Support of Mission and Work Scheduling by a Biomedical Fatigue Model

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ABSTRACT

Introduction: *It is a strategic advantage to be able to maintain high alertness and performance of soldiers during a mission. Factors that impair alertness and lead to fatigue are typically psychically and physically stressing, or monotonous and boring tasks. Rest periods are often too short and soldiers have to cope with sleep deprivation, short rest cycles and insufficient breaks. In worldwide missions jetlag may impair performance additionally.*

Rationale: *In the armed forces, a wide variety of different work schedules are used which are more often historically founded than based on knowledge about biological rhythms. Biomedical models that predict periods of impaired performance may provide decision aids, and they are one of the best available solutions to help soldiers to perform more effectively and with increased safety.*

Methods: *The German Aerospace Center DLR has developed a computer tool for the prediction of fatigue that is based on a biomedical model of fatigue combining four components. The circadian component describes the course of fatigue during the day with the maximum of alertness during the day and high fatigue during the night. The sleep-related component describes the effect of sleep timing, duration and quality. In general, fatigue increases with the time awake. The third component, sleep inertia, describes fatigue occurring after awakening even from a good sleep. These three components are task invariant. The fourth component, the time-on-task component, describes the fatiguing effect of a specific task. Breaks during a task or the change to a different task reduce the time-on-task effect. Results from the fatigue management tool about the analysis of schedules and soldier alertness are shown for the application areas navy, army or air force.*

Conclusion: *The computer program for the prediction of fatigue is a valuable tool for assessment and prediction of fatigue in crews as well as for comparison and optimization of different work schedules.*

INTRODUCTION

A large variety of work schedules is used in the armed forces. The development of biomathematical fatigue models provides the opportunity to predict fatigue for any of the schedules and compare different schedules with respect to their impact on fatigue and performance. This paper shall illustrate the potential of fatigue models by presenting some realistic examples.

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The level of fatigue during waking that is acceptable in a particular situation defines the needed amount of sleep. Models that relate daytime fatigue and the amount of sleep are usually based on the two-process model of sleep regulation (Daan et al., 1984), which is based on the measurement and quantification of slow waves (Delta waves) in the sleep EEG (Geering et al., 1993). The qualitative description of the two-process model presents the theoretical framework from which most fatigue models have been derived.

The two-process model combines chronobiological and homeostatic principles that have been deducted from many laboratory experiments on sleep and circadian rhythms. Today the two-process model plays an important role in the scientific discussion about sleep regulation. Its remarkable success has several reasons, first of all, the model's simplicity in explaining experimental results on sleep regulation. Secondly it has a physiological background and the power to generate research hypotheses to potentially falsify the model and to foster scientific progress.

In the model the timing of sleep is determined by a circadian process "C" and a homeostatic process "S" resulting in a circadian sleep-wake cycle. The process S increases during wakefulness until it reaches a circadian upper threshold and sleep is initiated. During sleep, process S decreases. When it reaches a circadian lower threshold sleep is terminated.

The homeostatic process S has been deducted from the quantification of slow waves in the sleep EEG. The larger S is the more slow-wave sleep may be observed. The circadian process S is mainly influenced by the light-dark cycle.

The generality of the model is underlined by its use for twenty years without important changes (Achermann 2004). Already Daan, Beersma and Borbély (1984) indicated that fatigue ratings may be explained by a two-process model incorporating a circadian and a sleep-related component. They communicated this idea without presenting a formal mathematical fatigue model.

FATIGUE MODELS

From the beginning scientists recognized the potential of the two-process model of sleep regulation for constructing mathematical fatigue models. However, the models that were constructed on this basis started with an intrinsic weakness resulting from the underlying assumption that fatigue and sleepiness are fully explained by the timing of sleep.

Human behaviour during the waking period has been largely neglected in the construction of fatigue models. In the original fatigue models a modification of this behaviour or environmental stimuli could not change, increase or decrease, sleepiness or fatigue. The main candidates for such changes are caffeine, stimulating or sedating drugs, the demand of a particular work, monotony and environmental factors. Since these modifications of human behaviour have little to do with sleep regulation through chronobiological and homeostatic principles there is no natural way to extend the model and incorporate these effects. Some of the existing models however try to incorporate these effects, e.g. as a time-on-task effect.

