# THE USE OF BIOMATHEMATICAL FATIGUE MODELS AS TOOLS OF FATIGUE RISK PREDICTION

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**Summary**. A shift duty can become challenging to the human body if it is not respecting its natural body rhythm, especially if the work schedule requires sleep in the daytime and working at night. Another form of shift lag is circadian desynchronisation caused by crossing multiple time zones. Advanced technologies help researchers in developing quantitative computerised scheduling tools that would be capable of estimating the individual fatigue risk level at shift work. These tools are called Biomathematical Fatigue Models. But, can fatigue be measured objectively? Quantifying fatigue might be a difficult task to accomplish due to its complexity of various physiological and psychological factors. The focus is on the physiological aspects of fatigue and relates to the long duty hours, time since awake and circadian rhythm. As with most of the aviation technologies, these models were initially introduced for military operations where pilots were required to stay awake for 30 or even 48 hours during deployments. Since then, computerised scheduling tools based on biomathematical modelling are finding their way into commercial use within the transport industry. The recent introduction of Safety Management System allows the models to be implemented as an optional component of a comprehensive Fatigue Risk Management System, assisting the airlines in crew fatigue mitigation.

**Keywords:** Biomathematical Fatigue Models, fatigue risk prediction, Fatigue Risk Management System, homeostatic sleep, circadian processes, sleep inertia, BAM, CAS, FAID, FRI, SAFE, SAFTE-FAST, SWP

## 1. INTRODUCTION

Human evolution has made the human body adjust to day-night by creating night sleep. According to one of the theories, impaired vision at night time when hunters could not sufficiently react to the environmental factors caused the body to adjust to the external conditions and developed a recovery time called sleep (Caldwell, 2016). With the invention of electricity and factory production, shift work and high productivity techniques to satisfy competition were introduced. Meanwhile, the human body, habituated over millions of years to rest at night, still struggles with adapting to the variable working periods.

Working shifts brought along challenges, such as a phenomenon called fatigue. It is still believed that fatigue is a “state of mind” rather than a physiological need of the body to recover. Defined by ICAO, fatigue is: “A physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can impair crew member's alertness and ability to safely operate an aircraft or perform safety-related duties.”

Fatigue thus defines physiological and subjective (mental) effects that affect performance, physiological health and mental wellbeing. Whenever performance and task-related duties are critical activities, fatigue becomes a focus, such as in sports science, medicine, clinical psychology and the transport industry.

There are six causal factors (Coombes, 2016) to take into account when considering fatigue: sleep/wake periods, circadian drive, genetics, workload, medical and psychological factors. Only the first two factors – sleep/wake and circadian drive - can be quantified scientifically via research, as they impose the most predictable influence on sleep and performance. Other factors vary according to the individual and thus cannot be quantified.

Today advanced technologies allow the development of computerised tools where these factors can be inserted to pro-actively predict fatigue levels for certain tasks. These evidence-based tools are called Biomathematical Fatigue Models (BFMs).

## 2. INTRODUCTION TO BMM

Historically, the Flight Time Limitations (FTL) eliminated the fatigue risk through maximum duty times and minimum rest times which evolved from scientific and laboratory research and from evidence-based data collection. Principally, the FTL served as guidance for the Airlines/operators. As years have advanced, FTL started to be perceived as limitations. There is a strong inclination towards higher utilisation of resources where the focus stands on performance-based crew management systems and techniques.

For the purpose of safety and back-up for the newly introduced EASA FTL, Fatigue Risk Management System (FRMS) within a Safety Management System (SMS) is mandatory within an airline operation, as a comprehensive safety risk mitigation.

FRMS further represents: "a data-driven means of continuously monitoring and maintaining fatigue-related safety risks, based upon scientific principles and knowledge as well as operational experience that aims to ensure that relevant personnel are performing at adequate levels of alertness." (ICAO 2012a, p. xiii)

