decision making. Therefore, it is generally assumed that new advanced systems may place high demands on the cognitive aspects of operator behaviour and reduce demands on other human capabilities. Thus, regarding the human-machin interface of such systems, it is essential to maintain an operator-centred design philosophy to overcome limitations, enhance abilities and foster acceptance. In this chapter, available analysis and design techniques according to this operator-centred approach will be listed.

6.2 Human engineering analysis techniques

This survey of techniques is largely based on the work of NATO RSG 14 on analysis and design techniques for man-machine systems design (Beevis, 1992).
In parallel to the essential steps as commonly encountered in systems engineering, human engineering analysis techniques may be ordered according to the following design steps in manned systems design:

- Mission and Scenario Analysis
- Functional Analysis
- Function Allocation Analysis
- Task Analysis
- Performance Prediction
- Interface and Workspace Design

Following this approach, operational needs for the human-machine system are transformed into the specification of the human-machine interface and workspace, following a series of steps involving analysis, synthesis, trade-off studies and simulation and test. First, by analysing the mission, system functions are determined. The analysis of systems functions leads to functional requirements which are the basis for allocating the functions to humans and machines. The detailed function analysis identifies the task performance required from the operator and the required machine processes. Finally, the analysis of the operator tasks and machine processes provide the data for the design of the operator workstation and work environment. Further, this
design process should be iterative, meaning that mission and function analysis, allocation of functions and determination of tasks and interface requirements may be repeated several times.

6.2.1 Mission and Scenario Analysis

Techniques for mission and scenario analysis describe the overall requirements of the system under development, in terms which provide information for subsequent human engineering analyses. They are used to describe what the system must do (the operational requirement) and the circumstances and environment in which it must be done.

For high complexity systems, two basic types of analyses were identified:
- Narrative mission descriptions, providing a written or point form of a mission,
- Graphic mission profiles, which provide the mission information in graphic form.

6.2.2 Function Analysis

Function analysis is a necessary step in systems engineering, leading to systems synthesis, trade-off studies and a system description. It consists of analysing the system in terms of the functions which must be performed, rather than in terms of specific sub-systems. Function analysis is hierarchical in nature, and proceeds in a top-down fashion. Each phase in the analysis is the basis for the analysis in the subsequent phases.

The main types of function analyses used in human engineering for the analysis of complex systems are:

Function Flow Diagrams – FFDs
Function flow diagrams identify the sequential relationships of the functions required to perform the mission and operations analysed in the mission and scenario analysis. They are developed at an increasing level of detail, down to the level where specific tasks can be identified for performance by hardware, software or human operators.

Behaviour Graphs
Behaviour graphs are combined control and information flow graphs for describing system behaviour within the Requirements Driven Development (RDD) systems engineering methodology. The graphs show system behaviour explicitly as a function of time. The data flow is shown on the horizontal axis and time on the vertical axis. The graphs are used for function analysis at the system level and for scenario modelling.

6.2.3 Function Allocation Analysis

Function allocation analysis, assigning functions to people (liveware), hardware or software, provide the basis for subsequent efforts relating to crew or operator task analysis and description, operator performance analysis, display and control selection or design and crew-station design, development and evaluation.
For the design of complex systems, three techniques have been identified having “medium” applicability:

**Review of potential operator capabilities**

The review of potential operator capabilities documents those abilities of expected system or equipment users which are relevant to the operation of the system. The technique requires information on the expected operator population and potential roles, duties and functions. Further, detailed in formation is required on operator capabilities to perform those functions.

**Function allocation evaluation matrix**

The technique sums weighted scores of human and machine capabilities to make function allocation decisions. The form used to record these comparisons is called a *function allocation screening worksheet*.

**Requirements Allocation Sheets**

Requirements allocation sheets (RAS) are used to translate functions into performance and design requirements. For each function identified, the corresponding RAS describes the purpose of the function, parameters of the design, design constraints and requirements for (human) performance.

### 6.2.4 Task Analysis

In the context of human engineering, a task is defined as a system function that has been allocated to a human operator. Task analysis, the analysis of these tasks, is one of the most common activities of the human engineering specialist. There are two major goals of task analysis: one is to define what an operator will be required to do, to permit the application of knowledge on human performance; the other goal is to define what an operator will do in order to determine how he or she will interact with the rest of the system. A completed task analysis specifies the activities of the operator.

For the analysis of tasks in high-complexity systems, the following techniques have been identified:

**Operational Sequence Diagrams**

Operational Sequence Diagrams provide a graphic presentation of the flow of information, decisions and activities in a system, using a set of five basic graphic symbols and an associated grammar. The technique is tailored for the representation of the flow of information, with symbols for the transmission, receipt, processing and use of previously stored information. The diagrams show the sequence of tasks or actions in a vertical sequence: they can be annotated with time information or a time line.

**Critical Task Analysis**

This technique analyses “critical” operator tasks in detail according to a specified standard. The standards require these tasks to be decomposed to the sub-task level and subjected to a detailed analysis. The analysis is performed in terms of the information required, perceptual load, decision(s) taken, action taken to implement the decision, feedback provided as a result of the
action, communication with others, and any constraints of the interface, workspace and environment.

6.2.5 Performance Prediction

Techniques for performance prediction are used to predict or analyse how well operators will perform their assigned tasks once these have been defined by the techniques surveyed in the previous sections. Performance prediction is related to interface and workspace design, since estimates of human performance are dependent on the features of the human-machine interface.

In general, approaches to describing human performance may include real world observations, field studies, man-in-the-loop-simulator studies, rapid prototyping, laboratory experiments and pure computer-simulation studies including simplified representations of human behaviour.

The first two approaches, which are relevant to both new and old systems, have the common drawback that they fail to consider and control an unknown number of variable factors which affect behaviour. Obviously, the conditions in which real world observations and field studies are made are very close to actual operations. This is true to a lesser extent for simulator studies. Generally, these approaches (real world observations and field trials) are suited to description and analysis of the mission, incidents and accidents and the operator’s activities.

Simulator and laboratory experiments are aimed at prediction of performance for routine and emergency conditions, for instance to test different interface concepts. However, these techniques may have the drawback of doubtful generalisation from the artificial test conditions to reality. Therefore, from a methodological point of view, there would be an optimum in simulator experiments, which have sufficient representation of the real world to generalise results for practical conditions and are sufficiently controlled to allow the interpretation of results. This type of experiment offers the opportunity to judge human variance in performance relative to the variance due to the use of alternative pieces of equipment, procedures, etc.

Rapid prototyping involves the use of representations of human-machine interfaces in quasi-realistic scenarios. This technique will be further elaborated in the next section.

6.2.6 Interface and Workspace Design

The final goal of the human engineering analyses as described here is to identify design requirements and to facilitate the application of human factors knowledge to the design of systems and equipment.

