Biomathematical Fatigue Modelling in Civil Aviation Fatigue Risk Management

Application Guidance

Civil Aviation Safety Authority (CASA)

Human Factors Section

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NB. This report may be updated at various times to ensure the report remains abreast of current practices related to biomathematical modelling. For further information and/or to provide feedback please email:

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1. Executive summary

As the aviation industry evolves from scheduling practices based on prescriptive duty time limits, to performance-based safety management, fatigue risk management systems (FRMS) are being adopted by civil aviation operators. This change requires methods for incorporating scientifically based, human-fatigue-related information into the decision making process to improve the identification and management of fatigue risk.

While not a necessary component of an FRMS, biomathematical models of human fatigue can provide a tool which incorporates aspects of fatigue science into scheduling through predictions of fatigue risk levels, performance levels, and/or sleep times/opportunity. Biomathematical fatigue models have limitations however, which must be appropriately considered. Fatigue model predictions cannot form the sole means upon which fatigue risk management operational decisions are made. Limitations of currently used fatigue models include a restriction to predicting risk probabilities for a population average rather than instantaneous fatigue levels of a specific individual, incomplete description of all fatigue physiology factors, qualitative data being misinterpreted as quantitative data and limited validation against aviation specific data. Due to these limitations and the relatively new use of biomathematical fatigue models in civil aviation, a cautionary approach should be taken and FRMS should be designed as comprehensive, multi-layered systems, in which biomathematical models, if used, provide a supporting role.

Availability of validation data from aviation operations is a key challenge that is limiting availability of aviation-validated models. Of seven models evaluated at a modelling workshop sponsored by the United States (U.S.) Department of Defense, U.S. Department of Transportation, and National Aeronautics and Space Administration (NASA) only two specifically relied upon aviation data for development or stated their relevance to aviation operations. While some model features and capabilities have advanced since this time, there has not been a substantial addition of validation data from civil aviation operations.

Furthermore, users of biomathematical models should ensure they are provided with written information regarding the dimensions of fatigue that are considered by the model, the mechanisms by which they are considered, data sets used to validate the model, and the cautions and limitations that should apply to interpretation of outputs. Model developers or distributors should discharge their duty of care to ensure that this information is comprehensive, accurate and does not overstate model capabilities.

As some operators may incorporate the use of fatigue models within their FRMS, this report aims to provide a plain language description of various biomathematical fatigue models and further awareness and considerations regarding their use within an FRMS.

This report goes beyond a comparison of the models by identifying appropriate opportunities for integrating models into an holistic FRMS, and developing management systems and corporate culture that understands the uses and limitations of qualitative/quantitative model predictions, utilises their outputs with caution and in the context of other operational opportunities and constraints, and adopts complementary multi-layered strategies to proactively identify and manage fatigue risk.

This report discusses some key factors to consider when selecting and applying a biomathematical fatigue model, which include:

(a) the type of data that will be used as inputs to the model;
(b) the physiological factors that are described by the model components;
(c) the types of model output predictions and their relevance to task risks or other desirable outcome variables;
(d) the data used for model validation and their level of equivalence to the operational environment and subject population; and
(e) interpretation of model predictions for use in decision making.

All of these factors must be considered, relative to the specific operational environment for their intended use.

Six fatigue models were examined along lines that focus on compatibility issues relative to civil aviation operational systems and scientific interpretation of model predictions for crew fatigue. The capabilities of the models are reviewed, based on published and self-reported information from model representatives. Thus, no warranties are made about the accuracy of claims relative to each model.

2. Scope

Biomathematical models of fatigue provide qualitative/quantitative predictions of human fatigue and/or sleep opportunity factors that can be utilised as one, non-essential component of a comprehensive FRMS. This report provides a survey of current capabilities of fatigue models and considerations regarding incorporation of biomathematical models into an FRMS, but does not cover overall FRMS strategies.

This report is provided as a resource to civil aviation operators that have elected to integrate biomathematical models as part of a flight crew FRMS, as a move towards performance-based regulatory frameworks. Recommendations, however, are also generally applicable to the use of biomathematical models for flight crew within the envelope of prescriptive flight/duty time limits or for non-flight crew personnel.

Data used to generate the summary of six available fatigue models were derived from publications and self-reports from model representatives. Direct evaluation of the model properties was not performed, so capabilities are presented as *claims* rather than independently verified properties. Not all considerations relevant to an operator's selection of model are covered here. The information is therefore presented only as a starting point for model assessment. Full assessment of model capabilities, validity and considerations such as cost, support services, data format and compatibility should be pursued directly with the model representatives. Recommendations on integrating models into FRMS are generally applicable regardless of specific model selection. However, as with the models themselves, the recommendations should be carefully considered and validated before any implementation is pursued.

3. Background

3.1. Fatigue risk and safety management context

A Safety Management System (SMS) is the paradigm that has been established by the International Civil Aviation Organization (ICAO) for mandating aviation operators to establish organisational structures, accountabilities, policies and procedures that effectively identify hazards, analyse and mitigate risks and provide the framework to manage safety. Human fatigue is one aspect of operational safety, and systems for managing the risk associated with fatigue are a required component of an SMS. Prescriptive flight and duty time limits have traditionally been used as primary fatigue risk control mechanism while an FRMS approach is evolving as an alternative approach that allows an operator to draw upon the growing body of fatigue science for improved fatigue risk management.

An official definition of FRMS has not yet been published by ICAO, however one suggested definition is *"a data-driven, flexible alternative to prescriptive flight and duty time limitations which is based on scientifically valid principles and measurements. It requires a continuous process of monitoring and managing fatigue risk".[1]*

In practice, FRMS is a holistic risk management approach that includes risk assessments, mitigation strategies, training and education programs, monitoring systems, and continual adaptation processes for reflecting changing circumstances and feedback. Operationally it may also be viewed from a prevention, prediction, detection, and intervention perspective.

FRMS is an approach that complements performance-based legislative structures that regulatory bodies, such as CASA, are moving towards. Performance-based legislation specifies what is to be achieved, but does not dictate how the outcome must be achieved. An example of a primary civil aviation safety outcome has been stated by the European Aviation Safety Authority (EASA) that:

"no crew member must allow their task achievement/decision making to deteriorate to the extent that flight safety is endangered because of the effects of fatigue[1]"[2].

Achieving such a broadly-stated outcome with scientific validity and a data-driven approach highlights the primary opportunity for biomathematical fatigue models. When used appropriately, with an understanding of their limitations, mathematical models provide a mechanism to quantitatively incorporate some of the latest data-driven, scientific knowledge into an FRMS.