The time-on-task component describes fatigue that builds up when a task is conducted that is demanding or monotonous. It can be reduced by a break or by switching to a different task. The time-on-task component seems to be stronger in more fatigued persons.

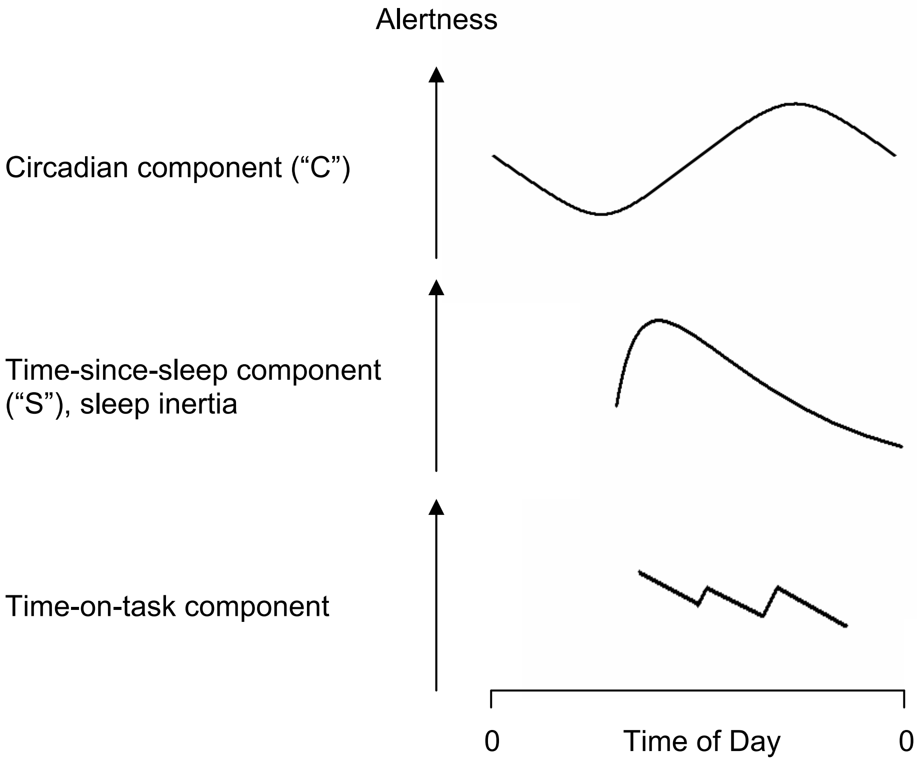

Figure 1: The fatigue model Alert that has been used to predict fatigue for the examples of this paper is comprised of a circadian component, a sleep-related component including sleep inertia and a task related component.

From a practical point of view fatigue models should explain work performance or accident risk. But there is no metrics available for modelling work performance or accident risk. Accidents are occurring too infrequent and scientists have rarely the opportunity to compare accident risk with the timing of sleep in a systematic way. Although general observations have been made as, e.g., shift work increases accident risk.

Even more difficult is the task to describe a metrics for work performance. Scientific studies are usually done by introducing an artificial task, e.g. a reaction time task, to measure task performance. There is an endless debate on how task performance predicts work performance. Relating a relatively simple laboratory task performance to the demands at the work place often reduces the acceptance of results deduced from task performance.

We believe that task performance is not a reliable predictor of work performance and if it is to predict work performance this performance has to be studied and measured. On the other hand it is not economical to measure all kinds of relevant work performances. A probably better and surely more economical way may be to rate work demands, fatigue and sleepiness and construct a metrics like the risk suffering from micro-sleep. Such a metrics may show face validity in work situations and may be accepted if results are in congruence with practical experience.

A list of successful applications follows. It illustrates how broad the field of potential applications is.