Two techniques have been reported by RSG 14, applicable to the interface design of complex systems:

Critical design requirements
The technique identifies design requirements which are critical to the operation of the system, to provide a basis for interface and workspace design. The technique identifies the following information:

- The functions performed by the system
- The operator tasks
- The outputs of each task
- The critical operating variables for each task
- The critical design requirements that affect these variables

The critical operating variables, or the design requirements identified by the analysis, may be weighted to facilitate evaluation of competing design concepts.

**Link Analysis**

Link analysis is a technique for evaluating and improving the layout of equipment and the operator-machine interface by minimising the “costs” associated with transitions between different items of equipment or different components of the interface. It is concerned with the relative positions, frequencies and importance of use of the different components, and how their use can be arranged most effectively. It can be applied to the layout of a specific human-machine interface, or to the layout of a crew compartment for several operators and items of equipment. Using the technique, the links are charted as a to-from matrix, noting the frequency and/or strength or importance of the links.

**Rapid Prototyping and User Interface Management Systems (UIMS).**

Besides the two previous analytical techniques to derive interface design requirements, in the computer science and human-computer interaction communities there is a growing emphasis on the use of Rapid Prototyping and User Interface Management Systems (UIMS). These tools permit the rapid creation and modification of the human-machine interface without the need to realize the complete underlying application software or hardware. However, most rapid prototyping tools require support facilities and application specific software to represent mission scenarios and operation dependent aspects of the human-machine interface, such as maps and mission event generators. The prototype interfaces primarily serve to enhance communications and feedback between designers and users. The rationale for rapid prototyping is that system interactions and user requirements cannot be predicted completely. It is argued that it is more effective to produce the equivalent of a dynamic mock-up and study how prospective users interact with the system, then modify it and thus develop it iteratively, rather than to analyse all requirements exhaustively. However, in this process care should be taken that evaluations are reduced to little more than judgements of appearance, rather than as an evaluation of functionality. Overall, what appears to be required is a task analytical approach which represents what the operator will be doing with a new system, coupled with a “usability analysis” which indicates how the user expects the system to behave, followed by prototyping and rigorous evaluation. A straightforward example in this field is the (partial) replacement of traditional wooden mock-ups by a virtual environment using 3D modelling techniques. In this way, design and user-based evaluation of, for instance, a particular bridge layout may be performed in a more iterative way, taking maximum advantage of the flexibility offered by these techniques.
For the actual development of user interfaces (prototypes), several software packages are available. Some of these COTS development tools are platform independent, others are platform dependent. A general classification scheme for these user interface development tools or components is the following:

- **UIDT**: User Interface Design Tools; Editors for designing user interfaces and user interface components
- **UIMS**: User Interface Management System; More advanced. Functionality of UIDT, plus interactive testing of code
- **VID**: Virtual Instrument Designers; Specialised UIDT with special widgets for virtual instruments
- **LIB**: Library for user interface components; Collection of specialised software components that can be used by programmers.

### 6.2.7 Summary

Table 7 below provides a summary to aid selection of appropriate Usability Engineering techniques, given the system development stage.

**Table 7: Summary of Usability Engineering techniques**

<table>
<thead>
<tr>
<th>Development stage</th>
<th>Human factors principles and guidelines</th>
<th>Specification techniques</th>
<th>Assessment techniques</th>
<th>Technological design space</th>
</tr>
</thead>
</table>
| **Task Analysis**  | - user adaptation  
                    | - goals conformance  
                    | - information needs conformance  
                    | - user’s complement  
                    | - use context  
                    | - task decomposition  
                    | - task allocation  
                    | - task features  
                    | - data model, flows  
                    | - scenarios, use cases  
                    | - action sequences  
                    | - UI requirements  
                    | - task load analysis  
                    | - interaction analysis  
                    | - UI requirements validation  
                    | - technical support to supply information  
                    | - technical support to support functionality  |
| **Prototype Design** | - compatibility  
                      | - consistency  
                      | - memory  
                      | - structure  
                      | - integration  
                      | - feedback  
                      | - interaction load  
                      | - individualisation  
                      | - sketching  
                      | - story-boarding  
                      | - user interface structure  
                      | - prototyping  
                      | - expert review  
                      | - user walkthrough  
                      | - thinking aloud  
                      | - constructive interaction  
                      | - user test  
                      | - portability  
                      | - efficiency  
                      | - maintainability  
                      | - strategy of software control  
                      | - strategy of data storage  
                      | - hardware selection  |
6.3 Alarm management

Alarm management is a wide issue about assuring the human response to an alarm and not just for continuous processes with distributed control systems. It applies equally to small major sites where reliance is placed on human response to alarms (e.g. tank storage). An important problem is that addition of alarms have apparently small costs for engineers, leading to large alarms lists and fast rates of alarm activation (“alarm flood”). Safety-related alarms require particular attention with respect to careful system design, display, operator training and integrated support systems. An appropriately configured alarm system can minimize the impact of plant upsets on profitability and significantly improve plant safety and environmental impact.

6.3.1 Quality Management

To support total quality management, the DMAIC (define-measure-analyze-improve-control) framework was developed. In order to implement a fundamental alarm management rationale, the DMAIC process intends to provide a systematic methodology for sustainable improvement (see Table 8)

1. Define: determine desired performance measure
2. Measure: establish metrics and collect data
3. Analyze: benchmarking and determine solution alternatives
4. Improve: implement solution
5. Control: validation and cost-benefit analysis

Table 8: Alarm management performance levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Selection Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overloaded</td>
<td>Alarm system is difficult to use during normal operation and in practice ignored during plant upset as it becomes unusable.</td>
<td>Overall operator loading including collaboration with field operations, maintenance, and other activities.</td>
</tr>
<tr>
<td>Reactive</td>
<td>Alarm system is more stable and useful during normal operation, but is often</td>
<td>Consequences of failure to act &amp; required response time.</td>
</tr>
</tbody>
</table>
6.3.2 Guidance for Improving Alarm Management Practices

The Engineering Equipment & Materials Users Association (EEMUA) developed a guide on alarm systems (“A Guide to Design, Management and Procurement”, EEMUA Publication No. 191) with a major contribution of the British Health & Safety Executive (HSE). It is written for engineers and managers and intended to stimulate discussion and encourage industry to develop its principles to meet specific safety applications. The guide distinguishes the following central design principles:

- Each alarm should alert, inform and guide
- Every alarm presented to the operator should be useful and relevant to the operator
- Every alarm should have a defined response
- Adequate time should be allowed for the operator to carry out the defined response
- The alarm system should be explicitly designed to take account of human limitations

The guide “Better Alarm Handling” of EEMUA is written as a practical guide for a wide audience and intended to improve uptake of the EEMUA guide. It describes a simple 3-stage approach: (1) find out if you have a problem, (2) decide what to do and take action, and (3) manage and check what you have done.

