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Final Report 2017-18: Sleep Models Validation and Parameters Optimization

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IMPORTANT INFORMATIVE STATEMENTS

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Abstract

The objective of this task was to compare and analyze sleep models results versus experimental data which were collected on sailors' work, rest schedule and fatigue onboard a Royal Canadian Navy vessel. This study is a continuation of the analysis presented in a previous report [1] with a new set of experimental data. Model predictions of Day workers' sleep were accurate; however, sleep prediction of Night workers was less satisfactory. Optimization algorithms were applied to the mathematical model to improve the accuracy of the predicted results of nightshift workers relative to the experimental results.

The following two sleep prediction models were considered and analysed: the Two-Process Model of Sleep Regulation (Model 1) by Acherman and Borbley [2] and the Three-Process Model of Alertness (Model 2) by the Akersted's group [3]. A third model, the Sleep/Wake Model by Darwent's group [4] was investigated [1,5] but not considered in the present study due to its low accuracy in comparison with Model 1 and Model 2.

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1 Introduction

1.1 Objective

The objective of this study was to analyze two sleep prediction models using operational experimental data collected from sailors' work, rest schedule and fatigue onboard a Royal Canadian Navy vessel. The present study is a continuation of the analysis presented in Reference [1]. The experimental data were collected from one hundred sixty (160) crew members; however, two participants were eliminated from the analysis due to missing data; as a result, the validation analysis in this report uses one hundred fifty eight (158) participants data. Two different sleep data sources were used in the present analysis: one sleep schedule was collected from 158 members through a questionnaire while the second set of sleep data was obtained from the actigraph. A detailed explanation of the actigraph data is provided in Section 2.1.1. The predicted results were compared to both sets of experimental data.

The following models were used for the analyses: (1) Two-Process Model of Sleep Regulation by Acherman and Borbley [2] defined as Model 1; (2) Three-Process Model of Alertness by Akersted's group [3] defined as Model 2.

In addition to the comparison between predicted results and experimental data, an optimization of the parameters of the selected sleep prediction model was performed to improve the model's accuracy.

1.2 Scope

The following tasks were completed:

1. The data from the master spreadsheet including all log data was extracted and written into a format which can be used as input by the DRDC Fatigue Model (DFM);

2. The predicted sleep schedules were compared to the experimental sleep schedules obtained from the master spreadsheet and the actigraphs;

3. Selection of the best model

4. Sensitivity analysis was performed to optimize the parameters of the selected model;

5. The results were obtained from the models and summarized in tables;

6. Implemented two sleep prediction modules in DFM based on crewmember's work schedules (day vs. night workers).

These tasks were completed by the project team, consisting of members from both DRDC and industry.

Table 1 – Project's Team Members

Dr. Fethi Bouak	Technical Authority – DRDC Toronto Research Centre
Dr. Henry Peng	Lead of the WBE: Integration of Crew Performance Models - DRDC Toronto Research Centre
Dr. Wenbi Wang	Co-investigator - DRDC Toronto Research Centre
Ms. Natalia Doubova	Contractor (Software developer and Matlab programmer)

This report has the following sections: Introduction – this Section, Method – Section 2, Results – Section 3, and Conclusion – Section 4.

1.3 Acronyms

The following gives a list of acronyms used in this document.

AVG	Average (arithmetic mean) of a given variable
DRDC	Defence Research and Development Canada
Port	Port Watch
SCORE	Simulation for Crew Optimization and Risk Evaluation
DFM	DRDC Fatigue Model
SD	Standard Deviation
Stdb	Starboard Watch
WBE	Work Breakdown Elements of the project

2 Method

2.1 Experimental Log Data

The sleep data was collected from one hundred fifty eight (158) crew members through a questionnaire. The study used a daily log to record daily sleep, work activity, personal time and fatigue rating over a period of 10 days. Every day during the trial, each participant was asked to record rest times, on-duty/off-duty activities, and subjective fatigue levels by entering the information into the log once every thirty minutes, except during sleep periods – the participants recorded their data when they went to bed and when they woke up. The first and last days of the trial (Day 1 and Day 10) were not considered in the analysis due to incomplete data for most of the participants.

In the questionnaire, the activity codes that we considered in the analysis were defined as follows:

On Duty		**Off Duty**	
Activity	**Code**	**Activity**	**Code**
Maintenance	M	Sleeping	S
Watch	W	Personal Time	P
Evolution	E	Food/Meals	F
Training	T		
Departmental	D		
Secondary Duties	X		
Other (e.g. cleaning station)	O		

The fatigue level was rated as follows:

1	Feeling active and vital; alert; wide awake
2	Functioning at a high level, but not at peak, able to concentrate
3	Relaxed, awake; not at full alertness, responsive
4	A little foggy; not at peak; let down
5	Fogginess; beginning to lose interest in remaining awake; slowed down
6	Sleepiness; prefer to lying down; fighting sleep; woozy
7	Almost in reverse; sleep onset soon; lost struggle to remain awake

The work schedule on the ship can be divided into two main groups: watch standers and non-watch standers (day or night workers). For watch-keepers, data was collected from crew members standing in either 1-in-2 or 1-in-3 watch systems. In this report, only day workers and crew members standing in 1-in-2 watch system were considered for the purpose of validation of the sleep prediction mathematical models. The work schedule of each group is as follows:

1. Day Shift (from 8:00 to 16:00);

2. Night Shift (also includes workers with irregular day);

3. Irregular Shift;

4. 1-in-2 watch system[1]:
    - Port Watch (Port): 7:30 to 12:30 and 17:30 to 0:30;
    - Starboard Watch (Stbd): 0:30 to 7:30 and 12:30 to 17:30.