- Simulations of alertness in a space environment (Achermann and Borbély, 1996)
- Evaluation of aircrew fatigue (Spencer et al., 1998)
- Analysis of sleep and alertness in aircrew during ultra-long flights (not published)
- Analysis of response to time zone transitions (Kronauer et al., 1999)
- Analysis of alertness in car drivers (not published)
- Analysis of truck driver fatigue risk (Moore-Ede et al., 2004)
- Evaluation of schedules for a truck fleet (not published)
- Analysis of work schedules (Fletcher and Dawson, 2001)
- Analysis of shift work schedules (Folkard et al., 1999)
- Predicting accident risk (Folkard et al., 2000)
- Predicting sleep after shifts (Akerstedt and Folkard, 1996)
- Soldier fatigue countermeasures (Eddy and Hursh, 2001)
- Simulation of soldier performance under hypothetical combat scenarios (Hursh, 1998)

In spite of the criticism that fatigue models have received recently the success and the strength of the models is remarkable. In addition, all scientists who work with these models see a large potential for improvement (Spencer and Gundel, 1998; Dinges 2004; Neri 2004). Models are continuously applied and improved (Akerstedt et al., 2004; Belyavin and Spencer, 2004; Hursh et al., 2004; Jewett and Kronauer, 1999).

Undisputed is the usefulness of fatigue models in educating people about fatigue in non-standard work situations and in generating scientific hypotheses that can be tested by experiments. In general, it has become obvious through simulations that driving time regulations are sub-optimal in that they do not consider the time of day when the operation takes place.

FOUR EXAMPLES OF MILITARY AND CIVILIAN WORK SCHEDULES

The fatigue model Alert of DLR will be applied to four watch and work schedules to demonstrate how it can be used to analyse and compare schedules:

- Maritime schedule with two 4-hour watches, 4/4 rhythm including rotation of watch times
- Maritime schedule with two 6-hour watches, 6/6 rhythm without rotation of watch times
- Improved watch schedule for two watches, 6/6 rhythm without rotation of watch times
- Shift schedule of physicians in German hospitals

Figure 2 shows a maritime 4-hour watch system. A 2-hour shift is introduced between 16:00 and 20:00 hours to achieve rotating watches. The grey bars represent sleep that has been estimated by using a two-process sleep model under the restriction that sleep can occur between watches only. Having estimated sleep periods the program can simulate alertness during watches. The level of alertness is colour-coded and switches from light blue to light red when there is a risk to suffer from micro-sleep.

Until day 12 it is assumed that sleep can take place between all watches. Beginning with day 13 the actual conditions on board of the ship are considered; the time between 18:00 and 20:00 hours was occupied by work. In addition soldiers were woken up always 30 minutes before a watch.