In the first stage, the assessment of the current situation refers to alarm rate targets. The long-term average alarm rate during normal operation should be no more than one every ten minutes; and no more than ten displayed in the first ten minutes, following a major plant upset (p. 37, EEMUA guide). Operators, safety representatives and managers should be asked for their experiences and current approaches (policies, strategies, standards, …). Additional questions should center around how new alarms are being managed (e.g. in HAZOP sessions) and how human factors are being taken into account. In the second stage, an adequate team should be formed, including technical, operational and safety representatives. Implement some quick and relatively easy technical solutions that can provide immediate benefits for the operators (see EEMUA guide), establish operating team competency, and provide operators with sufficient help and support to respond effectively to alarms. In the third stage, draw up a company or site alarm strategy and standard, including formal audits, reviews, etc.

6.3.3 Design principles

<table>
<thead>
<tr>
<th>Stable</th>
<th>Alarm system is well defined for normal operation, but less useful during plant upsets with improvements in both the average alarm and peak alarm rates as compared to reactive.</th>
<th>Complexity and interactive nature of process units – what is the collateral/tangential disturbance propagation impact?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robust</td>
<td>Alarm system is reliable during all plant modes, including normal operation and plant upsets.</td>
<td>Peak loading scenarios with realistic probability of occurrence (e.g., start-up, disturbances, transitions, failures, etc.)</td>
</tr>
<tr>
<td>Predictive</td>
<td>Alarm system is stable at all times and provides the operator with the right information at the right time to avoid process upset or minimize the impact of any upset that does occur.</td>
<td>Criticality of this specific plant operations in the context of overall site operations</td>
</tr>
</tbody>
</table>

unusable in practice during plant upsets.
Neerincx (2003) distinguishes the following relevant design principles:

1. Due to the increasing availability of information, situation awareness can deteriorate without support. Sensor information should therefore be combined into alarms that are structured according to their function, such as fire control, propulsion and energy supply.

2. The user interface should provide an overview of state and process variables, showing the correspondence to system's components (i.e. structure) and the fluctuations in time (history).

3. Alarms should be prioritised according to the current situation and provide information about how to (start to) solve the problem. Important alarms should stand out and irrelevant alarms should be hidden.

4. The support should enable fast and easy access to the requested information with adequate orientation cues and state explanation. It should correspond to the optimal search strategy for the specific task and situation, i.e., support several accurate information acquisition processes of users.

General guidelines on when to use auditory or visual signals are given in Table 9. See for specific criteria with regard to frequency and level of auditory alarm signals ISO 7731: ‘Danger signals for work places--auditory danger signals’. For other more detailed guidelines and standards we refer to annex 1 Standards & Guidelines.

**Table 9: When to use the auditory or visual form of presentation (Deatherage, 1972).**

<table>
<thead>
<tr>
<th>Use auditory presentation if:</th>
<th>Use visual presentation if:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The message is simple</td>
<td>The message is complex</td>
</tr>
<tr>
<td>2. The message is short</td>
<td>The message is long</td>
</tr>
<tr>
<td>3. The message will not be referred to later</td>
<td>The message will be referred to later</td>
</tr>
<tr>
<td>4. The message deals with events in time</td>
<td>The message deals with location in space</td>
</tr>
<tr>
<td>5. The message calls for immediate action</td>
<td>The message does not call for immediate action</td>
</tr>
<tr>
<td>6. The visual system of the person is overburdened</td>
<td>The auditory system of the person is overburdened</td>
</tr>
<tr>
<td>7. The receiving location is too bright or dark adaptation integrity is necessary</td>
<td>The receiving location is too noisy</td>
</tr>
<tr>
<td>8. The person’s job requires him or her to move about continually</td>
<td>The person’s job allows him or her to remain in one position</td>
</tr>
</tbody>
</table>

**6.3.4 User Interface Framework for Integrated Alarm Handling and Maintenance Support**

The Supporting Crew OPERations (SCOPE) framework, developed in the space domain, integrates several task support services into a transparent user interface: context-specific procedures, multimedia information access, virtual control panels, alarm management and diagnosis guidance (Bos et al., 2004). The combination of services improves routine and non-routine operations, and enhances the availability and deployment of complex equipment.
dealing with anomalies, SCOPE detects system failures, guides the isolation of the root causes of failure, and presents the relevant repair procedures in textual and graphical formats. In this way, the diagnosis process is a joint operator-SCOPE activity: when needed, the system asks the operator to perform additional measurements in order to help resolve uncertainties, ambiguities or conflicts in the current system status model. As a “best practice”, a SCOPE prototype was developed. Usability tests showed effective and efficient user performance, and high user satisfaction.

6.4 Staffing requirements

6.4.1 Assessing the safety of process operations staffing arrangements
This method assesses the adequacy of staffing arrangements for normal and more particularly abnormal and emergency situations and was developed by Helen Conlin whilst at Entec UK Ltd. In conjunction with Philip Brabazon. The technique facilitates assessment of a complex issue drawing on Human Factors research into process control and socio-technical systems thinking which acknowledges that operator performance is influenced by deeper organisational and management factors. The method has been developed in collaboration with industry and the UK Health and Safety Executive (HSE) to ensure it provides a coherent and practical framework for understanding and appraising factors that significantly influence the safety of staffing arrangements. The method demystifies staffing and in most circumstances an operations team can apply it confidently without recourse to specialist support.

The method comprises two stages:
1. Physical assessment – this is a fundamental check that it is feasible for staff to detect, diagnose and recover from representative scenarios, including major accident hazards, in time. It requires demonstration of the reliability of critical control measures (hard and soft).
2. Ladder assessment – these assess the management of individual and organisational factors influencing staffing arrangements effectiveness in normal and more particularly abnormal situations, and their sustainability.

The method seeks to assess ‘reality’ by requiring the involvement of operators, line management, key specialists and the use of historical examples and documents to give supporting evidence. Therefore several views, that may differ, of the staffing arrangements and their management are combined.

More details and contact address of Helen Conlin are found in Annex 2 and on the website:

6.5 Conclusions

The Cognitive and Functional (COLFUN) framework for envisioning and assessing such high-demand situations helps to realize an adequate human resource deployment (Neerinck et al. 2003; annex 3). In general, COLFUN supports the integration of human factors in the iterative development process of complex human-machine systems. The framework consists of two models, a cognitive load model and a functional model, that support a coherent scenario analysis of the task demands and information flows. Annex 4 provides a questionnaire that is based on the
load model. The COLFUN framework supported the identification of critical situations and provided concrete proposals for improvement of procedures, support systems, manning, organization and training. Annex 3 discusses two example assessments in early development processes: a traffic-control-center analysis and a task analysis for a naval ship’s bridge. Both analyses supported the development and refinement of operating procedures, support systems, manning schemes, work organization and training requirements.