3.2. Mathematical fatigue models

A "biomathematical model" may be simply understood as set of equations that quantitatively predict the output of a system when it is subjected to a known set of inputs. Biomathematical models of human fatigue contain equations that predict a fatigue risk metric or correlate thereof based on factors such as sleep history, time of day and workload. Models are typically developed using a data-driven process, in which their equation structures and parameter values are selected to match empirically observed outcomes; after which the model is validated against additional data and refined as needed (and this process is repeated when new data and/or new scientific information become available). The power of models lies in their ability to embed scientific understanding from empirical observations into generalized, qualitative/quantitative prediction tools.

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[1] Not to be misinterpreted that responsibility rests solely with the crew member. It is also a responsibility of the company to utilise strategic and tactical fatigue risk management practices to ensure no crew member is allowed to operate if there is reason to suspect that safety could be endangered due to fatigue.

In aviation operations, from the perspective of a crew member, a sequence of fatigue risk factors cascade from fatigue-causing conditions, to a fatigue state of the individual, to the risk of committing task errors, through to the risk of a serious incident or accident. Given knowledge of the fatigue-causing conditions, a biomathematical fatigue model generates predictions of a probability or risk associated with one of the real-world outcomes. Important considerations in the application of fatigue models to decision making include the inputs used by a model, the components that are captured by the model's equations, the types of outputs generated by the models, the process used to validate the model, and the methodology used to interpret the model outputs. The relationship between real-world aviation environments and model-based fatigue risk predictions is shown in Figure 1. Five important considerations in the application of models to fatigue risk assessment are highlighted in Figure 1 and discussed in detail.

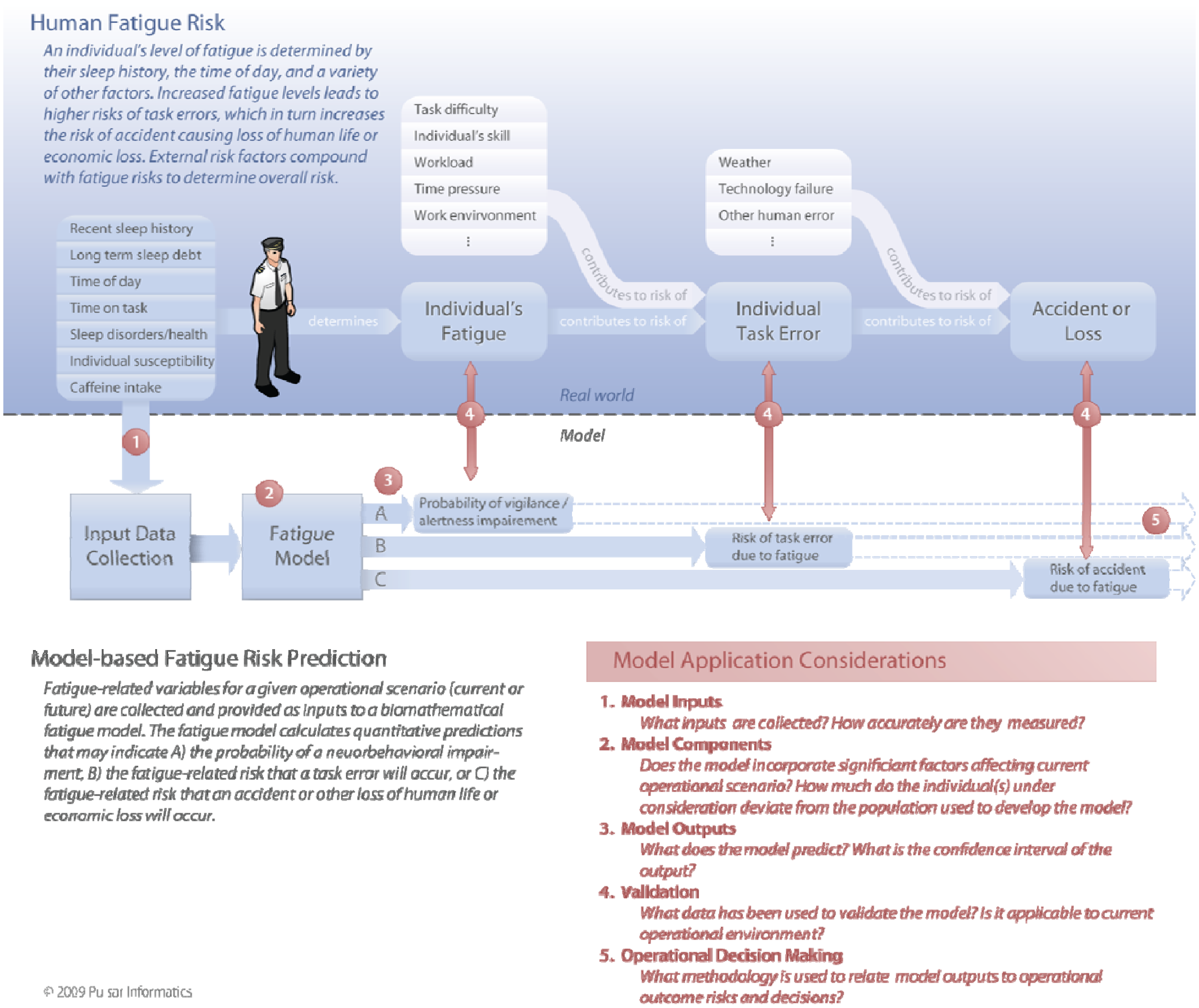


Figure 1. Real-world aviation fatigue risk flow chart, the parallel model-based fatigue risk prediction, and model application considerations.

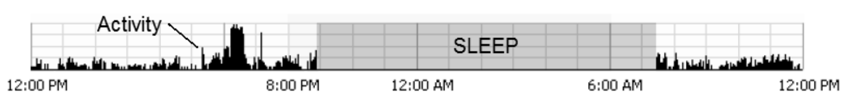
3.2.1 Model inputs

The inputs to a biomathematical fatigue model are the fatigue-causing factors that the model uses, with the model component equations, to determine output predictions. In a model's equations, the inputs are the 'independent variables'. For a given fatigue-causing factor, there may be multiple distinct input types that provide data for the model. For example, while all models incorporate a component that reflects sleep history, the input may take the form of actual sleep times, scheduled sleep time, or work hours. The *quality* of input data and *availability* of sources within an organisation to provide the data are two important considerations for selecting and utilising a fatigue model.