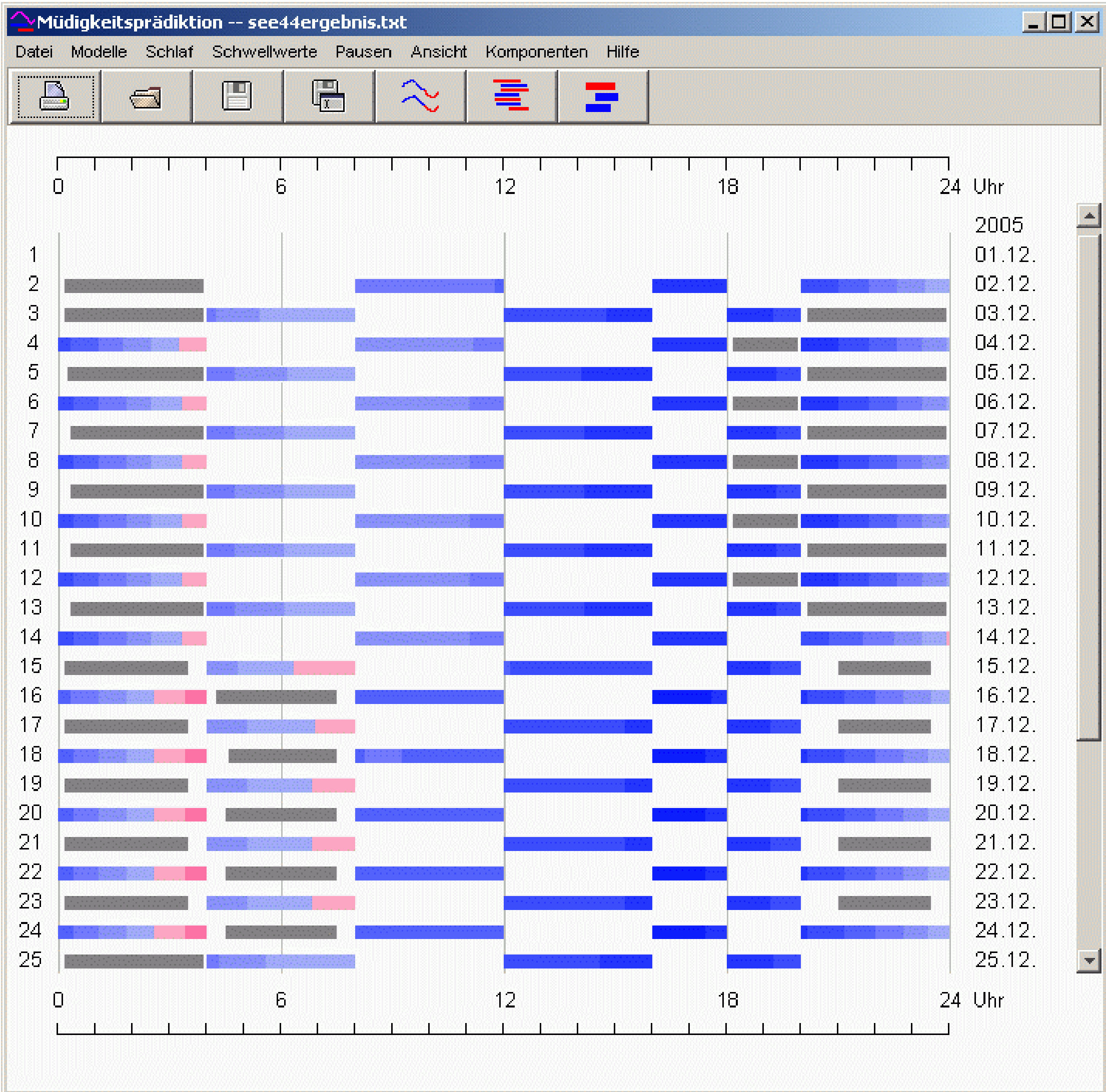

Figure 2: A 4-hour watch schedule as it is widely used in maritime operations. The grey bars represent sleep periods. The level of alertness during watches is displayed colour-coded from saturated blue for very alert to deep red for very tired. Levels displayed in red should be avoided.

The actual work schedule allows for 5:30 hours and 3:15 hours sleep in two subsequent nights compared to 5:15 and 3:45 hours when the actual conditions are not considered. The actual soldiers are more fatigued in particular during the 4:00 to 8:00 hours watch. For the watch between 00:00 to 4:00 hours fatigue levels to be avoided are observed almost an hour earlier.