7 Links to Safety culture and Organisational factors

Focus Group 1 of the PRISM project concerned 3 topics: safety culture, behavioural safety and teamworking. Safety culture is now generally accepted as a “good thing” to have, and there is a growing consensus about the main features of a positive safety culture. The links between safety culture and organisational and occupational accidents are becoming increasingly clear. Again, this was concluded during the second FG3 seminar, in which the importance of an alarm philosophy within the whole organisation was emphasised (See Annex 5 for seminar conclusions). A local plant’s safety culture is likely to be influenced by national cultural differences, but this does not mean incoming organisations cannot develop their own safety cultures. Rather, they will have to take into account existing national cultural influences as they develop their own.

The HSE developed a method to guide employers responsible for major hazards through the process of organisational change and its impact on their control of hazards:

“Organisational change is often an opportunity to improve health and safety, for example though reappraisal of safeguards or clarification of personal accountabilities. However, HSE’s experience is that in many instances organisational changes are not analysed and controlled as thoroughly as plant changes, resulting in reduced defences against major accidents, sometimes with fatal consequences (as in the Hickson & Welch incident). This is because, unlike management of plant change, impacts of organisational change are less well understood, and there is a lack of robust, generally accepted approaches to ensuring safety. This guidance aims to help employers manage change that impacts on health and safety.”

The guidance sets out a three-step framework:
Step 1 - Getting organised for change
Step 2 - Assessing risks
Step 3 - Implementing and monitoring the change

Details of this method are found on the HSE information sheet that is found on their website: http://www.hse.gov.uk/pubns/chis7.pdf

8 General discussion and Conclusions

The previous chapters showed that the COLFUN framework offers a tool for a structural analysis of operator tasks, while at the same time the cognitive task load can be measured systematically. The first seminar confirmed this, although some refinements were necessary (see Annex 5). Where other methods maintain a macro level approach (e.g. cultural and organisational aspects) or a micro level approach (e.g. perception and detection), this framework approaches the safety problem from in intermediate level. Together with the identification of
critical situations, the framework helps to identify possible solutions in the area of procedures, support systems, manning and organisation. By offering the right (decision) support tools, performance of the operator can be improved.

Besides that, the information presented by these tools must be detected and comprehended by the operator at the right time. Therefore, the information presentation and coding should be compatible with user or task concepts and human capacities. This can be realised by considering some basic cognitive support principles, based on general characteristics of human information processing. Chapter 6 shows some useful tools and techniques to facilitate this process.

Performance of human operators also depends on applying suitable training methods. Structured Troubleshooting is a method that makes the process more explicit, facilitates the communication and exchange of knowledge between technicians and it leads to faster and better performance.

The chances of success, however, are highly dependent on the safety culture within a company. As concluded in the second seminar (Annex 5), a safety philosophy must be present at all levels of the organisation. If this is not the case, changes at a lower level (e.g. alarm handling) might be just a fight against symptoms, and safety measures at a high level might never affect the actual situation at the working floor.
9 References

Alarm systems, a guide to design, management and procurement, Engineering Equipment & Materials Users Association Publication No 191. Available from EEMUA.


Better alarm handling (Chemicals Sheet No. 6), information sheet available from HSE website at www.hse.gov.uk/pubns/chis6.pdf


Ergonomic design of control centres, Parts 1-7, ISO 11064 Covers design principles, control room arrangements and layout, workstations,. displays, controls, interactions.,temperature, lighting, acoustics, ventilation, and evaluation


Annex 1: Standards & Guidelines

Standards

In Europe, the European Directive 90/270/EEC on display screen equipment addresses minimum requirements necessary to meet objectives for the usability of operator-computer interfaces. These requirements refer to general issues like 'suitability for the task', 'easy to use' and 'applying principles of software ergonomics'. Although these issues seem rather vague, standards are under development by international organisations like the International Organisation for Standardisation (ISO) which may serve as a reasonable alternative for demonstrating compliance with good ergonomics practise. The general consensus is that these ISO standards will become the most likely candidates for future international standards. ISO comprises 107 countries all over the world, including the USA. Wherever appropriate, ISO standards are adopted by the European Standardisation Organisation (CEN) as part of the creation of the Single Market. CEN standards will also replace national standards in the EC and EFTA member states (e.g. DIN, BS and NEN). Furthermore, ISO or its European equivalents are often referenced to by EC member states to implement the obligations placed on them by the European Directive 90/270/EEC on ergonomic requirements for display screen workstations. In doing so the member states transpose these obligations into appropriate national laws and regulations. So, the message is, that the best strategy is to focus on the ISO standards.

ISO standards

Designing man-machine systems
ISO 6385:2004  Ergonomic principles in the design of work systems
ISO 13407:1999  Human-centred design processes for interactive systems

Mental load
NEN EN 614-2  Safety of machinery - Ergonomic design principles - Part 2: Interactions between the design of machinery and work tasks
ISO 9241-2:1992  Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 2: Guidance on task requirements
ISO 10075:1991  Ergonomic principles related to mental work-load -- General terms and definitions
ISO 10075-2:1996  Ergonomic principles related to mental workload -- Part 2: Design principles

Control centres
ISO 11064-1:2000  Ergonomic design of control centres -- Part 1: Principles for the design of control centres
ISO 11064-2:2000  Ergonomic design of control centres -- Part 2: Principles for the arrangement of control suites
<table>
<thead>
<tr>
<th>Standard</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 11064-3:1999</td>
<td>Ergonomic design of control centres -- Part 3: Control room layout</td>
</tr>
<tr>
<td><strong>Alarms</strong></td>
<td></td>
</tr>
<tr>
<td>ISO 7240-1:1988</td>
<td>Fire detection and alarm systems -- Part 1: General and definitions</td>
</tr>
<tr>
<td>ISO 7240-2:2003</td>
<td>Fire detection and alarm systems -- Part 2: Control and indicating equipment (available in English only)</td>
</tr>
<tr>
<td>ISO 7753:1987</td>
<td>Nuclear energy -- Performance and testing requirements for criticality detection and alarm systems</td>
</tr>
<tr>
<td><strong>Software</strong></td>
<td></td>
</tr>
<tr>
<td>ISO 9241-1:1997</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 1: General introduction</td>
</tr>
<tr>
<td>ISO 9241-2:1992</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 2: Guidance on task requirements</td>
</tr>
<tr>
<td>ISO 9241-3:1992</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 3: Visual display requirements</td>
</tr>
<tr>
<td>ISO 9241-4:1998</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 4: Keyboard requirements</td>
</tr>
<tr>
<td>ISO 9241-5:1998</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 5: Workstation layout and postural requirements</td>
</tr>
<tr>
<td>ISO 9241-6:1999</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 6: Guidance on the work environment</td>
</tr>
<tr>
<td>ISO 9241-7:1998</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 7: Requirements for display with reflections</td>
</tr>
<tr>
<td>ISO 9241-8:1997</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 8: Requirements for displayed colours</td>
</tr>
<tr>
<td>ISO 9241-9:2000</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 9: Requirements for non-keyboard input devices</td>
</tr>
<tr>
<td>ISO 9241-10:1996</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 10: Dialogue principles</td>
</tr>
<tr>
<td>ISO 9241-11:1998</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 11: Guidance on usability</td>
</tr>
<tr>
<td>ISO 9241-12:1998</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 12: Presentation of information</td>
</tr>
<tr>
<td>ISO 9241-13:1998</td>
<td>Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 13: User guidance</td>
</tr>
</tbody>
</table>
Guidelines

