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Cognitive and Functional (COLFUN) Framework for Envisioning and Assessing High-Demand Situations

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ABSTRACT
The human role in complex task environments will more and more focus on handling non-routine situations with increasing information velocity and ubiquity. This paper 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. 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.

Keywords
Cognitive task analysis, mental load, human-computer interaction, control centers, process control, user-centered design.

1. INTRODUCTION
Addressing Human Factors in the development processes of complex and dynamic human-machine systems is essential to enhance safety in a large set of application domains, such as industrial process control, aviation, ship navigation and motor traffic. Within each domain, research and collaboration initiatives have been developing human-centered analyses and "best practice" guides. In the European project PRISM (Process Industries Safety Management, http://www.prism-network.org), the Focus Group *Human Factors in High-Demand Situations* aims at improving the joint human-system task performance by reduction of the risks for human resource conflicts and cognitive biases that may appear in high demand situations. This Focus Group explicitly aims at knowledge transfer from other domains to the process control domain. For this purpose, we combined approaches from different domains into a generic Cognitive and Functional (COLFUN) framework for envisioning and assessing high-demand situations. This paper presents the framework and will, subsequently, summarize two example applications from different domains. The first example consists of an analysis of the task load on a naval ship's bridge to assess envisioned task allocations and support functions. The second example comprises an assessment of the tasks for the operator in the future control room of a motor-traffic tunnel.

2. THE COLFUN FRAMEWORK
High-demand situations can be defined from different perspectives. On one hand, for instance, high demand can be described in terms of the *functional* setting and corresponding information transfer processes. For example, the production of the plant might deviate from the planned production, in which case urgent action is required to prevent any production losses. On the other hand, high demand situations can be defined in terms of the *workload* of the human task performer. For example, situations may occur in which the number of tasks or time pressure is so high that the operator cannot perform his or her tasks adequately. The work demands do not match the cognitive capacity of the operator, resulting in mental overload. In the COLFUN framework for the analysis of high demand situations, the functional process and human-factors 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, we will argue that the integration of both these two models, in combination with a scenario-based design and assessment approach, will help to identify potential critical situations and provide concrete proposals to better handle such situations.

2.1 Cognitive Load Model
Neerincx [4] 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 1 summarizes a number of indicators of possible problems for each load factor.

Table 1. Some risk indicators for each load factor.

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

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 1 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.

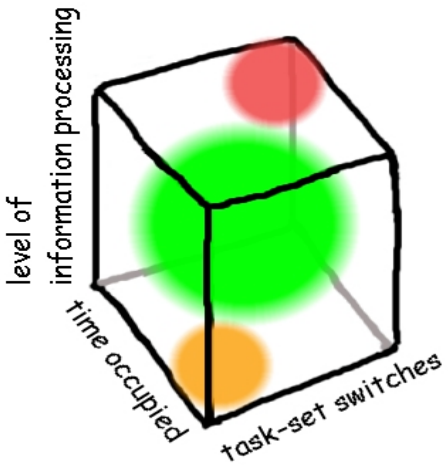

Figure 1. Schematic representation of the task load model.

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 [7]. 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; [3]). The cognitive load model has been used in different domains for task-reallocation *and* design of support functions [4].

Based on the theory and our method for cognitive task analysis, we developed 4 support concepts and for each high-level design principles [6] (table 2):

The Information Handler filters and integrates information to improve situation awareness, i.e. knowledge of the state of the system and its environment, and reduces the *time occupied*. Due to the increasing availability of information, situation awareness can deteriorate without support. Correct information should be presented at the right time, at the right abstraction level, and compatible with the human cognitive processing capacity.

The Rule Provider provides normative procedures for solving (a part of) the current problem and affects the *level of information processing*. Due to training and experience, people develop and retain procedures for efficient task performance. 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.

The Diagnosis Guide affects the *level of information processing*. The level of information processing increases when no complete (executable) procedure is available to deal with the current alarms and situation. This support function guides the operator during the diagnosis resulting in an adequate problem-solving strategy for a specific task.