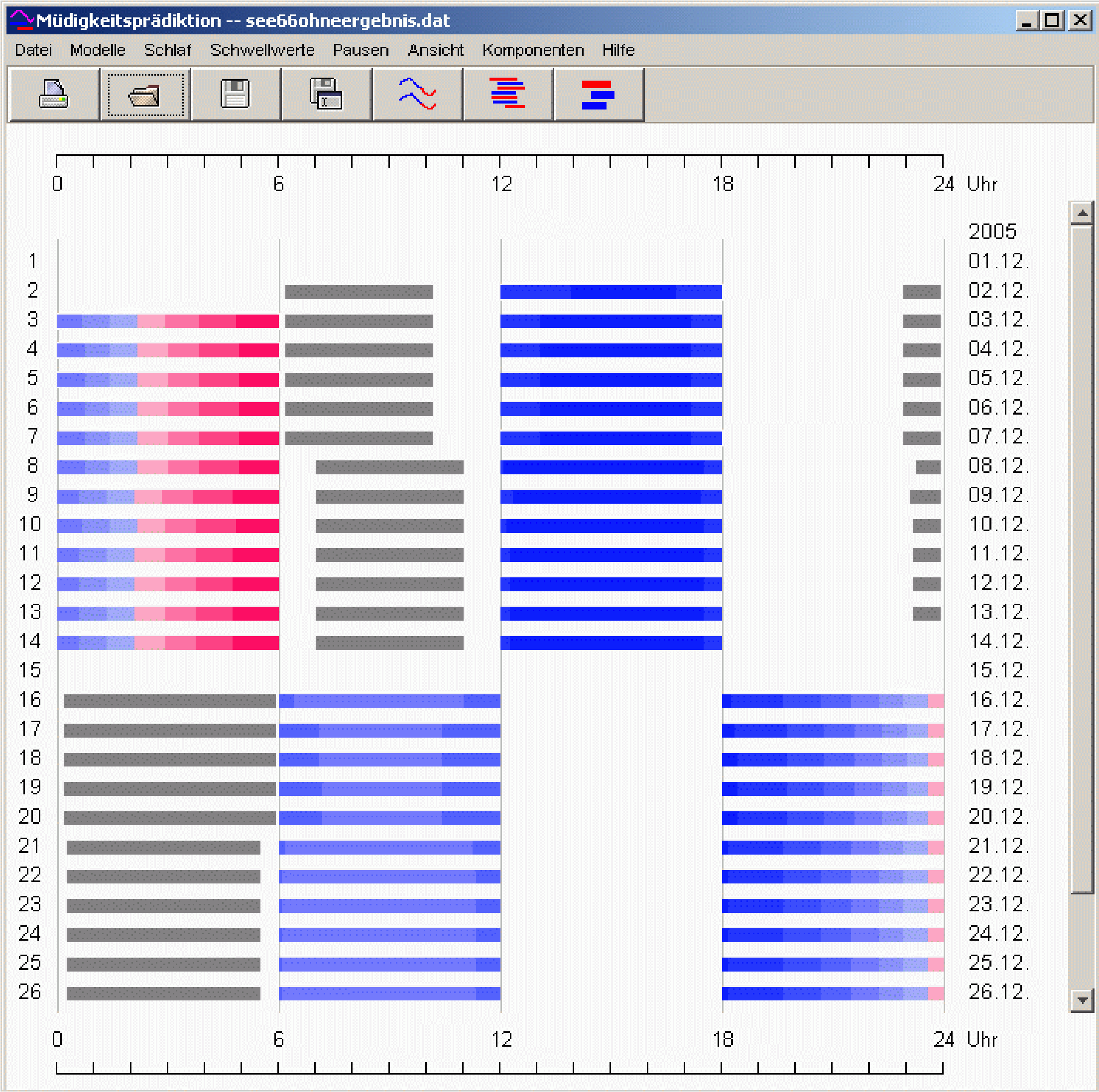

Figure 3: A 6-hour watch schedule as it is also widely used in maritime operations. The grey bars represent sleep periods. The level of alertness during watches is displayed colour-coded from saturated blue for very alert to deep red for very tired. Levels displayed in red should be avoided.

The second example concerns the simulation of a 6-hour watch schedule without rotation. Though this schedule allows for five to six hours sleep every night, the soldiers are expected to be too tired during half of the watch-time between 00:00 and 6:00. In general, it seems that the 4-hour watches are better. The actual work situation shown in the latter part of each shift does not change the situation. The high fatigue falls into the window of circadian low suggesting that a shift of the watches by 3 hours (Figure 4) may improve alertness.