In the 80’s, the Graphical User Interface (GUI) became familiar to more and more users who did not have specific computer expertise. These interfaces were based on the ‘WIMP’-concept (Windows, Icons, Mouse and Pull-down/pop-up menus). In particular the direct manipulation, provided by WIMP-interfaces, was thought to improve the usability for non-expert users. In the 90’s, GUI’s are becoming widespread and a standard “look-and-feel” has been developing for user interfaces of different platforms (Mac, Motif, PM, Windows). Usability guidelines and style guides have been developed for these interfaces. Many of these guidelines are of a more or less overlapping nature (see, for instance, Williges et al., 1987 for a classification scheme or Smith & Mosier, 1986 for an extensive review of guidelines for software interface design).

Currently, a new development has been started. In Cern Swiss, a first version of a graphical user interface for hypermedia, the contraction of hypertext and multimedia, was developed for Internet, called Mosaic. Web browsers, such as Mosaic, can be used to search for multimedia information in databases via a network. New web browsers are being developed and used by more and more people (Netscape Navigator, MS Explorer). These browsers involve a new “look-and-feel” and standards are being set currently. As this technology is developing fastly, empirical-founded guidelines and style guides are hardly available.
Annex 2. Assessing the safety of process operations staffing arrangements

Assessing the safety of process operations staffing arrangements

This method assesses the adequacy of staffing arrangements for normal and more particularly abnormal and emergency situations and was developed by Helen Corbin whilst at Enlec UK Ltd. in conjunction with Philip Brabazon. The technique facilitates assessment of a complex issue drawing on Human Factors research into process control and socio-technical systems thinking which acknowledges that operator performance is influenced by deeper organisational and management factors. The method has been developed in collaboration with industry and the UK Health and Safety Executive (HSE) to ensure it provides a coherent and practical framework for understanding and appraising factors that significantly influence the safety of staffing arrangements. The method demystifies staffing and in most circumstances an operations team can apply it confidently without recourse to specialist support.

The method comprises two stages:

1. **Physical assessment** – this is a fundamental check that it is feasible for staff to detect, diagnose and recover from representative scenarios, including major accident hazards, in time. It requires demonstration of the reliability of critical control measures (hard and soft).

2. **Ladder assessment** – these assess the management of individual and organisational factors influencing staffing arrangements effectiveness in normal and more particularly abnormal situations, and their sustainability.

The method seeks to assess ‘reality’ by requiring the involvement of operators, line management, key specialists and the use of historical examples and documents to give supporting evidence. Therefore several views, that may differ, of the staffing arrangements and their management are combined.

The table below shows the level of interest in the method since the first consultation seminar was held in September 2000. The HSE Contract Research Report (CRR 348/2001) was published in June 2001.

<table>
<thead>
<tr>
<th>Number of companies interested</th>
<th>Country</th>
<th>Industries</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>UK</td>
<td>Chemical, Oil and Gas, Insurance, Legal, Water, Marine, Rail, Nuclear, Trade Associations (including CIA)</td>
</tr>
<tr>
<td>2</td>
<td>Switzerland</td>
<td>Insurance, Research</td>
</tr>
<tr>
<td>1</td>
<td>Sweden</td>
<td>Oil and Gas</td>
</tr>
<tr>
<td>3</td>
<td>Australia</td>
<td>Oil and Gas, Chemical, Water</td>
</tr>
<tr>
<td>1</td>
<td>Canada</td>
<td>Oil and Gas</td>
</tr>
<tr>
<td>1</td>
<td>USA</td>
<td>Oil and Gas</td>
</tr>
</tbody>
</table>

The method achieved second place in the 2001 IChemE Severn Trent Safety Award and an article written for ‘The Chemical Engineer’ in October 2000 titled ‘Safe Staffing Levels: won the IChemE Safety & Loss Prevention Subject Group’s Frank Lee Medal 2000. Some feedback from sites who have applied the method plus HSE inspectors and industrial representatives involved in the method’s development, is appended.

The method’s objective is to minimise the likelihood of process related accidents which could harm employees, neighbours, environment and shareholders. The technique uncovers shortcomings in staffing arrangements and proposes means of reducing residual risks. It is fundamental to the...
method that the health and welfare of staff essential for safe operation of plants is protected and sustained, and that the effectiveness of management controls is demonstrated.

A 'benchmark' of acceptable achievement for elements is given to assist the demonstration of ALARP. The design of the ladders and physical assessment trees help companies to identify and evaluate improvements to their performance. Therefore wide uptake and application has the potential to improve standards across industry.

An objective implicit in the method is to reduce accidental releases to the environment by avoiding emergency shut-downs, de-pressurising, venting or flaring and through having sufficient control to perform orders, safe shut-down when necessary but preferably having the system (organisational and technological) capability to maintain plants within normal operating parameters.

In essence the method assesses the effectiveness of a defined group of people and hardware which has to respond to stimuli and carry out a defined series of tasks within a specified time-scale. The feasibility of the tasks being physically completed is assessed along with the management and organisational controls that influence and shape the team's ongoing performance.

With some modification it is anticipated the method can be applied in other operational environments such as Power Stations, Electricity and Gas Grids, Railway signalling centres and offshore installations.

Feedback from Industry and HSE

Industry users comments
- "Has changed the way I think about introducing changes in staffing arrangements."
- "The methodology has led me to think about issues I would otherwise not have considered relevant."
- "The methodology demonstrates the benefits which can be derived from using desk top exercises both in terms of developing understanding and highlighting areas of concern and weakness."
- "Pilot study was a useful exercise and aim to implement the recommendations and would like to apply methodology to other areas of the site."
- "We have now identified several action items from the assessment process and we think the process is very useful, as much in changing the way we look at human-factors related issues, as in other ways."