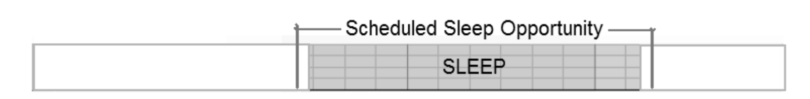
Sleep inputs

Actual sleep time: The quantity and timing of actual sleep acquired is the primary determining factor in predicting fatigue related to sleep deficit. Most models accept sleep times as a direct input, however in regular operational settings sleep times are not directly known and must instead be measured or predicted using a proxy input variable.

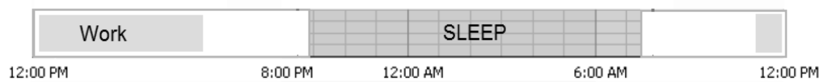
Actigraphy: Measuring the physical activity of an individual over a twenty-four hour period, typically using a wrist-worn accelerometer, provides a motion signal from which manual or computerised analysis can reliably estimate wake and sleep periods. Actigraphy input to a model provides an accurate, objective estimate of sleep timing and duration; however it requires individuals to wear a physical sensor. Actigraphy provides information about sleep times that occurred for a specific individual, but cannot serve as an input for model predictions of future scenarios.



Scheduled sleep: In some circumstances there may be a window of time which is scheduled for sleep, and a model may estimate the likelihood of actual sleep obtained during the window. As a wide variety of factors affect sleep, such as time of day, social interactions and physical sleep environment, sleep time estimates can be based on only a subset of factors. For example, physiological factors such as the degree of prior sleep debt and time-of-day are used in some models to estimate the maximum obtainable sleep.



Work schedule: Work schedules are used by some models to estimate sleep periods that are likely to occur between on-duty shifts. The same variety of factors that affect scheduled sleep input apply here, and in addition other factors such as commute times introduce individual variability. Although work schedule is a data source that is directly available as part of operational crew scheduling, it will provide a less accurate estimate of actual sleep obtained, relative to more direct measurement methods (e.g. actigraphy).



Circadian inputs

Light exposure: Light exposure directly influences shifts in the timing of an individual's circadian biological clock cycle. Adaptation to a new time zone, for instance, occurs due to exposure to the shifted hours of daylight and the resulting gradual synchronization of the circadian biological clock. Shifts in circadian clock phase may be accelerated or delayed due to the specific pattern of light exposure timing and intensity. Models with a light exposure component utilise light timing and intensity in order to predict circadian phase shifts. Sources of data for light levels include direct measurement from wrist-worn devices with ambient light sensors, and light estimation based on latitude, longitude, and time-of-day. Wrist-worn sensors have been used primarily within research studies. Location and time-of-day light estimation is more amenable to operational planning, however specific light estimation models for aviation operations have not been widely studied or validated.

Aviation specific inputs

Crew type, sleep location, number of sectors, and departure/destination points: Inputs specific to aviation operations may be used by some models to indirectly generate estimates of the sleep, circadian inputs and workload. If the assumptions involved in the model are appropriate to specific operational conditions in which they will be applied, then data sources for these inputs may be readily available to an operator.

3.2.2 Model components

The internal components of fatigue models are the characteristics of human neurobehavioral physiology that are described by the biomathematical equations in the model. The following characteristics may be included:

Homeostatic Sleep Drive: The homeostatic process models the change in sleep propensity and fatigue attributed to time awake and time asleep. Obtaining inadequate amounts of sleep relative to individual sleep need leads to detectable deficits in alertness. These deficits manifest in a dose dependent manner (i.e. the more sleep is restricted the worse the level of deficit) and are modulated by a 24-hour fluctuation in alertness associated with a circadian process.

Circadian Process: The circadian process is governed by an internal biological clock with a period of approximately 24 hours (circadian pacemaker) that decreases levels of fatigue and sleep propensity during habitual day, and increases fatigue and sleep propensity during habitual night. This process operates independently of the time awake (modelled by the homeostatic process). Desynchronization of the internal circadian pacemaker from habitual waking and sleeping hours contributes to the increased fatigue risk of irregular shifts or jet lag conditions.

Chronic Sleep Restriction: Models of the homeostatic process have demonstrated predictive accuracy in explaining fatigue resulting from continuous extended wakefulness (total sleep deprivation). More recent data has shown that when a person experiences chronic sleep restriction (restricted sleep across a period of days), more sleep time than previously predicted is needed to restore alertness to baseline levels. Accounting for the accumulation of longer term ‘chronic’ impairment and recovery has been recently added to some biomathematical models, but it is an area of scientific uncertainty.

Circadian Phase Adaptation: The circadian clock aligns itself to external cues such as the timing of light/dark cycles (e.g. sunrise/sunset). Disrupting the timing of these cues by travel across time zones (jet lag), working at night or on irregular schedules may result in a realignment of the circadian clock that needs to be modelled in the fatigue algorithms in order to generate accurate predictions. Individuals alter their light exposure by the choices they make about when to sleep, go outside, etc. In the long haul aviation context, behaviour during layovers is likely to be an important factor affecting adaptation in different time zones and there is limited data available on this. Some circadian models adapt the phase of the circadian clock by using light exposure and timing as inputs, whereas others use rules based on magnitude of the time-zone shift to produce a circadian adjustment.

Because very few studies have tracked the circadian rhythms of crewmembers during flight operations, the rate of adaptation of the circadian clock after time-zone shifts is another area of scientific uncertainty.

Sleep Inertia: Sleep inertia decreases performance and alertness, and increases sleep propensity transiently after waking. Its effects are most severe immediately after waking from deep sleep and can last for as long as two hours [3].

Individualisation: Predictions are made to reflect the alertness of the "average" person. There is considerable variability between individuals in the amount of sleep needed and in vulnerability to impairment due to sleep loss [4]. Thus, alertness predictions for individuals can be improved by adjusting the models using individual-specific information.

Caffeine: Caffeine is a commonly used drug that provides a temporary alerting effect and a decrease in sleep propensity in a dose dependent manner. There are large differences among individuals in both the sensitivity to dose and time course of its effects. Although caffeine models have not been extensively validated, some models accept an input corresponding to a dose and timing of caffeine intake.

Time-on-Task: Fatigue is affected by a number of task-related factors. The duration of a task (time-on-task) has been shown to affect task performance with greater fatigue associated with longer sustained efforts on a given task. The time-on-task related effects are worsened with increased sleep loss and are modulated by the circadian clock.