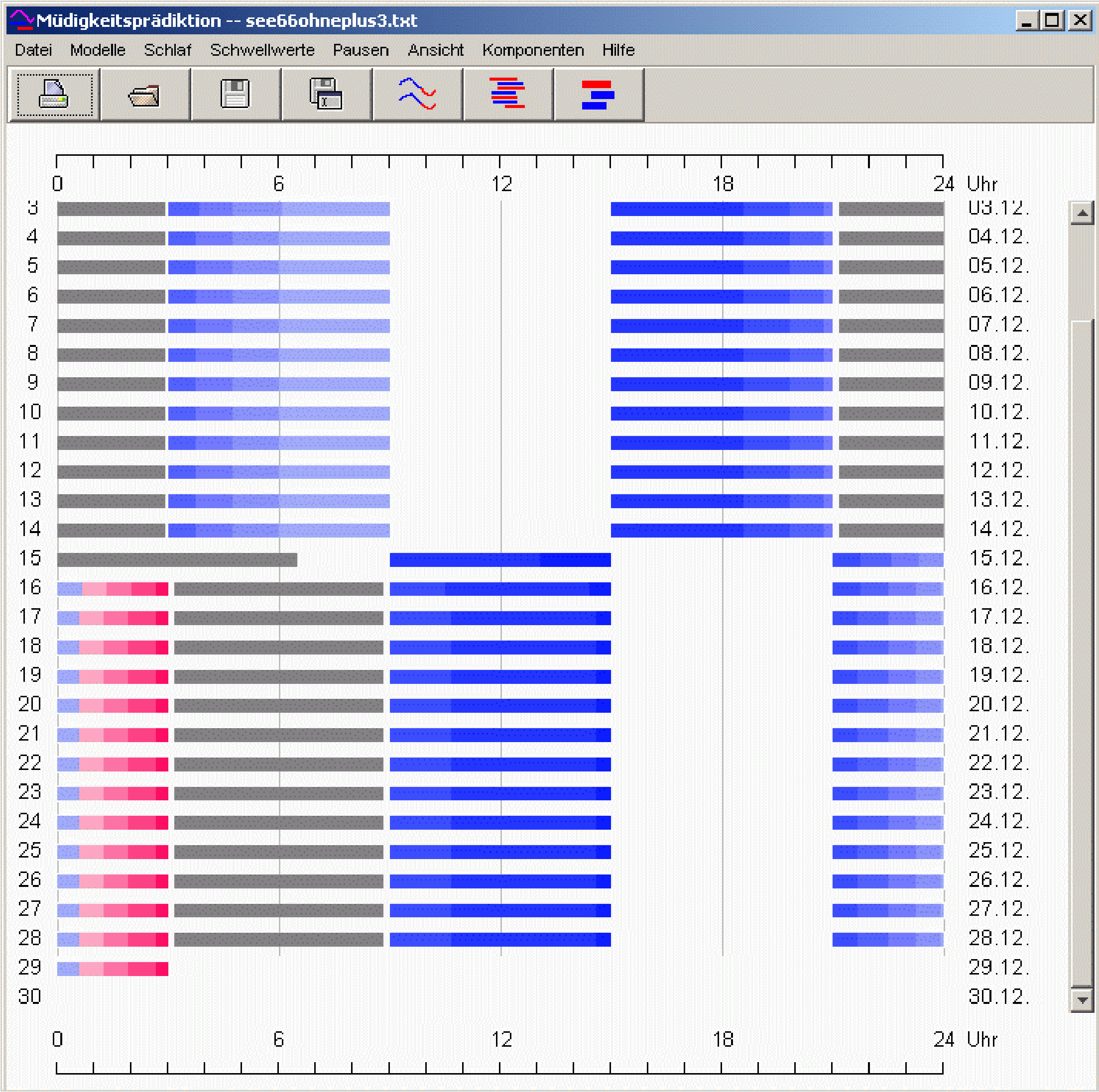

Figure 4: A 6-hour watch schedule shifted by three hours. The grey bars represent sleep periods. The level of alertness during watches is displayed colour-coded from saturated blue for very alert to deep red for very tired. Levels displayed in red should be avoided.

Indeed, Figure 4 shows that fatigue may be reduced if the watches are shifted by three hours. The watch that starts at 3:00 hours into the window of circadian low, benefits from the almost six hours sleep before the watch. The recuperative effect of sleep turns out to be more important for maintaining a sufficient level of alertness than the circadian low around 5:00 hours.

With Figures 5 and 6 actual working schedules of physicians at German hospitals are studied. Figure 5 displays a work schedule of a physician for three weeks. There are regular daytime shifts from 7:30 to 16:00 hours. On Thursdays or Fridays this regular shift may be extended by a time on duty until the next morning 8:00 hours. In addition, there are periods of 24 hours on duty during weekends.

A physician on duty stays in the hospital. 49% of the time on duty can be utilized for work. In the display of Figure 5 it was assumed that there is continuous work when a physician is on duty. It clearly shows that the physician would have to fight against sleep for many hours.