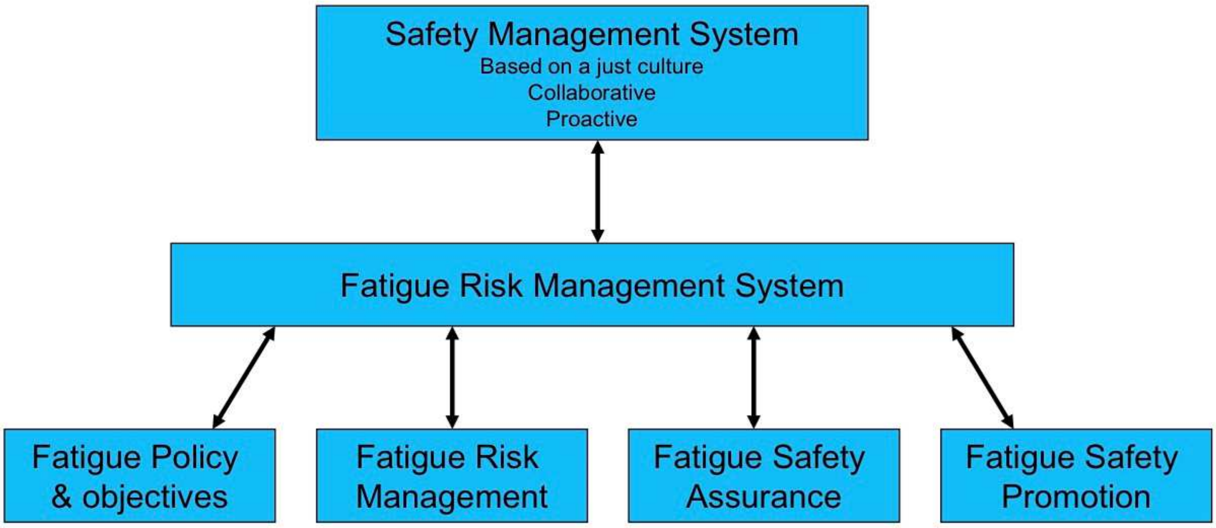


**Figure 1** - Relationship between SMS and FRMS
Source: (Robertson, K. Fatigue Management to SMS, FRMS and SAFE)

Advances in computer technology have allowed the Biomathematical Fatigue Models to be introduced along with the FRMS. These computerised scheduling tools are the only optional portion of the broader FRMS that requires a full understanding of their functionality and their limitations. It lies entirely with the operator whether an implementation of BFMs is necessary and if, the determination of appropriate model features are needed.

Biomathematical Fatigue Model is defined as:

"A computer programme designed to predict crew member fatigue levels, based on scientific understanding of the factors contributing to fatigue. All biomathematical models have limitations that have to be understood for their appropriate use in Fatigue Risk Management System (FRMS). An optional tool (not a requirement) for predictive fatigue hazard identification." (ICAO Annex 6, Part 1, Appendix 8, Section 2.1)

## 3. EVOLUTION OF BMM - BORBELY AND THE THREE-PROCESS MODEL

Borbély's original model of sleep regulation (Borbély, 1982) was based on many laboratory experiments and was intended to explain the timing and duration of sleep as a result of the interaction between two processes – Sleep (Process S) and Clock/Circadian (Process C).

Process S is also called a homeostatic pressure, where sleep onset occurs when S reaches a high threshold and wake up occurs when S drops below a low threshold. Process S decreases exponentially during sleep. Sleep loss and the so-called "sleep pressure" that builds up over time awake, are related to process S.

Process C is a sinusoidal function that relates to the time of a day and to the Circadian Rhythm. Despite its 24-hour cycle, it is influenced by "zeitgebers" such as the light and dark cycle of the local environment. Both processes operate independently.

Borbély's two-process model was intended to describe sleep and its purpose was not modelling fatigue or alertness. An extension to Borbély's model, by adding the Process W (Waking) had to be introduced in a Three-Process Model of Alertness (TPMA; Akerstedt&Folkard, 1995 and 1996) where W relates to sleep inertia and level of alertness prediction.