3.2.3 Model outputs

The primary outputs from fatigue models are predictions of a fatigue-related risk score. The risk factor that the output score represents will be dependent primarily on the data used to develop and validate the model. The common types of model outputs include the following:

Objective measures of neurobehavioral performance: The probability of neurobehavioral performance such as vigilant attention, cognitive throughput, executive function, etc. is an output that may be predicted by models that have been designed based on data collected from studies in which individuals conducted neurobehavioral assessment tests (e.g. brief vigilance tests). The metrics of neurobehavioral predictions may be expressed in terms of test performance e.g. reaction time, lapses in vigilant attention, or number of correct responses, etc.

Subjective assessments of fatigue: Models may be designed to predict the probability of subjective fatigue assessment, if they have been developed based on data from subjective questionnaires. Subjective measurements have limitations due to biases introduced from self-assessment of fatigue, so should be treated cautiously in their interpretation relative to objective fatigue risk, however predicting the experience of fatigue may still find a role within an FRMS.

Subjective fatigue measures are relatively easy and cheap to collect and analyse in an aviation operation. They reflect how crewmembers feel, which will influence their choices about the use of countermeasures. Crew reporting of fatigue-related incidents provides vital feedback on the effectiveness of an operational FRMS. It is inconsistent to encourage an open reporting culture for this purpose, but to dismiss as unreliable crewmembers experiences as captured by subjective fatigue measures.

Fatigue-related task errors: The probability of a fatigue-related task error is a type of model output that has relevance to a particular operational environment. Objective assessments of fatigue-related task errors can be accomplished by measuring the operational task directly. Often times the task does not lend itself to measurement and so performance measures are embedded into the task (e.g. steering deviations, optimal use of thrust, etc.).

Models could also be used to predict the relative risk of fatigue-related performance errors by making inferences based on objective measures of neurobehavioral performance. An important limitation of this approach is that neurobehavioral performance tests are only limited 'part-tasks' that do not capture all the skill dimensions required for safe operation of an aircraft. In addition, neurobehavioral performance testing measures the status (and compliance) of an individual crewmember, not the functional capacity of a multi-person crew. Task error risk metrics assign a relative probability of a specific type of task error at a given point in time.

Fatigue-related risk of operational accidents: Predictions of fatigue-related contribution to the risk of an operational accident causing loss of human life or financial costs would be the most easily interpreted model output for use in an FRMS. This type of prediction is different than fatigue-related task errors, as most aviation systems are built with safety factors and layers of redundancy that provide a degree of tolerance to human error. Fatigue-related operational accidents usually involve an unfortunate concomitance of multiple contributors and occur with a very low base rate. Accident risk metrics assign a relative probability about the presence of fatigue related risk factors for an operational accident, but developing such models would be especially difficult in the aviation industry with low base rates of accidents.

Estimated sleep/wake times: Models that accept work times, or scheduled sleep opportunities as inputs may estimate sleep/wake times as an intermediate variable that can be provided as an output. The duration of sleep obtained during a sleep opportunity window is affected by numerous factors, including a biological sleep propensity that is determined in part by homeostatic and circadian states. There are "circadian forbidden zones" during the day when initiating sleep is difficult especially when combined with a low homeostatic sleep drive. In addition to use in predicting fatigue, estimations of timing and duration of sleep can be used to develop biologically compatible schedules.

Confidence intervals: Model predictions typically represent estimated average fatigue or risk levels. Actual levels can vary from this mean, and confidence intervals are used to represent the range of values that can be expected as part of the random variation.

3.2.4 Data sets and validation

The data sets used to develop a model impact the scientific validity of its risk predictions to specific operational tasks and the range of operating conditions over which its predictions can be considered applicable. Ideally, civil aviation fatigue models would be developed based on large data sets of embedded task performance metrics (from flight data collection systems such as FOQA, for example) and accident rates from flight crew operating over a range of flight times and operating conditions identical to those that the model is predicting. In practice, difficulty of measuring operational task performance, low rates of aviation accidents, and the cost of data collection present barriers to such an approach to model validation.

The common scientific foundation for most fatigue model development has come from laboratory experiments, in which the temporal profile of fatigue of healthy subjects under imposed sleep restriction or simulated time zone shifts is measured using objective neurobehavioral tests (e.g. reaction time) and/or subjective questionnaires (e.g. subjective sleepiness scales). Direct relationships between test measures and risks for specific operational tasks has not been widely established, however objective measures such as lapses in vigilant attention on reaction time tests are generally held as good indicators of factors that will increase relative likelihood of error risks for a wide range of tasks.

Of seven models evaluated at a modelling workshop sponsored by the United States (U.S.) Department of Defense, U.S. Department of Transportation, and National Aeronautics and Space Administration (NASA) only two specifically relied upon aviation data for development or stated their relevance to aviation operations. At the time of the workshop in 2002, the System for Aircrew Fatigue Evaluation (SAFE) model was specifically developed for aviation operations. The Sleep, Activity and Fatigue Task Effectiveness (SAFTE) model was developed for military and industrial settings, and included a translation function for pilots [5]. While some model features and capabilities have advanced since this time, there has not been a substantial addition of validation data from civil aviation operations.

The state-of-the-art in fatigue model development is seeing the incorporation of some field-collected operational task error data into model refinement for specific industries. This is a not a highly mature area in the modelling community and the quantity of data collected is not substantial, but steps forward have been taken in ground transportation environments. However, some data from aviation operations is needed before models can be refined to provide quantitative estimates of fatigue-related risks of task errors and accident rates in the aviation environment.

3.2.5 Model applications

A primary role of many models within an FRMS is to provide a strategic rostering support tool aimed at providing an initial validation for newly developed or modified rosters. This still requires other elements of the multi-layered FRMS to validate these changes and/or to detect problems with the changes. Specific model application recommendations are provided in subsequent sections, but the general types of decision making support that can be provided by models depending on their capabilities are:

Schedule risk assessment: Models can be used to estimate a fatigue risk score for a crew roster. Models will typically provide fatigue risk over time, which may for example be examined to identify periods of high risk. The schedules can be varied to optimise different criteria to maximise overall efficiency while reducing risk exposure due to fatigue. The risk assessments are understood to only be a fatigue risk probability based on a representative population, and need to be tailored to specific operational environments for risk assessment interpretation.

Countermeasure proposal: Models can be used to evaluate the opportunity for countermeasures such as caffeine intake, light exposure or napping to reduce effects of fatigue.

Individualised fatigue predictions: Models can be tailored to specific individuals to predict fatigue levels over a time horizon. Individualised fatigue predictions can provide fatigue predictions with less uncertainty than generic population average predictions. Models capable of this function require further data inputs specific to individuals e.g. actigraphy data.