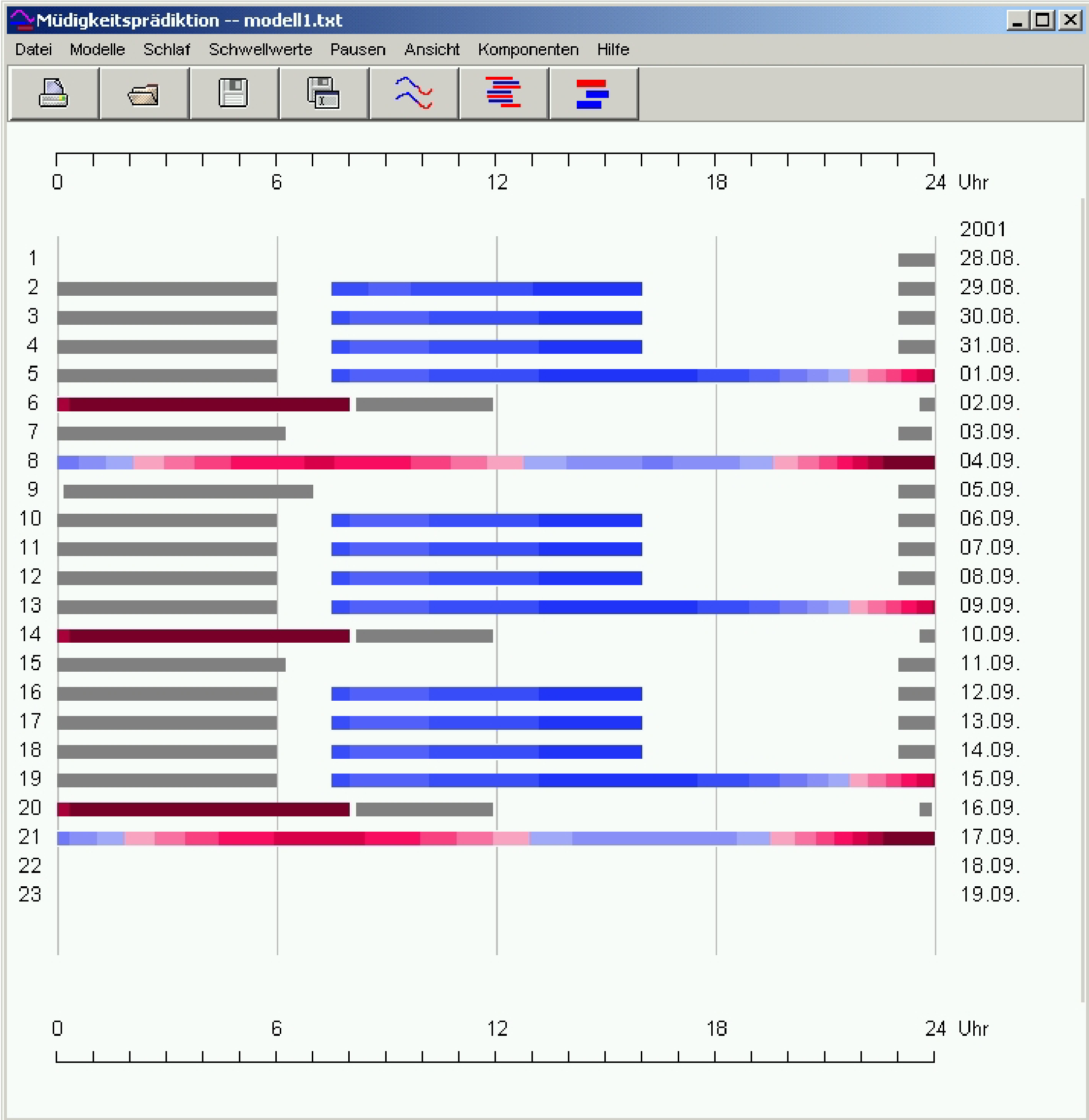

Figure 5: A work and on duty schedule of a physician in a German hospital. The grey bars represent sleep periods. The level of alertness during watches is displayed colour-coded from saturated blue for very alert to deep red for very tired. Levels displayed in red should be avoided.

In Figure 6 the rule that only 49% of the time on duty may be used for actual work was implemented through regular and long periods without work that could be used to sleep. These breaks lead to additional sleep ameliorating the situation of the physician. However, fatigue remains critical during the window of the circadian low.