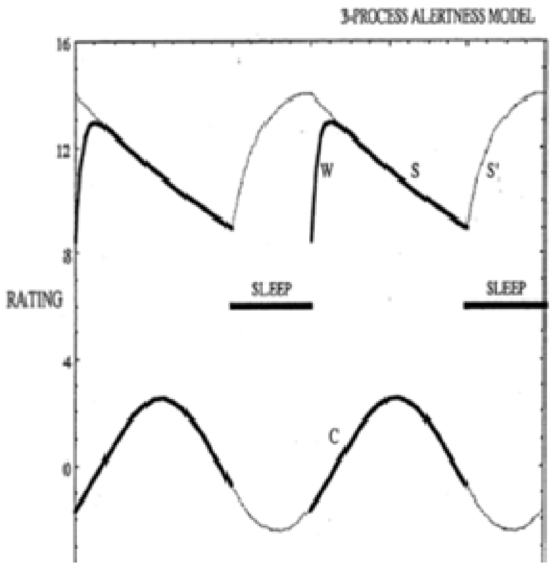


**Figure 2** - TPMA graphic illustration
Source: (CASA, Biomathematical Fatigue Models)

## 4. MODEL COMPONENTS AND INPUTS

The essential inputs are represented by work-rest schedule and/or sleep data. Sleep data can be obtained from subjective data or objective data. Subjective data are represented by Visual Analogue Scale (VAS), Samn-Perelli Scale (SP) and Karolinska Sleepiness Scale (KSS) which are described in the next paragraph of this text.

As the two- and three-process models prescribe, the main components are homeostatic pressure, circadian cycle and wakefulness.

**Homeostatic sleep drive**

Individual sleep requirement and the time since awake regulate the homeostatic process, called as process S. Insufficient sleep generates sleep deprivation and in a linear dependency, e.g. the higher chronic sleep restriction over consecutive days the more recovery sleep is required to restore the alertness.

**Circadian processes**

Process C works independently from the homeostatic sleep drive and is run by the internal body clock in an approximately 24-hour interval. During the habitual day, it decreases the level of fatigue and sleep propensity and increases the level of fatigue and sleep propensity at habitual night. Any de-synchronisation due to shift work or jet lag causes levels of fatigue to increase because it promotes sleep at times when the body is active and vice versa.

**Sleep inertia**

When the brain progresses through the process of waking up, a temporary performance impairment, grogginess or disorientation can occur causing sleep inertia (process W). Sleep inertia increases sleep propensity after waking up, especially from a deep sleep. It can last up to two hours since being awake.

Additional components to the three-process model include circadian phase adaptation, work type and time on task. Furthermore, some of the model inputs are required and are considered as essential, while work-related and individual inputs increase the accuracy of the fatigue prediction calculation.

Required inputs represent objective or evidence-based data, such as polysomnography, actigraphy and sleep diaries. Their priority is to collect a sufficient amount of sleep records. While polysomnography is an in-depth, precise and a very expensive way of obtaining laboratory data, actigraphy data collection can be run long-term in parallel with sleep logs. Sleep diaries would include additional resources, such as daily activities, nutrition and subjective fatigue.

Air transport industry is very specific when it comes to working related inputs as crews are affected by time zone changes, in-flight sleep opportunities, multiple sectors, workload, take off and landings and by the crew composition. Three or more time zone changes create sleep disturbances, fatigue and performance decrements and represent a significant input in long haul operation. Possible mitigation is the use of augmented crew and in-flight rest facilities, such as bunks or seats booked especially for the crew. Short haul operation would rather look at inputs related to the number of sectors flown at the day, time of take off and landing and workload.

The ability of individual inputs refines data above but the calculations are based on an average individual and should be used with caution. Individual data include individual's need for sleep (habitual sleep duration), morning or evening type (chronotype) and time spent on commuting.

## 5. OUTPUTS AND MEASURING FATIGUE

Prediction outputs reflect inputs and calculations involved. Identifying outputs with a lot of variable inputs would be very difficult without establishing rating scales. The standardisation of metrics is based on the range of the data and calculations involved, giving an estimated fatigue or alertness level over certain work period. Karolinska Sleepiness Scale and Samn-Perelli are the most commonly used subjective scales that define fatigue or alertness level.

KSS, the Karolinska Sleepiness Scale consists of 9 evaluation points on an one-dimensional scale and has been validated against objective measurement of sleepiness and performance evaluation. Values 1 to 4 describe alertness while values 6 to 9 outline sleep probability and performance degradation.

| | |
|---|---|
| 1 | Extremely alert |
| 2 | Very alert |
| 3 | Alert |
| 4 | Rather alert |
| 5 | Neither alert nor sleepy |
| 6 | Some signs of sleepiness |
| 7 | Sleepy, but no difficulty of remaining awake |
| 8 | Sleepy, some effort to keep awake |
| 9 | Extremely sleepy, fighting sleep |