4. Model comparison and assessment

Six biomathematical models from commercial and academic organisations are reviewed. All data presented here is based on responses from each organisation to a survey conducted in September 2009. No independent verification of claims has been conducted. Users should ensure that they are provided with written information regarding the dimensions of fatigue that are considered by the model, the mechanisms by which they are considered, data sets used to validate the model, and the cautions and limitations that should apply to interpretation of outputs. Model developers or distributors should discharge their duty of care to ensure that this information is comprehensive, accurate and does not overstate model capabilities.

An overview of the models and their related products and services is provided, followed by a detailed feature comparison table, then a discussion of model features in the context of commercial aviation applications.

4.1. Model overview

Four models are offered by commercial organisations, and two models are supported by academic institutions. A brief description of each model and information regarding products and services is provided to allow a quick familiarisation. This information is indicative only and may be subject to change. For further information on model specifics a selection of references provided by model representatives is listed, and contact details are provided to allow direct inquiries.

Circadian Alertness Simulator (CAS)

Institution: Circadian Technologies Inc., United States, www.circadian.com
Contact: Todd Dawson, VP Technology, tdawson@circadian.com
+1-781-439-6307
Model version: CAS 4.2
References: [6, 7]
Description:

The Circadian Alertness Simulator model incorporates sleep history (homeostatic) and circadian components, and an estimator of sleep timing. The model has been primarily applied in ground transportation and shift work environments. Validation studies have examined correlations between fatigue indexes and accident rates in ground transportation operations. As of September 2009, Circadian Technologies is participating in long-haul aircrew fatigue studies with three airlines which may result in an aviation specific version.

Products and services:

- Software package with single seat annual licenses, or a corporate license with annual maintenance.
- Model intellectual property can be licensed for rebuilding/integrating into client's software, or embedded in other tools such as the Fatigue Accident/Incident Causal Testing System (FACTS).
- Consulting and training services using the model include: designing and implementing comprehensive Fatigue Risk Management systems for transportation and other industry clients; fatigue risk assessment for a workgroup, population or schedule, and implementation of fatigue mitigating tools; and accident analysis/investigation to determine the likelihood that fatigue was a contributing factor.

Fatigue Audit InterDyne (FAID)

Institution: InterDynamics Pty Ltd, Sydney, Australia, www.interdynamics.com
Contact: Len Pearson, len.pearson@interdynamics.com
References: [8-11]
Description:

The FAID model originated from research at the Centre for Sleep Research, University of South Australia, and was designed to predict worker fatigue directly from shift schedules. It accepts start of work shift and end of work shift as sole inputs, and does not predict actual sleep obtained or fatigue per se but rather a fatigue-related score based on 'sleep opportunity'. It was designed to enable organisations to demonstrate that they have provided employees with an adequate opportunity to sleep. The model has been validated against laboratory and field studies. It has been applied to estimating work-related fatigue during shift work, extended work hours, and as a decision-support tool for managing fatigue-related risk.

Products and services:

- Software packages in standard versions, customised to suit corporate reporting systems, and as a dynamic linked library for inclusion into third party rostering systems and web-based aviation management systems.
- Consultancy services for risk-based integrated fatigue management and development of fatigue tolerance levels for individual task-based risk assessment.

Interactive Neurobehavioral Model (INN)

Organisation: Brigham and Women's Hospital, Boston, United States.
Contact: Elizabeth Klermann, MD, Ph.D
References: [12-19]
Description:

This model has been developed based on laboratory studies examining both fatigue factors, and adaptation of circadian phase to light exposure. While used primarily within academic settings, this model is notable in the landscape of fatigue models for its dynamic model of circadian physiology that predicts circadian phase shifts from different patterns of light exposure.

Products and services:

- No commercial products or services are currently offered.

Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE)

Organisation: Fatigue Science, United States, www.fatiguescience.com
Contact: Dr. Steve Hursh, Dr. John Caldwell, info@fatiguescience.com
References: [14, 20-22]
Description:

The SAFTE model includes a sleep reservoir, circadian rhythm , and sleep inertia component, and has an 'auto sleep' function that calculates likely sleep times based on work schedules and sleep physiology. The SAFTE model has been originally based on laboratory data, but the sleep calculations have been validated in ground transportation operational studies. A software version of a Fatigue Avoidance Scheduling Tool (FAST) has been tailored to accept aviation-specific inputs.

Products and services:

- Software packages in two versions: FAST and FAST AVIATION. License terms dependant on the duration of the licensing period (1 vs. 2 years), and the intended use of the software (i.e. corporate versus consultant).
- Consulting services, using both FAST and FAST AVIATION are available through Fatigue Science.

Sleep / Wake Predictor (SWP)

Organisation: IPM/KarolinskaInstitutet, Stockholm, Sweden

Contact: Dr. TorbjörnÅkerstedt, torbjorn.akerstedt@ipm.ki.se

Model version: 2009:1

References: [23-25]

Description:

The Sleep/Wake Predictor model (previously known as the Three-Process Model of Alertness) has been developed by Dr. Akerstedt at the academic Karolinksa Institute. It is similar to the basic two-process model, but also accounts for sleep-inertia effects, predicts likelihood of sleep onset and sleep termination based on physiological parameters, and has been recently modified to better account for chronic sleep restriction conditions. The model has been validated in a number of shift work studies and a road accident study.

Products and services:

- A no-cost web-based interface to the model is currently under development.
- Advice on flight routes, truck routes, and evaluation of fatigue in crash investigations are services that the model has been used.

System for Aircrew Fatigue Evaluation (SAFE)

Organisation: QinetiQ, Centre for Human Sciences, United Kingdom, www.qinetiq.com

Contact: Douglas Mellor, dmellor@qinetiq.com

Model version: 5.0

References: [26-38]

Description:

U.K. Civil Aviation Authority (CAA) sponsored research has driven development of the System for Aircrew Fatigue Evaluation (SAFE) software model, with the original objective of supporting assessment of permissible Flight Time Limitations for operators. The model has been further validated using operator data, an improved cumulative fatigue function and information from the updated CAA Paper 2005/04 'Aircrew Fatigue: A Review of Research Undertaken on Behalf of the UK Civil Aviation Authority.' Version 5 of SAFE, has been delivered to the CAA, which it is now using for fatigue risk assessment of rosters proposed by industry.

Products and services overview:

- At the time of this report commercial availability was not finalised, but work is in progress for it to be made available to rostering companies and possibly individual operators.