HSE Inspectors involved in piloting the method comments
- "Excellent bullet points on ladders."
- "Good for making you think about the issues."
- "Liked ladders a lot."
- "Particularly keen on the training and development ladder and thought it was very good."
- "Found the ladders easy to use."
- "Did not need any help with the ladders and thought the anchors were good."
- "Would have found the method extremely useful when regulating in Scotland and would have saved a great deal of time and effort by asking the right questions in a systematic way and focussing on the issues and things to look for."
- "Definitely see it as a self-assessment tool that companies either do pro-actively or an Inspector issues due to concern."
“Pleased that the assessment has been widened to safe process operation rather than just looking at the de-manning issue because otherwise it would have limited the way Inspectors view it.”

“Could not think of additional issues that should be covered.”

“Method logical and unfolds.”

“Assessment of systems and organisation rather than the individual is correct (makes it sustainable).”

“Systematic approach is what is required and is trying to pin down an ephemeral problem.”

“It is a ‘managerial’ approach which is the HSE’s current focus.”

“It is fairly logical.”

**Case study participants comments**

- “Found exercise beneficial and the assessment process comprehensive.”
- Site Health and Safety Advisor commented that “in comparison to a recent corporate management audit, the staffing assessment ‘got inside people’s heads’ and both the anchors and physical assessment trees provided discrete measures to gauge themselves and set targets to aim for.”

**Industry seminar participants comments**

- “The ‘ladder’ principle is an easy concept to work with.”
- “The principles are easy to understand, but I feel that certain areas (e.g. physical assessment trees) require more explanation.”
- “The method is easy to understand as long as the definitions of what you are assessing are clear.”
- “It is a proactive approach to manning levels.”
- “Technical, individual and organisational factors all have an input into overall control room / operator interactions especially on COMAH sites.”
- “The method does not simply identify areas of unacceptable risk but is also looking for continuous improvements when looking at the ladders.”
- “Believe the method could be of benefit.”
- “I would like to apply the method on site following more training on the method.”
- “The method would seem to fit into the work that is already in progress.”

*The full report is available in HSE’s contract research report series Summer 2001 (CRR 348/2001).*

For further information about the tool please contact Helen Conlin, E-mail: ConlinH@Chemworld.com, Telephone: + 44 (0)1244 390690, Fax: + 44 (0)1244 398298
Annex 3: Cognitive and Functional (COLFUN) Framework

Introduction

Addressing Human Factors in the development processes of complex and dynamic human-machine systems is essential to enhance the human role in complex task environments. The human role in complex task environments will more and more focus on handling non-routine situations with increasing information velocity and ubiquity. This annex presents a generic Cognitive and Functional (COLFUN) framework for envisioning and assessing such high-demand situations in order to realize an adequate human resource deployment (Neerincx et al. 2003). The framework consists of two models, a cognitive load model and a functional model, that support a coherent scenario analysis of the task demands and information flows. We briefly discuss two example assessments in early development processes: a traffic-control-center analysis and a task analysis for a naval ship’s bridge. Both analyses supported the development and refinement of operating procedures, support systems, manning schemes, work organization and training requirements. In general, COLFUN supports the integration of human factors in the iterative development process of complex human-machine systems.

The COLFUN framework

High-demand situations can be defined from a “functional process” or a “human-factors workload” perspective. In the COLFUN framework, these two perspectives meet. First, a model for cognitive task load is described that can be used for the (re)design of cognitive tasks and computer support in complex, real-time, task environments. Second, a model is presented that describes generic process-control functions and information transfer processes. Third, these two models are integrated and incorporated in a scenario-based design and assessment approach, to identify potential critical situations and provide concrete proposals to better handle such situations.

Cognitive Load Model

Neerincx (2003) developed a cognitive load model, distinguishing three load factors that have a substantial effect on task performance and mental effort. The first classical load factor, percentage time occupied, has been used to assess workload in practice for time-line assessments. Such assessments are often based on the notion that people should not be occupied more than 70 to 80 percent of the total time available. Secondly, the cognitive load model incorporates the Skill-Rule-Knowledge framework of Rasmussen [9] as an indication of the level of information processing. At the skill-based level, information is processed automatically resulting into actions that are hardly cognitively demanding. At the rule-based level, input information triggers routine solutions (i.e. procedures with rules of the type ‘if <event/state> then <action>’) resulting into efficient problem solving in terms of required cognitive capacities. At the knowledge-based level, the problem is analyzed and solution(s) are planned, in particular to deal with new situations. This type of information processing can involve a high load on the limited capacity of working memory. To address the demands of attention shifts, the cognitive load model distinguishes task-set switching as a third load factor. Complex task situations consist of several different tasks, with different goals. These tasks appeal to different sources of human knowledge and capacities and
refer to different objects in the environment. We use the term task set to denote the human resources and environmental objects with the momentary states, which are involved in the task performance. Table A summarizes a number of indicators of possible problems for each load factor.

Table A. Some risk indicators for each load factor.

<table>
<thead>
<tr>
<th>Load factor</th>
<th>Indicators of possible problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time occupied</td>
<td>Work overtime</td>
</tr>
<tr>
<td></td>
<td>Work not finished</td>
</tr>
<tr>
<td></td>
<td>Insufficient interim, brief rests</td>
</tr>
<tr>
<td>Task set switches</td>
<td>Interruptions from the environment (e.g. phone calls)</td>
</tr>
<tr>
<td></td>
<td>Several problems or tasks to be handled “simultaneously”</td>
</tr>
<tr>
<td>Level of information processing</td>
<td>Hardly time for concurrent actions like conversation</td>
</tr>
<tr>
<td></td>
<td>Extensive use of manuals, help systems etc.</td>
</tr>
<tr>
<td></td>
<td>Need for advise or assistance</td>
</tr>
<tr>
<td></td>
<td>Occurrence of non-routine situation for which</td>
</tr>
<tr>
<td></td>
<td>• the critical elements are hard to identify</td>
</tr>
<tr>
<td></td>
<td>• it is not immediately clear what actions to perform</td>
</tr>
</tbody>
</table>

The combination of the three load factors determines the cognitive task load: the load is high when the percentage time occupied, the level of information processing (i.e. the percentage knowledge-based actions) and the number of task-set switches are high. Figure A presents a 3-dimensional “load” space in which human activities can be projected with regions indicating the cognitive demands that the activity imposes on the operator.

Figure A. Schematic representation of the task load model.