SP, the Samn-Perelli Scale is another one-dimensional 7-point scale rating alertness and sleepiness in a range from “fully alert” to “completely exhausted”. Just as the Karolinska Sleepiness Scale, it is commonly used in aviation. Values 5 and 6 define “Fatigue Class II” where “duty is permissible but not recommended” and the highest value is considered as “Severe Fatigue”. A little disadvantage of the Samn-Perelli is the lower amount of values on the scale against the 9-point KSS scale. There is also a difference in wording, KSS spreads between “alert” and “sleepy” while SP is ranging from “alertness/ wakefulness” towards a “complete exhaustion and inability to function effectively”.

| | |
|---|---|
| 1 | Fully alert, wide awake |
| 2 | Very lively, responsive, but not at peak |
| 3 | Okay, somewhat fresh |
| 4 | A little tired, less than fresh |
| 5 | Moderately tired, let down |
| 6 | Extremely tired, very difficult to concentrate |
| 7 | Completely exhausted, unable to function effectively |

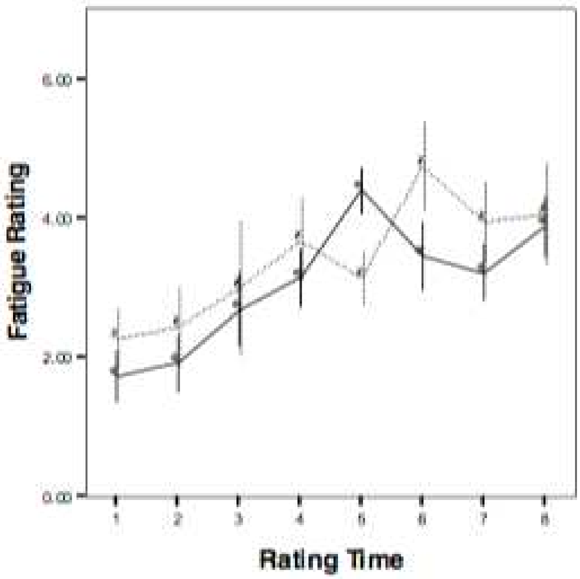


**Figure 3** - Fatigue rating on a scale
Source: (CASA, Biomathematical Fatigue Models)

VAS, the Visual Analogue Scale represents a linear analogue scale usually 10 cm long where the subject marks a point along the line corresponding the fatigue level. This is a very simple solution with a high sensitivity to small changes but there is no clear definition between "no fatigue" and "fatigue" along the line which makes the comparison generally difficult.

## 6. TYPES OF THE BIOMATHEMATICAL FATIGUE MODELS AND THEIR STRUCTURES

Most of the BFMs use the two- or three-process models and in addition, a "task related" function to consider the aspect of workload during the work period. Only the Fatigue Risk Index (FRI) relies on empirical data from shift work and aviation by using three separate components – cumulative pattern of work, duty-timing and task/break component. Prediction based on average individual is the common limiting aspect of all the models.

**Table 1** - Main underlying scientific background of seven models
Source: (CASA, Biomathematical Fatigue Models)

| Model | Main underlying scientific background |
|---|---|
| **BAM** | 3-process model + task related |
| **CAS** | 2-process model + task related |
| **FAID** | 2-process model + task related |
| **FRI** | Cumulative, duty time and job/breaks data from aircrews, train drivers and laboratory studies |
| **SAFE** | 3-process model + task related |
| **SAFTE-FAST** | 2-process model |
| **SWP** | 3-process model + task related |

Boeing Alertness Model (BAM) has been developed by the Jeppesen group and it is a three-process model with advanced sleep prediction, task load, augmentation, and ability to blend in actual sleep/wake when available (CASA, 2014). The model advantages are integration speed with pairing and roster optimisers, large-scale application, individual fatigue monitoring and fatigue mitigation strategies. The output of the model predicts sleepiness on the KSS scale and allows visualisation as well as individual fatigue level prediction on the CrewAlert application. The only limiting disadvantage of such a model is its cost.

Circadian Alertness Simulator (CAS). Model mainly focuses on individual's sleep-wake-work pattern in a combination of individual-specific settings. The specific fatigue risks include commuting, long haul, corporate and freight aviation. Just as the BAM, CAS model is costly but it has the capability of large-scale usage and crew planning integration.