4.2. Comparison of model features

The features reported by representatives for each model are listed in Table 1 and organised by the supported inputs, components, and outputs; types of validation data sets used to develop the model; and the model application goals. This information is not independently verified, so prior to use, operators should obtain written information from model distributors. A comparison of data sources used to validate models is provided in Table 2.

Table 1. Comparison of model features. Bullets indicate capability or feature is claimed by model representatives to be supported in some degree.

	CAS	FAID	INM	SAFE	SAFTE	SWP
Model Inputs						
Actual sleep time	●		●R	●	●	●
Actigraphy data			●		●	●
Sleep schedule	●			●	●	●
Work schedule	●	●R		●R	●	●
Time zone changes	●			●*	●	●
Light exposure	●		●R			
Crew type				●R		
Sleep in bunk or seats				●		
Take-off and landing waypoints				●	●	
Caffeine dose	●				●	
Model Components						
Homeostatic sleep drive	●	●	●	●	●	●
Circadian	●	●	●	●	●	●
Chronic sleep restriction (Cumulative fatigue)	●	●		●	●	●
Sleep inertia	?		●	●	●	●
Circadian phase adaptation	●		●	●	●	●
Caffeine	●				●	
Sleep quality	●			●	●	●
Work type	●			●	●	
Time on task	●	●		●		●

	CAS	FAID	INM	SAFE	SAFTE	SWP
Trait individualisation	●				●	●
Model Outputs						
Objective neurobehavioral metric	●		●	●	●	●
Subjective alertness metric	●	●	●	●		●
Fatigue risk metric	●	●		●	●	●
Estimated sleep/wake times	●			●	●	●
Confidence intervals	●				●	●
Model Application						
Schedule assessment with graphical interface	●	●	●	●	●	●
Schedule assessment with data file batch processing	●			●	●	
Caffeine countermeasure	●				●	
Light exposure countermeasure			●			
Napping countermeasure	?		●	●	●	●
Individualized Fatigue Prediction	●				●	●

● Capability/feature reported by model representatives to be supported in some degree

^{R} Required input

* Time zone changes are automatically calculated

CAS = Circadian Alertness Simulator
FAID = Fatigue Audit Interdyne
INM = Interactive Neuro-behavioural Model
SAFE = System for Aircrew Fatigue Evaluation
SAFTE = Sleep, Activity, Fatigue, and Task
SWP Effectiveness = Sleep/Wake Predictor

Table 2. Comparison of data sources used to validate models. Solid bullets indicate data collected in aviation operational environments; solid triangles indicate data collected in laboratory or non-aviation operational environments.

	CAS	FAID	INM	SAFE	SAFTE	SWP
Validation Data†						
Laboratory neurobehavioral tests / subjective questionnaire studies	▲	▲	▲	▲	▲	▲
Aviation operational environment neurobehavioral tests & subjective questionnaires	(Note 1)			●[39]		
Operational task error	(Note 1)	▲[40]			▲[41]	
Operational accident risk	▲[42]				▲[41]	▲[43]
Sleep duration prediction from work schedules				●[44-46]	▲	

● Data collected from aviation operational environment

▲ Data collected from laboratory or non-aviation operational environment

† References provided to validation data sets are representative rather than comprehensive

CAS = Circadian Alertness Simulator
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Note 1: As of September 2009, Circadian Technologies is participating in long-haul aircrew fatigue studies with three airlines. Data from these studies are anticipated by Circadian Technology to improve model predictions of in-flight and layover sleep, fatigue risk and crew performance.

4.3. Discussion of model capabilities relative to civil aviation

All models reviewed contain a homeostatic component, predicting increasing/decreasing fatigue with time awake/asleep, and a circadian component, predicting periodic changing of fatigue within a 24-hour cycle. The models are similar in this regard as they derive a common foundation from the first two-process model of sleep regulation[47]. Differences between the models exists in some easily differentiated areas like the types of inputs accepted, and also in more difficult to compare areas such as the modelling accuracy of chronic sleep restriction effects. Some of the notable comparison points are discussed below.

Aviation specific operational inputs

The SAFE and SAFTE models have been tailored to accept inputs that are unique to aviation operations. Crew type, in-flight bunk type, and take-off and landing waypoints are operational parameters that the models use to infer sleep times, quality of sleep and circadian shifts. The quality of the inferences from these parameters to sleep and circadian variables, and the advantages of these inputs over just work schedules or scheduled sleep times would need to be determined for a specific operational environment.

Data sets and validation for aviation risk

Assessing the accuracy of a model prediction's trends, and the validity of risk assumptions for aviation-specific task errors or incidents that can be drawn from the predictions is naturally of high importance when considering the application of the model. Due to the relatively sparse validation data collected in operational civil aviation environments, this is not easy to directly address. Examining the data that has been used to validate a model from aviation, laboratory, or other industrial applications, may inform this question. The SAFTE, CAS and SWP have published validation results for ground transportation risks. Railway incidents have been predicted by SAFTE, and trucking incident data has been used with CAS and SWP. Sleep patterns analysis from aviation flight crew have been examined with the SAFE model, and data from 30 ultra long haul aviation operations has been incorporated by the SAFE model.

Sleep time inputs

The accuracy of models is contingent on accuracy of the inputs, and exact timing of sleep episodes would be a preferred input for biomathematical fatigue models. In research environments sleep/wake times may be known exactly, but in operational settings, sleep/wake times are rarely known and are difficult and costly to collect. In contrast work schedules are known and controllable.

All models except FAID accept actual sleep times as an input, which would allow use in fatigue prediction tasks where the data is available. The INM model requires input of actual sleep times, however other models have been augmented to allow proxy inputs as alternatives when sleep times are not available. An input such as scheduled time in bed may be applicable to estimating sleep during scheduled naps during ultra-long haul flight, whereas inputs like work times would be applicable to estimating sleep obtained during layovers.

Chronic sleep restriction components

A model's ability to account for cumulative sleep debt and efficacy of recovery sleep are important in civil aviation applications, especially given objectives for efficient, high productivity rosters with minimal crew downtime. One of the weaknesses identified in all models evaluated in a 2004 study [48]was their lack of ability to predict the effects of chronic sleep restriction and recovery from it. The INM model was built primarily from total sleep deprivation data and still does not include chronic effects, the FAID model utilises a weighted sliding window that incorporates sleep from the previous seven days and has not changed since 2004, and the CAS, SAFTE, SAFE, and SWP models claim incorporation of chronic sleep restriction effects using variations of accumulation and dissipation functions, some of which have been updated since 2004. The SAFTE model has been validated on a sleep restriction study with a fourteen day duration. The CAS parameters were initially developed using data sets of 2-4 weeks of sleep, alertness and performance data collected from real world transportation operators working a variety of work and sleep schedules. Quantifying the effects of chronic sleep restriction is still an open issue in the scientific community especially since relatively few long-term sleep restriction data sets exist due to the prohibitive cost of studies. While differences exist between the models' chronic effect components, it is likely that the negative impacts of chronic sleep restriction are underestimated to varying degrees in all models. The analysis of chronic effects is currently an area of active scientific research, and new modelling approaches that specifically address chronic effects have recently been identified [49]. As new and existing models mature, commercial availability of enhanced chronic effects modelling may become available.