The Scheduler affects the number of *task-set switches* by providing an overall work plan for emergency handling. Task priorities are dynamically set and shown in a task-overview to the operator resulting in effective and efficient switches.

Table 2: Load factors and support concepts.

Cognitive load factor	Support concept
Time occupied	Information Handler
Level of info processing	Rule Provider Diagnosis Guide
Task-set switches	Scheduler

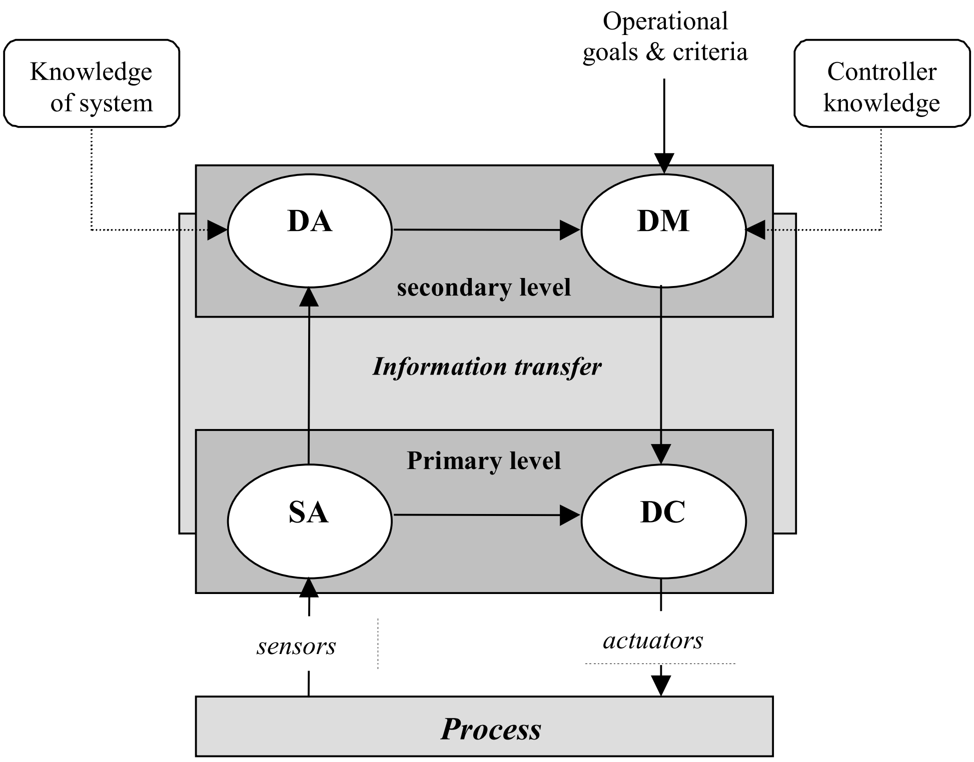

Figure 2. General process-control functions SA, DA, DM and DC, arranged according to two levels of information transfer.

2.2 Functional Model

In general, four generic functions are fulfilled within the control room at two levels of information transfer (figure 2). 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 [8].

2.3 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* [1]. 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.