Fatigue Assessment Tool by InterDynamics (FAID) is based on scientific research (laboratory and simulator) and knowledge (field study) gained over several decades on circadian factors, the effects of shift lengths, the timing of shifts, previous work periods and circadian phase adaptation (CASA, 2014). FAID has been primarily used within the Australian rail industry but a study of pilot performance and shift schedules (Stewart&Abboud, 2005) provided useful validation data from aviation. On a large-scale application, it can manage manually built rosters, assess evaluation across multiple locations, workgroups or fleet. The output is given in Key Performance Indicator (KPI) indicates the likely sleep opportunity. The FAID model disregards sleep inertia effects.


**Figure 4**- FAID analysis
Source: (Transport Canada. Chapter 2: Automated Fatigue Audit Systems.)

Fatigue Risk Index (FRI) was designed by the UK Health and Safety Executive and serves for comparing different work schedules, or for examining the potential impact of schedule changes. It combines the Risk Index (risk of an error) and the Fatigue Index (probability of sleepiness) which is expressed by extensively validated KSS value. The data originate from the rail industry shift work and newer data have been obtained from aircrews, empirical data and relevant scientific literature. With little inputs required, FRI is suitable for shift comparisons, fatigue and risk predictions but it is not reliable for forward scheduling. It is not aviation-specific and might tend to overestimate the fatigue risk of circadian adjustment for some individuals.

System for Aircrew Fatigue Evaluation (SAFE) is supported by the UK Civil Aviation Authority and has been validated by laboratory measurements of performance and onboard studies on long haul, short haul and cargo flights. The objective is a risk evaluation on particular scheduled duties and aircrew fatigue prediction. Safe provides a rapid assessment that is effective in all types of aviation operation by using a large database of pilot sleep and fatigue (CASA, 2014). It does not consider extended commute times and can be entered only via duty start of finish times alteration.

SAFTE-FAST combines Sleep, Activity, Fatigue and Task Effectiveness (SAFTE) with the Fatigue Avoidance Scheduling Tool (FAST). Its development by Dr Steven Hursh has been sponsored both by the US Federal Railroad and the US Federal Aviation and should provide operators with a prospective forecast of expected fatigue risk, detect roster vulnerabilities, estimate fatigue and cognitive effectiveness, optimise schedules and plan napping and recovery sleep. The model should also recognise "safety critical" events ("crewing") and other events ("non-crewing"), just as sleep fragmentation caused by environmental factors. Model analyses performance and sleep-wake metrics on a graphic interface. It will display flags in case of an exceedance.