Circadian adaptation

Two distinct approaches are utilised for tracking circadian adaptation. The INM and SAFE models use mathematical equations representing human sensitivity to light and its time-shifting effects on circadian physiology. These equations have been matched to laboratory data sets of observed circadian phase shifts as a result of simulated jet lag or other light exposure conditions. The INM model requires ambient light level as a direct model input, whereas the SAFE model estimates light intensity based on location and time of day. Cockpit light level data has been collected in at least one study [50]; however, studies documenting the specific SAFE light estimation algorithm have not been published. Operational use of the INM would require portable light sensors, or the addition of a light estimation component. The SAFE, SAFTE, and SWP models utilise simpler circadian adaptation approaches based on rule-of-thumb principles (e.g. x-hours of circadian shift per day in the direction of a new time zone). The FAID model does not contain a circadian phase adaptation component, and assumes a fixed relationship between time-of-day and circadian phase. The more scientific method used by the INM and SAFE models may provide greater accuracy in predicting circadian adaptation, however circadian adaptation has not been extensively validated in operational settings and at this time should be considered largely unknown, especially in operations with relatively short layovers as are common in civil aviation

The importance of circadian phase adaptation effects in civil aviation operations will be significantly affected by the types of flights flown. For short haul routes with crew sleep scheduled during typical night time hours, circadian adaptation may be of minimal importance. On the other hand, it may be extremely significant in long-range or ultra-long haul routes with crew layovers in very different time zones and/or crew sleep irregularly scheduled.

Individual variability and confidence intervals

The effects of sleep loss vary considerably among individuals. In general alertness models have been calibrated to represent group average, or the alertness of the 'typical' person. From a fatigue risk management perspective, the use of average predictions may be unsatisfactory for producing schedules which properly account for the risks of more demanding rosters. Models tuned to each crew member would provide the greatest accuracy and the least uncertainty, however this requires personal assessments of traits. Morningness/eveningness questionnaires used by the CAS model provide one aspect of individualisation, however full state-of-the art individualisation to specific traits based on relevant performance measurements has not been incorporated into any of these models.

Another approach to addressing the complexity of individualising a model, and assessing operational risk for a crew population is the use of prediction confidence intervals. Confidence intervals are now produced by the CAS, SAFTE, and SWP models and provide a range of values for each prediction that attempt to account for the variability within the population. However, the reliability of confidence intervals depends on how well the population for which they were originally calculated matches the population to which the model is being applied (age, gender, health status, task familiarity, testing conditions, etc).

Risk decision making based on confidence intervals can more accurately address statistical objectives such as minimising the probability of high risk fatigue conditions.

5. Possible application of models in FRMS

Discussion of overall FRMS strategies is beyond the scope of this document but a successful FRMS will include a broad spectrum of programs, including risk assessments, mitigation strategies, training and education programs, monitoring systems, and continual adaptation processes. While biomathematical fatigue models are a non-essential part of an FRMS, they can provide support in highlighting aspects of fatigue-related risk within FRMS programs. They cannot, however, form the sole means upon which fatigue risk management operational decisions are made, and it is essential that operational personnel avoid overreliance on the outputs of biomathematical models to support their decision making. The outputs of biomathematical models can provide numbers which are compellingly concrete values, which can adversely influence decision making with a significant risk of overreliance on the numbers.

Should an operator elect to utilise a biomathematical model as part of a multi-layered FRMS, considerations should include selection of an appropriate model, applications of the model with the FRMS, additional factors to support appropriate model use, and trends for future use.

Selecting an appropriate model

When selecting a biomathematical model for use as a component within an FRMS, organisations should take into account a number of factors to ensure that the model is relevant and valid for use in the specified organisational context. The following are some of the factors that should be considered:

- Whether the supporting user guidance, training and tutorials are sufficient to educate end users on how to use the model, the assumptions and limitations of the model, and the dimensions of fatigue that are modelled.
- The database on which the model is based and its equivalence to the population to be assessed.
- Whether the degree of individual variance in the database population is acceptable and relevant to the population to which the model is to be applied. This will be dependent on how the scores are to be used, as the degree to which the model is applicable to individuals' decreases as the variance increases, necessitating the use of additional risk management controls.
- Whether published literature (reflecting the current state of knowledge on fatigue management) supports the use of the model for its proposed use and what has been found regarding the operational strengths and weaknesses of the model.
- Whether the model output predicts what the organisation is trying to predict. For example, some models predict cognitive effectiveness, others opportunity for sleep and others both sleepiness and risk, etc.
- How the model will fit into the FRMS.
- The potential risks and opportunities associated with use of the model. For example, rostering staff may find ways to use the model to achieve operational outcomes in ways that are contrary to the intended uses of the model (work arounds).
- How an SMS supports the appropriate use of the model such as the level of competency and training of users and the quality assurance processes necessary to ensure the model continues to be relevant to organisational goals.

Furthermore, any opportunity to take organisational lessons already learned from rostering practices (e.g. rosters previously modified due to the impact of fatigue) and/or known fatigue risk(s) provides an opportunity to match that information with model outputs to gain a broad benchmark on how well the proposed model identifies known fatigue risk(s). Some organisations, when provided a trial of a biomathematical model, utilised this approach as part of their decision making to determine if the model was appropriate for their organisation. Even with limited technical knowledge of the model on the part of the end-user, this approach can provide an opportunity to ask the modelling representative further questions, in the case that the model fails to detect known fatigue risks.

Model applications within an FRMS

Due to limitations of biomathematical models and the relatively new practice of using fatigue models in civil aviation, a cautionary approach should be taken and FRMS should be designed as comprehensive, multi-layered systems, in which biomathematical models, if used, provide a supporting role.