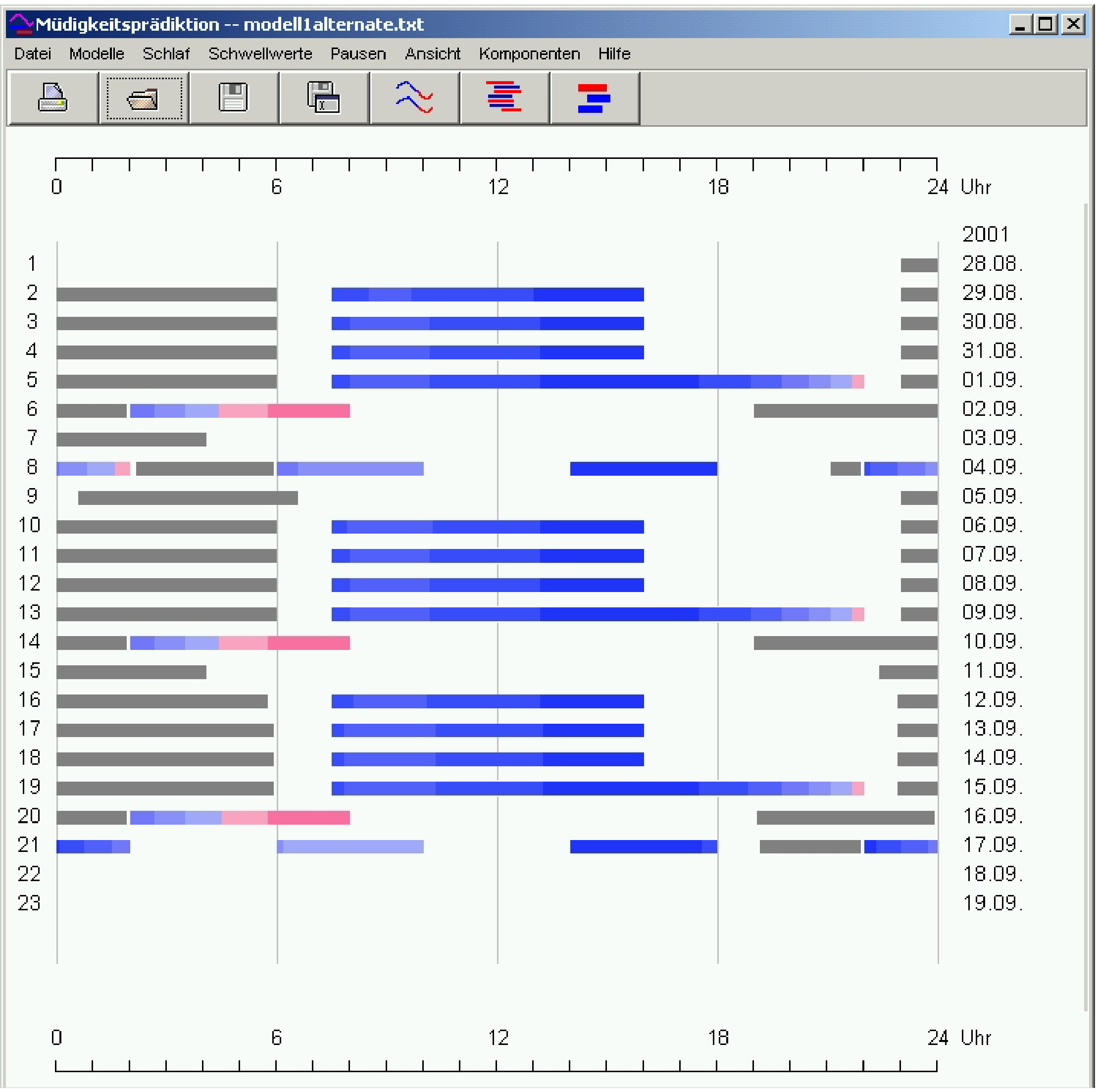

Figure 6: A work and on duty schedule of a physician in a German hospital. The time on duty shows periods of time without work and an opportunity to sleep. The grey bars represent sleep periods. The level of alertness during watches is displayed colour-coded from saturated blue for very alert to deep red for very tired. Levels displayed in red should be avoided.

CONCLUSIONS

The examples of different schedules frequently occurring in military and civilian environments may have demonstrated the potential of fatigue models for the analysis of work schedules. Whenever such an analysis is conducted it should be complemented by actual data obtained in the field. This regularly increases the face validity of the simulations. Finally, a list of possible applications of fatigue models shall conclude this brief study.

- The computer program Alert is a valuable tool for the assessment and prediction of fatigue as well as for the comparison of work schedules.
- Analysis and optimization of shift or watch schedules can be accomplished.

- Alert is applicable in different areas, e.g. aviation, seafaring and road transport.
- It can be used in computer networks, on handhelds and on mobile phones.
- It can be combined with road navigation systems and route planners.
- Alert can be used as the basis for counselling logistics and transport companies.
- Alert can support training of drivers to adopt an alertness management.
- It is used to create scientific hypothesis and experimental designs.
- The latest success of another fatigue model has been achieved in aviation. A concept for the safe operation of ultra-long-range aircraft as the A340-500 has been developed.

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