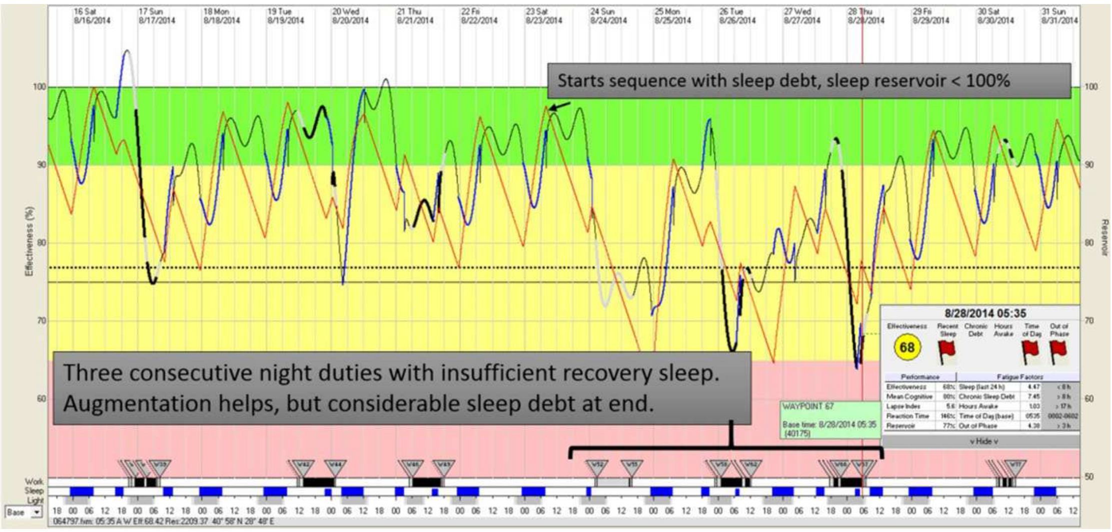


**Figure 5** - SAFTE-FAST visual interface
Source: (SAFTE-FAST. Visual SAFTE-FAST.)

Sleep/Wake Predictor (SWP) has been developed at the Karolinska Institute by Professor Torbjorn Akerstedt and originates from the Three-process Model of Alertness. The model accounts for sleep inertia effects, the likelihood of sleep onset and sleep termination based on physiological parameters and chronic sleep restrictions (CASA, 2014). By establishing the level of sleepiness on an alertness curve(1-21 point generic scale or KSS), the model aims to evaluate the potential for obtaining a restful sleep or alertness duration. The subjective data were validated by a number of experiments of altered sleep/wake patterns, laboratory performance tests, EEG parameters and from recent field studies. At calculation, the model requires very few inputs but all have to be inserted manually. It is suitable for individual fatigue risk analysis.

Implementation

The implementation of a specific Biomathematical Fatigue Model consists of a few assessment stages. The initial consideration should be based on the availability of specific applications in the operational environment. All of the models have been designed to fulfil different purposes, using different inputs computations and outputs (CASA, 2014). The selection should suit the best outcome delivery under the specific operational conditions.

Forward scheduling and non-scheduled operations application are supported by all the models. FRI was primarily designed for schedule comparison outside aviation. SWP is more suitable for an individual schedule assessment while other models were fitted to absorb and evaluate large-scale data. BAM, FAID and SAFE are capable of roster optimiser interaction.

The table below illustrates application possibilities in different models.

**Table 2 -** Model applications comparison (CASA, Biomathematical Fatigue Models)

| Model applications | BAM | CAS | FAID | FRI | SAFE | SAFTE-FAST | SWP |
|---|---|---|---|---|---|---|---|
| Forward Scheduling | X | X | X | X | X | X | X |
| Non-scheduled / Irregular operations | X | X | X | X | X | X | X |
| Work / Rest Cycles in Augmented Crew | X | X | X | | X | X | |
| Light Exposure and Countermeasures | X | X | | | | | |
| Napping Countermeasures | X | X | | | X | X | X |
| Individual Fatigue Prediction | X | X | | | X | | X |
| Training | X | X | X | X | X | X | X |
| Safety Investigation | X | X | X | | X | X | |

Model components

The next stage compares model features. There is a high commonality within all models, only FAID does not take sleep inertia and work type into consideration. FRI disregards the circadian phase adaptation.

**Table 3 -** Model components comparison (CASA, Biomathematical Fatigue Models)

| Model Components | BAM | CAS | FAID | FRI | SAFE | SAFTE-FAST | SWP |
|---|---|---|---|---|---|---|---|
| Homeostatic Sleep Drive | X | X | X | X | X | X | X |
| Circadian Processes | X | X | X | X | X | X | X |
| Sleep Inertia | X | X | | X | X | X | X |
| Circadian Phase Adaptation | X | X | X | | X | X | X |
| Work Type | X | X | | X | X | X | |
| Time on Task | X | X | X | X | X | X | X |

Model inputs

Actual sleep timing, habitual rest duration and chronotype are optional items of assessment with many models. Required inputs are work schedule and time at take-off and at landing. There is an obvious variation in models inputs due to the different scope and logic of selected biomathematical models.

**Table 4** - Model inputs comparison
Source: (CASA, Biomathematical Fatigue Models)

| Model Inputs | BAM | CAS | FAID | FRI | SAFE | SAFTE-FAST | SWP |
|---|---|---|---|---|---|---|---|
| Actual sleep timing | Op | Op | Op* | | Op | Op | Op |
| Work schedule | X | X | X | X | X | X | X |
| Time zone changes | X | Op | X | | | X | X |
| Crew composition | X | X | Op | | X | X | |
| In-flight rest facilities | Op | Op | Op | | X | Op | |
| Take off and landing waypoints | X | X | X | | X | X | |
| Multiple sectors | X | X | Op | | X | X | |
| Workload | | Op | Op | X | | | |
| Habitual sleep duration | Op | Op | | | Op | | Op |
| Chronotype | Op | Op | | | | | Op |
| Commuting | X | Op | Op | X | Op | Op | |

Model outputs

A difference can be seen at model outputs. Except for SAFTE-FAST, all models rate subjective alertness. FRI does not estimate sleep and wake times. Fatigue-related risk at operational accidents is not included in BAM and SAFE models prediction.