The middle area represents the area in which task load matches the operator’s mental capacity in a certain task setting. In the top area task load is too high. The bottom area represents the area in which performance is not optimal due to underload. The load factors represent task demands that affect human operator performance and effort. When the time occupied is high, and level of information processing and number of task-set switches are low, vigilance problems can appear. When the time occupied and the number of task-set switches are high, cognitive lock-up can appear (i.e., the tendency of people to focus on single faults, ignoring the other subsystems to be controlled). The cognitive load model has been used in different domains for task-reallocation and design of support functions.
Functional Model

In general, four generic functions are fulfilled within the control room at two levels of information transfer (figure B). At the primary level, information provided by sensors is used as input for the crew’s situation awareness (SA). Deviations between pre-set values (set points) passed from the secondary level and actual values are directly compensated via the direction and control (DC) function. Based on lower-level feedback control loops, adjustments are made, either automatically or assisted by the operator. For example, when the carbon monoxide (CO) level is too high in a tunnel, it will be directly compensated by switching on the ventilation, or when a too-high vehicle approaches, it has to be stopped immediately by the tunnel operator.

At the secondary level, higher-order objectives, determined by the operational goals and criteria for safety and efficiency, are translated into pre-programmed rules for the primary level. Based on the situation awareness and knowledge about the system (e.g., the tunnel) disturbance assessment (DA) actions are employed when there are deviations from the planned state. Pre-set goals and criteria, and crew’s knowledge are used for decision making (DM). When the goals or criteria cannot be achieved with the current plan, the plan has to be reconsidered. For the tunnel example, when a truck is on fire, the disturbance has to be assessed (e.g., traffic, smoke, and casualties) and adequate decisions have to be made (e.g., announcements in tunnel, resource employment fire control). The functional framework has been used in different domains to identify human and machine tasks, and to improve information transfer in human-machine systems such as naval command center and medical diagnosis.
Scenario Development and Assessment

Cognitive task load can only be analyzed for specific, concrete task contexts. An effective method to create such a context is the use of scenarios. Scenarios presuppose a certain setting. Within the setting, roles are played by actors. In complex scenarios different actors can be involved, possible interacting with each other. Actors have specific goals or tasks. To achieve this goal actions have to be taken. Neerincx (2003) provides a method and description format to systematically create and assess normal and critical situations with the corresponding action sequences. Such an action sequence displays actions of different actors on a time-line, including the interaction with support systems. The actions can be triggered by events, and are grouped according to their higher-level task (goal).

The motor traffic example

Rypkema et al. (2003) assessed a design of the control room for supervising the traffic in the future Westerscheldetunnel in the Netherlands. The tunnel will measure six kilometers and consist of two separate tubes, each with two driving lanes, connected by corridors. A monitoring and control system (TUBES) has been developed for operating the tunnel, containing 94 cameras, 20 monitors, various sensors and different systems to control the tunnel like traffic lights, speed reduction signs and barriers. The objective of this assessment was to identify possible bottlenecks for the future operator and the envisioned task organization.

Function analysis. First, an inventory of operator tasks was made based on the four generic functions of the process control model (Figure B). The primary level functions involved mainly tasks that are related to the monitoring and control system TUBES (e.g., SA tasks like watching monitors, monitoring sensors and communication systems, and DC tasks like control of speed signs, traffic lights and barriers). On the secondary level, a distinction was made between the assessment and handling of incidents—caused by road-users who bring themselves or other road-users in danger—and threats—situations that could bring road-users into danger or lead to incidents.

The scenario design was based on three variables: frequency, severity and expected mental load. Highly frequent scenarios occurred more than once a week, low frequent scenarios less than once a month. Severity expressed the number of casualties within a scenario. The expected mental load was defined by domain experts during an interview. Considering the coincidence of variables (e.g. highly frequent severe accidents do not occur), five scenarios were generated.

The cognitive load model was used to assess the five scenarios. In three scenarios the complexity and the number of task-set switches showed a peak from the start of the incident to the arrival of the emergency response teams. After their arrival, these teams become responsible and take over a major part of the tasks, so that the operators task load decreases to a lower level.

Results. During serious incidents the mental load is very high just after the incident occurs, especially when there is a fire and the operator has to evacuate the people out of the tunnel. The overload was due to the large number of tasks, the task complexity and in some cases the large number of task-set switches. Also the sudden change from low to high mental load and the operator’s responsibilities are burdensome. It was recommended to improve procedures and clustering of tasks. Besides that, it was recommended to support the operator during incidents by deploying a second person who is able to assist the operator within a short period of time (e.g. someone who is working in the same building). Finally, it was recommended to use a simulator that creates a dynamic task environment for selection, training and freshening-up courses.
The ship’s bridge example

Van Veenendaal (2003) assessed alternative designs for the naval ship’s bridge, comprising different task allocations and support functions for navigation and platform supervision. The function analysis resulted in an inventory of operator tasks (i.e. a task hierarchy) and corresponding information needs. It provided insight in the contextual factors that affect the information transfer, in particular for the communication of information about the tactical situation. Furthermore, the functional model helped to define the role of the Officer of the Watch on a naval ship’s bridge.

Normal and critical scenarios were specified with domain experts, according to the method of Neerinx (2003). Furthermore, for every scenario, support functions were specified and included in the action sequence specifications (i.e. information handler, rule provider, diagnosis guide and task scheduler). The action sequences have been validated with domain experts.

The cognitive load model was used to assess these action sequences, with and without the four support functions. First, the three load factors were calculated per 6 minutes task performance, showing the dynamic load fluctuations in the 3-dimensional load cube of figure A. Subsequently, via questionnaires experts assessed the action sequences to acquire subjective load measures and estimations of the effects of the support functions.

Results. The analysis showed that the task of the Officer of the Watch can be extended with platform control tasks under normal conditions. The support functions will complement the knowledge and experience of the bridge crew to realize an adequate performance level. In critical situations, extra, technical personnel have to be called up. This study provided the first indicators for implementing such a dynamic task allocation.

Conclusions

The prevention of and the response to incidents highly depend on the performance of the human task performer. However, during critical situations the task load might become too high for adequate task performance. As a result, incidents may be handled improperly and might escalate. The method described in this annex provides a framework for the identification of these critical situations through analysis of the functional demands and cognitive load. Both the cognitive load and the functional model have been individually used before. Combining the two has resulted in a tool for a structural analysis of operator tasks and information flows, while at the same time the cognitive task load can be measured systematically. The COLFUN framework supported the identification of critical situations and provided concrete proposal for improvement:

- **Procedures.** Transformation of highly complex knowledge-based tasks into less complex rule-based tasks by provision of context-specific procedures and diagnosis guidance.
- **Support systems.** For the four process-control functions, the analyses provided proposals for a support system (from cameras and sensors to advanced decision support).
- **Manning.** The analyses showed when dynamic task allocation helps to handle critical situations (e.g. an (extra) employee takes over some of the operator tasks).
- **Organization.** The framework conveyed requirements for efficient information transfer. For example, the communication between the tunnel operator and the emergency response teams should be supported to prevent an overload of communication tasks for the operator.
- **Training.** It was recommended to train and refresh operators for handling of envisioned critical situations (e.g. in a simulator).
References


Annex 4: Workload Questionnaire

TNO

Cognitive Task Load Questionnaire

(time occupied) task-set switches information processing level of
This questionnaire is about the workload of your daily activities at work. Questions will be asked about the time you spend on your work, the complexity of your work and activities you have to do at the same time. The questionnaire will end with some general questions.