It must be emphasised that it is vital to avoid overly simplistic interpretations of numerical fatigue scores when utilising biomathematical models, particularly given the propensity for qualitative information to be interpreted as quantitative. Furthermore, any specified upper limit for fatigue scores must be validated within the operational environment in which they will be used. In some organisations inappropriate use of fatigue scores has resulted in practices (e.g. overreliance by managers/supervisors on fatigue scores for decision making) that have undermined the quality of the FRMS and ultimately led to an FRMS in which operational staff has minimal confidence in the system to appropriately manage fatigue. In the worst cases, the overuse of and overreliance on biomathematical modelling has resulted in an FRMS which actually degraded fatigue management.

Some opportunities for integrating models into an holistic FRMS are listed below as well as some further considerations (limitations). Applicability should be evaluated on a case-by-case basis considering the specific capabilities of a selected model and the needs of the organisation.

1. **Identify high risk fatigue vulnerabilities within existing flight crew schedules to provide a focus for mitigation strategies.** Given a roster with fixed flight times, predictions of fatigue risk can highlight operational periods where elevated fatigue levels may coincide with critical tasks. During these high risk periods, mitigation strategies for crew members may be encouraged (e.g. extra rest time, strategic caffeine consumption) or other risk management actions from an FRMS may be emphasised.

2. **Compare fatigue risk scores of alternate crew roster options.** Output predictions of current biomathematical fatigue models are suited for performing relative comparisons. The strongest scientific basis of fatigue models is they capture important fatigue *trends*, rather than predicting absolute values of error or accident probabilities. When evaluating alternative flight schedules, a comparison of model predictions of the magnitude and timing of high fatigue periods may be included in the selection criteria.

3. **Inform fatigue risk assessments during the design of schedules and fatigue mitigation strategies for crew rosters that extend beyond prescriptive Flight Time Limits (FTL) and Flight Duty limits (FDL)**. Demonstrating the safety of a flight schedule and crew roster against a scientifically-based standard, especially when outside of traditional FTL/FDL, is a task that biomathematical models may contribute towards. Operational validation data should be used to further support and justify this decision making. One approach may include comparing predicted risk scores of newly considered rosters against benchmark risk scores of rosters with good safety records (e.g. certain long range flights) using the relative comparison strategy outlined in the previous point, provided suitable benchmark rosters can be identified. This determination should not be an isolated decision but rather made with an understanding of complementary sets of other fatigue risk management strategies.

4. **Test efficacy of countermeasure recommendations within envelope of other operational constraints.** Exploratory scenarios may be passed through biomathematical fatigue model to test the potential impact of behavioural fatigue countermeasures such as at-home sleep timing, naps, caffeine intake, or light exposure management. Optimal strategies developed from comparison of model predictions may be used to complement educational material for crew or be integrated into other operational procedures.

5. **Develop interactive tools for fatigue risk management education programs for individuals and organisations.** Understanding the latest scientific knowledge about the effects of sleep and circadian factors on fatigue can be difficult for a lay person to absorb from technical documents. Computerised implementations of biomathematical fatigue models that allow users to interactively observe changes in fatigue predictions through a dynamic user interface could form a useful component in a fatigue risk management educational program.

6. **Do <u>not</u> interpret model predictions as indicating levels of fatigue for a specific individual at a specific time.** Biomathematical fatigue models predict fatigue risk for an average healthy person, or for a population distribution (if shown with population standard deviation). Direct assessment of fatigue state such as neurobehavioral tests should be used in cases where knowledge of a specific individual's fatigue state is desired. Development of fatigue model individualisation approaches may contribute to enhanced individual fatigue prediction in the future.

7. **Do <u>not</u> use models as fitness for duty tests to provide a 'green' light condition for an individual.** Predictions from biomathematical fatigue models cannot be used as basis for verifying that an individual will be in a safe fatigue state. Many

factors such as individual variability, environmental circumstances and operator (in)experience, could negatively affect an individual's risk level.

Additional supporting factors that should be considered in an FRMS:

An FRMS will include a broad range of components beyond the scope of this document. However, if biomathematical models are included, some complementary multi-layered strategies to pro-actively identify and manage fatigue risk should be considered. Some of these supporting factors are discussed below (this is not intended to be a complete list):

1. **Educate flight crew and operational decision makers about the appropriate interpretation of biomathematical model predictions.** The outputs of biomathematical models can provide quantitative numbers which are compellingly concrete values for decision making when contrasted to many other qualitative and process-oriented aspects of an FRMS. There is a risk of overreliance on these quantitative numbers, so education efforts and audits should ensure that a balanced view of the opportunities and limitations of models is maintained within an organisation's fatigue risk management culture and operating practices. In many practical applications of the models, the inputs are relatively imprecise data (e.g. estimates of sleep time and quality etc) which are then used to compute an output value. This numerical output can give the illusion of being precise and quantitative, even when it is attempting to predict a qualitative measure such as subjective fatigue.

2. **Ensure additional fatigue risk management controls provide redundancy to model-based fatigue risk identification.** Fatigue models cannot provide 'green light' for operational safety; additional fatigue risk management controls such as crew fatigue monitoring, and practices for ensuring sufficient adherence to rest times should also be in place.

3. **Create continuous model evaluation and improvement cycle through collection of fatigue-related data from operational environments.** Creating closed-loop feedback as part of an FRMS program, with fatigue measurements, task errors, or incident data collected and assessed relative to model predictions would provide a strong basis for long-term success with model-based fatigue management within an operational aviation environment. The scale of investment would likely be proportional to the size of an organisation, the emphasis within an organisation on optimising fatigue related costs and the maturity of the FRMS. Any such efforts, if shared among the industry, will help to advance fatigue science, improve models, and increase safety and cost-effectiveness.

Future trends

Some applications of biomathematical models for fatigue risk management that are at the forefront of technological research and development but have not yet been widely evaluated for use within civil aviation FRMS are listed below:

1. **Incorporation of fatigue models into automated roster optimisation algorithms.** The qualitative/quantitative output of biomathematical fatigue models presents an opportunity for fatigue-related cost functions or constraints to be incorporated in roster optimisation algorithms. Previously mentioned caveats about overreliance on the quantitative numbers would have to be carefully considered in these applications.

2. **Individualised feedback with data collection providing individually tailored fatigue predictions.** If fatigue or task error measurements and sleep monitoring data were available for specific individuals, then programs for providing individualised fatigue predictions [51] could be used for a variety of applications, including on-line fatigue monitoring and as an educational tool to help individuals develop mitigation strategies that work uniquely for them. These types of 'individualised' programs may improve predictions for individuals, but the same caveat applies, that they are only one estimate of the probability of fatigue, not an absolute measure of fatigue risk.

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