**Table 5** - Model outputs comparison 2
Source: (CASA, Biomathematical Fatigue Models)

| **Model Outputs** | **BAM** | **CAS** | **FAID** | **FRI** | **SAFE** | **SAFTE-FAST** | **SWP** |
|---|---|---|---|---|---|---|---|
| Subjective alertness | X | X | X | X | X | | X |
| Estimated sleep/wake times | X | X | X | | X | X | X |
| Performance | | X | X | | | X | X |
| Fatigue-related tasks errors | | X | | | | X | X |
| Fatigue-related risk of operational accidents | | X | X | X | | X | X |
| Confidence intervals | X | | | | | X | X |

## 7. USE AND LIMITATIONS

Generally, there is no fatigue concern providing that the crew member completes his or her duties in a safe and effective manner. A level of fatigue perception is subjective and the individual might not recognise or will neglect the actual severity of fatigue. The concern of not taking appropriate and corrective in-time actions is actually greater rather than the risk of falling asleep while at the task, as proven by some of the incidents.

Once applied, there is a range of possibilities when using a Biomathematical Fatigue Model. The hazard prevention acts in predictive, pro-active and reactive phases.

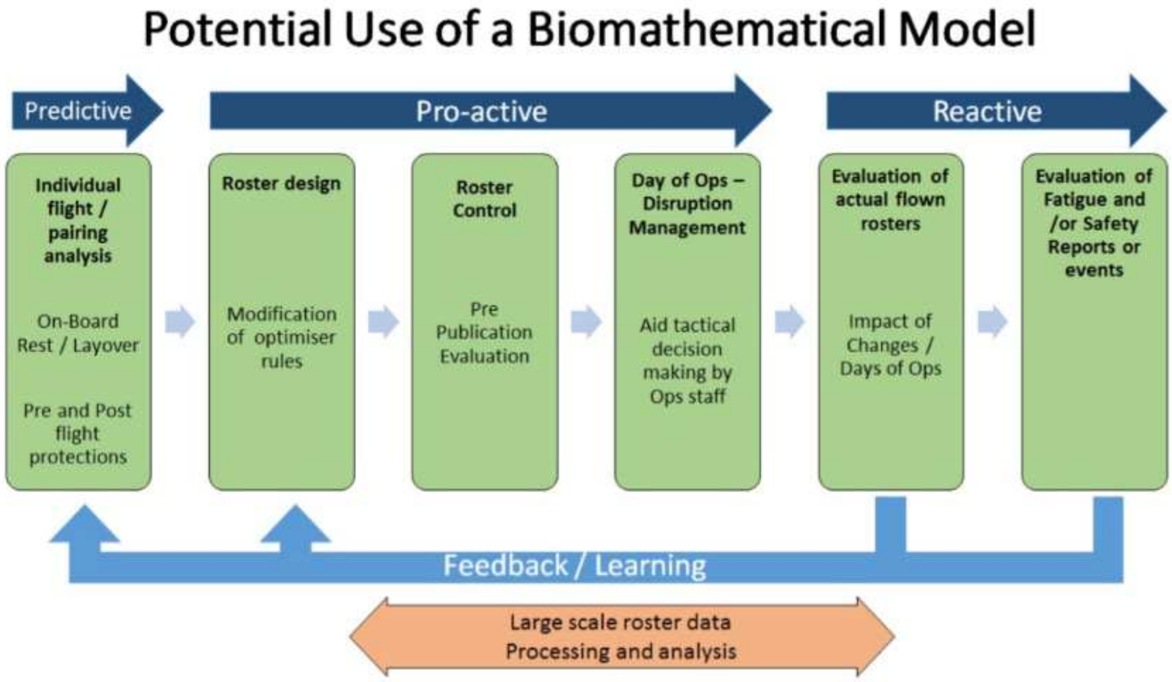


**Figure 6** - Potential use of a Biomathematical Fatigue Model
Surce: (IATA, Uses and Limitations of Biomathematical Fatigue Models – White Paper)