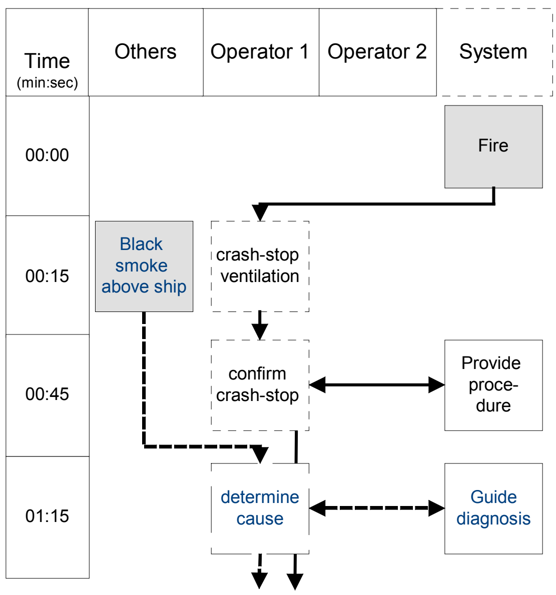

Figure 3: Outline of a Compound Action Sequence (CAS) consisting of 2 Basic Action Sequences (BAS) (i.e. handling of both the fire and the black smoke events).

Neerincx et al. [6] provide a method and description format to systematically create and assess normal *and* critical situations with the corresponding action sequences (figure 3). 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).

3. THE MOTOR TRAFFIC EXAMPLE

Rypkema et al. [10] 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 2). 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 freshing-up courses.

4. THE SHIP'S BRIDGE EXAMPLE

Van Veenendaal [12] 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 Neerincx et al. [6]. 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 1. 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.

5. DISCUSSION

Schraagen et al [11] describe individual Cognitive Task Analysis (CTA) approaches and methods for (1) individual training, performance assessment, and selection; (2) the design of human-system interaction; and teamwork situations. They aimed at generic task taxonomy, but concluded that current CTA approaches are diverse and differ on a number of dimensions such as scope, theoretical and empirical foundation, and utility. Consequently, deriving a generic taxonomy is hardly possible.

The COLFUN framework supports a specific type of Cognitive Task Analysis (CTA) that has some similarities and differences with the cognitive work analysis approaches of Rasmussen [9] and Vicente [13]. First of all, our CTA applies the Skill-Rule-Knowledge framework of Rasmussen to determine the level of information processing. Further, both COLFUN and the cognitive work analysis provide a functional view on information processing although at a different level of detail. The main difference seems to be that we do a rather extensive analysis of scenarios and normative procedures, whereas Vicente [13] focuses on supporting knowledge workers in adapting to change and novelty. He challenges the theoretical predisposition of the instruction-based task analyses. The demands of the task domain should be the focus of analysis; such as in the constraint based approaches to work analysis. For training, these approaches help to develop understanding of the task domain, as opposed to learning procedures, holding the promise of flexible response to novel situations. However, they may not result in the required (fast) generation of actions. The more closed a system is, the more amenable it is to instruction-based forms of task analysis. For open systems, workers must adapt online in real time to disturbances that cannot possibly be foreseen by analysis. For this, constraint-based analyses are suitable (although they can be applied when the precise goals cannot be predicted).

In our view, however, design can aim at supporting procedural ("instruction based") task performance, while still enabling adaptive problem solving processes (e.g. by application of the abstraction hierarchy for virtual control panels according to the principles of ecological interface design; [14]). However, the effects of implementing "instruction-based" performances should be well evaluated and should prove to enable adaptive problem solving processes. For example, Grootjen et al. [2] designed a user interface prototype for a ship's bridge that provided the four support functions of table 2. Subsequently, they conducted an experiment to test the effects of the support functions, under high and low task load, on task performance, mental effort and possible side effects (such as operator's loss of situation awareness). In this experiment, 50 RNlN students had to solve damage control problems with the prototype interface. The support proved to result in substantial effectiveness and efficiency profits, i.e. the use of support functions leaded to a substantial improvement of task performance, especially at high task load. Possible costs of being "out of the loop", like not reacting on an implemented wrong advice or a decrease in understanding of performed actions, could not be found.

In process control and related domains, such as aviation and space, improved procedure support can have a major impact on the mission performance (Neerincx et al. [5]). In order to do early, cost-effective assessments, we need instantiations of future work conditions and contexts. COLFUN seems to be a good starting point to realize such a human factors integration in iterative system development processes.

6. 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 chapter 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, e.g. [8], [4], [2]. 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).

7. ACKNOWLEDGMENTS

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