First, some questions are asked about your company and function

Name of Company:

Department:

Function:
The following questions are about the time you spend on your work

How many hours per day are you normally at work?

_______ Hour

Do you work in shifts?

Yes  No

If yes, what are the times you work in the different shifts?

Shift 1:
Shift 2:
Shift 3:
Shift 4:

Below some timelines are shown. Please indicate for every shift how your day is divided in working hours and breaks (e.g. coffee break, lunch, tea break). Write down the start and end times.

Shift 1:
Start work  End work

Shift 2:
Start work  End work

Shift 3:
Start work  End work

Shift 4:
Start work  End work
### How many hours per week do you work overtime?

<table>
<thead>
<tr>
<th></th>
<th>1 hour or less</th>
<th>1-5 hours</th>
<th>5 hours or more</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tick</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### How often does it occur that you are not able to finish your daily activities?

<table>
<thead>
<tr>
<th></th>
<th>Seldom (less than 1 per month)</th>
<th>Sometimes (1-5 per month)</th>
<th>Often (more than 5 per month)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tick</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Considering your working hours, how many minutes per hour do you rest or wait without having to pay attention?

<table>
<thead>
<tr>
<th></th>
<th>1 minute or less</th>
<th>5-15 minutes</th>
<th>15 minutes or more</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tick</strong></td>
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</tbody>
</table>

### What part of the time do you perform tasks on a routine basis, which you could for instance perform while having a conversation?

<table>
<thead>
<tr>
<th></th>
<th>less than 25%</th>
<th>25%-75%</th>
<th>more than 75%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tick</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### How often do you have to look up information in manuals, guidelines, help systems, etc.?

<table>
<thead>
<tr>
<th></th>
<th>Seldom (less than 1 per week)</th>
<th>Sometimes (1-5 per week)</th>
<th>Often (more than 1 per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</tbody>
</table>

### How often do you have to ask for advise or assistance from colleagues or others (e.g. help desk, suppliers)?

<table>
<thead>
<tr>
<th></th>
<th>Seldom (less than 1 per week)</th>
<th>Sometimes (1-5 per week)</th>
<th>Often (more than 1 per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</tbody>
</table>

### How often appear critical situations such as process disturbances or system malfunctions (e.g. alarms)?

<table>
<thead>
<tr>
<th></th>
<th>Seldom (less than 1 per week)</th>
<th>Sometimes (1-5 per week)</th>
<th>Often (more than 1 per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</table>

### Can the critical elements in such situations (like system components and climate conditions) easily be identified?

<table>
<thead>
<tr>
<th></th>
<th>Seldom (less than 25%)</th>
<th>Sometimes (25%-75%)</th>
<th>Often (more than 75%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</tbody>
</table>

### Is it directly clear how to handle such critical situations (i.e. what actions to perform)?

<table>
<thead>
<tr>
<th></th>
<th>Seldom (less than 25%)</th>
<th>Sometimes (25%-75%)</th>
<th>Often (more than 75%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
The following questions are about switching between different activities

<table>
<thead>
<tr>
<th>How often do you have to stop your work because of some interruptions (e.g. phone calls, questions of colleagues, incoming messages)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seldom (less than 1 per hour)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How often do you have to switch between different tasks (problems or procedures) related to your work (e.g. when alarms from different systems have to be managed simultaneously)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seldom (less than 1 per hour)</td>
</tr>
</tbody>
</table>
The following are general questions about your work

<table>
<thead>
<tr>
<th>Question</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do you generally have enough time to complete your work within time?</td>
<td>Yes, more than enough</td>
</tr>
<tr>
<td>How do you rate the complexity of your work?</td>
<td>Generally too simple</td>
</tr>
<tr>
<td>Does your work suffer from interruption, task switching or re-scheduling of work during daily performance?</td>
<td>Never</td>
</tr>
<tr>
<td>How do you judge the overall workload?</td>
<td>Too low</td>
</tr>
<tr>
<td>How often do overload situations appear that cause performance decrease (e.g. errors or delays)?</td>
<td>Seldom (less than 1 per month)</td>
</tr>
</tbody>
</table>
Can you give some examples of such situations?


Thank you for filling in this questionnaire
Annex 5: Seminars conclusions

Conclusions seminar 1

Conclusions workshop

The aim of the workshop was to give an introduction to the COLFUN method. Limited time was available, so it was not possible to discuss it into detail. Besides that, the attendants came from different backgrounds and relatively few people had operational experience, so it was difficult to get into detail in specific domains. However, some preliminary conclusions about the method can be drawn.

1. It appeared that the method, originally from the naval domain, is applicable for process control
2. Refinements of the model are possible (see results group 1)
3. The method needs more extensive explanation (see questions group 2)
4. There is an area of tension between the levels in which safety problems can be approached:
   - Macro level approaches, which emphasises cultural and organisational aspects, as dealt with in FG1
   - Meso level approaches, that can be applied on an intermediate level. The COLFUN method is an example of it
   - Micro level approaches, which go into low level details. Examples are found in the refinements suggested by group 3 (e.g. perception, detection, etc.)

Overall seminar conclusions

1. There are a large number of human factors approaches that can be used in the field of high demand situations
2. The seminar provided an overview of the state-of-the-art of most promising approaches in the field
3. The COLFUN method is a systematic approach that results in an overview of problems that might occur during process control. At the same time it shows where in the process solutions can be found. Besides that, the framework reveals the relationship between the different themes that were defined within FG3.
4. However, the COLFUN framework does not solve every problem that exists it the field. Therefore complementary methods and analysis on other levels, particularly in the understanding of cognitive load, are needed when studying high demand situations

Conclusions seminar 2

The fact that control room operators have to deal with an enormous amount of alarms justifies the effort that has to be put in alarm handling and alarm rationalisation. However, poor alarm design might be a symptom of other causes.
Therefore, alarm handling should be part of a wider alarm philosophy, in which other aspects (like environment, interface, control room design) are taken into account as well. To accomplish this, the participation of operators and the use of their knowledge is essential. But also, the participation and commitment from all layers of the organisation is a prerequisite to achieve a proper overall philosophy for control & alarm, just like the presence of a strong champion within the organisation. On the other hand, the goals that are set should be realistic and achievable.

Especially in SMEs, who often have limited resources, it might be impossible to realise drastic changes. Furthermore, the creation of a good control & alarm philosophy is an evolutionary process, which takes different stages to accomplish. It is impossible to get it right at once.