Forward scheduling

ORO.FTL.110 define good rostering practices as a general responsibility of the operator and recognises fatigue as one of the safety related risks. An approved FTL scheme and good rostering practices within a comprehensive FRMS are means of fatigue mitigation. Crews should be allowed to have appropriate sleep opportunity and minimum roster disruption i.e. the crew member's circadian rhythm. Initial and primary application of BFMs should thus be done pro-actively, in the pre-planning stage at pairing and crew schedules optimisation. It is important to determine the upper limits of fatigue scores and the maximisation of restorative sleep. BFMs are capable of establishing fatigue scores and predicting fatigue trends. Identification of high-risk fatigue vulnerabilities is also important once the roster is released and fatigue might be moderated through the use of augmented crew or extended rest times. The same applies to work periods that extend beyond the FTL. Using Biomathematical Fatigue Models within irregular or charter operations might be contributive in terms of identifying fatigue risks associated with unplanned changes. Eventually, well-designed rosters serve as an effective barrier against crew fatigue.

Light exposure and napping countermeasures

Research shows that human body is very sensitive to certain “zeitgebers”, such as light exposure. BFMs are capable of recognising performance fluctuations and can take into account exposure to bright light or in-flight napping. Controlled Rest on the Flight Deck and light exposure might serve as fatigue mitigation when integrated into company operational procedures.

Individual fatigue prediction

Sleep requirement is individual and will vary, giving on average seven to eight hours per day. Sleeping less than the individual's body needs will create sleep debt and cumulate fatigue.

Furthermore, sleep loss in conjunction to shift duty adjustments will cause performance degradation. Practical application of, three-process models demonstrated a high accuracy at the expected level of fatigue prediction. It has to be emphasised that any computerised scheduling tools are based on predicting alertness levels for an average individual under standard conditions and will not include additional factors. E.g. any domestic disharmony or sleep disorder.

Training

Education of all aviation industry personnel including; crew members, management and scheduling departments is essential in understanding the complexity and severity of fatigue. Effects and causes of fatigue, as well as good sleep habits and the importance of an effective sleep, should be incorporated into every company's Fatigue Manual and Safety Management System. The implementation of an appropriate BFM serves as a backup tool for fatigue levels prediction.

Safety investigation

Using a Biomathematical Fatigue Model during an incident or accident investigation should be the last option. This would indicate that both predictive and pro-active hazard prediction has failed. Once a computerised scheduling tool is in place, its primary role is seen in the pre-planning stage to avoid excessively fatiguing rosters. A safety investigation reacts to a situation in the past by re-evaluation of data. It is worth noting that proving fatigue as a factor in the related safety accident/incident is extremely difficult. Furthermore, aviation is a very safe environment due to the already established barriers – Standard Operating Procedures and Crew Resource Management training were established decades ago, that mitigate fatal accidents from happening.

Limitations

Biomathematical models undergo a constant development process. Weak places can be found both on the interface as well as the user side. Models focus on the physiological aspect of fatigue, just as time since awake, sleep requirement and circadian phase disruption. The amount of required sleep and responses to sleep deprivation vary between people and there is a variability proven in individual circadian shift adaptation. To average these conditions, an interpolation of parameters had to be conducted at each model design. The final analysis thus will always display an average individual at standard conditions and will disregard any alteration, such as stress factors (domestic disharmony, private life unease) or sleep disorders. Consideration of all limitations, proper understanding of the model and appropriate training and education will result in a correct use of the selected model and correct prediction of relative fatigue.

## 8. CONCLUSION

As an optional part of the enhanced and comprehensive FRMS, Biomathematical Fatigue Models are advanced computerised tools that found their use in transport industry where a sophisticated approach towards shift planning is necessary. Currently, there are seven models of different structure and components available. Operators should be aware of model's characteristics and prior to an implementation of such a model, a thorough assessment of all available Biomathematical Fatigue Models should be accomplished. The choice of a best suitable model depends upon the size of the company, type of operation, stages of model application and actual model functionality in the “real world”. In addition, most of the models were developed in controlled laboratory conditions with a little input from field studies. If the same route was flown but every day is different in terms of workload factors, then it is fairly ambitious to apply realistic conditions into the laboratory environment.

Models are useful tools if they help to predict fatigue risk and aid to long-term roster planning in conjunction with pilot fatigue reports. The users should be aware that these models do not consider the variability in individual needs. These are still imperfect tools requiring fining up and should not be used with too much confidence. Also, none of the biomathematical models should serve as an individual fatigue state assessment. A subjective fatigue report and pilot's own judgement should therefore always overtake any computerised fatigue risk prediction.

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