The sleep records format of the original raw data from the logs were adapted to the input formats of DFM-SCORE. The 'On Duty' activity codes (i.e., M, W, E, T, D, X, and O) were converted into "*allocated*" while the 'Off Duty' activity codes (i.e., S, P, and F) were converted into "*unallocated*". Any missing experimental activity was assigned as "unallocated". The sleep predictions were generated based on the work schedule provided in the experimental data. In order to validate the sleep models, the actual and predicted sleep duration, the number of sleep episodes and sleep/work schedule were compared versus the experimental data.

2.1.1 Actigraphy Data

In addition to the experimental data collected through the questionnaire (Log data), Actigraphs was used to monitor rest/activity cycles for the crew members. The actigraph data was collected from 75 crew members and every participant's data was written into a Microsoft Excel file.

Three different approaches were applied to define the sleep schedule.

1. Actigraph sleep 1 (**slp1**): the sleep was obtained from the "Raw Data" sheet of the file: "Sub 1.xlsx" and calculated as follows:

    slp1 = Columns "E+F" - columns "B+C". An example is provided below:

Col: A	Col: B	Col: C	Col: D	Col: E	Col: F
Start Day	**Start Date**	**Start Time**	**End Day**	**End Date**	**End Time**
Wed	26/10/2016	13:53:00	Wed	26/10/2016	17:31:00

2. Actigraph sleep(**slp2**): the sleep was extracted from the "Calculated Values" sheet of the file: "Sub 1.xlsx" and computed as follows:

    slp2 = Columns "D+E" – columns "B+C"

Col: B	Col: C	Col: D	Col: E	Col: F
Date Fell Asleep	**Time Fell Asleep**	**Date Awoke**	**Time Awoke**	**Sleep Efficiency**
26/10/2016	10:55	26/10/2016	14:31	100

[1] The 1-in-2 watch system schedule in this study is different compared to Reference [1].

3. Actigraph sleep duration 3 (**slp3**) was obtained by multiplying the sleep duration that was obtained in Approach 2 (see above) by the sleep efficiency from Column F.

slp3 = slp2 x Column "F"

The results from both Log data and Actigraphy are summarized in **Table 2**.

Table 2 – Total Sleep from the Actigraph and Log data

Subject #	Watch	logslp-tot (h)	slp1 (rawactslp-tot) (h)	slp2 (actslp-tot) (h)	slp3 (acteffslp-tot) (h)
1	Stbd	59.5	77.9	76.6	75.7
2	Stbd	48	61.1	55.3	48.2
5	Irregular	35.5	45.2	37.9	29.1
6	Irregular	46	56.1	53.9	48.3
8	Day	56.5	54.0	53.3	49.4
13	Day	62	70.9	68.7	60.7
16	Port	52.5	59.3	57.0	43.1
17	Stbd	72.5	65.4	60.8	55.4
18	Port	71	65.3	61.1	55.5
25	Stbd	66	63.3	58.5	45.0
26	Port	60	69.1	60.2	46.1
29	Stbd	64	61.2	52.5	35.7
31	Day	61.5	58.5	55.0	51.8
32	Stbd	66.5	69.0	67.1	63.2
35	Stbd	66.5	54.9	52.4	46.6
36	Port	65	49.3	43.7	37.4
41	Port	57	63.4	57.4	45.9
42	Stbd	63	63.4	54.1	46.6
48	Port	57.5	57.3	52.9	49.0
49	Port	53	55.8	53.0	47.8
53	Stbd	51.5	56.6	51.4	46.4
60	Stbd	66.5	66.0	54.9	48.1
61	Stbd	60	62.1	56.9	44.8
63	Port	52	55.6	52.0	47.6
68	Port	87	67.9	60.4	55.4
71	Stbd	65.5	64.8	60.7	53.4
72	Stbd	58	47.2	37.5	26.1
73	Day	41.5	40.2	38.8	35.1
75	Day	44.5	42.2	40.9	38.5
78	Port	52.5	50.0	47.2	44.3
79	Stbd	54.5	52.8	49.2	44.3
80	Port	64	57.7	54.0	46.1
82	Port	61.5	52.1	45.6	36.2
84	Port	51.5	58.4	56.8	53.5
86	Stbd	66	57.1	54.3	50.4
87	Port	67	71.6	66.8	53.9
90	Stbd	68	66.3	56.3	45.1

Subject #	Watch	logslp-tot (h)	slp1 (rawactslp-tot) (h)	slp2 (actslp-tot) (h)	slp3 (acteffslp-tot) (h)
91	Port	71	59.1	53.3	46.4
96	Port	66	64.6	53.9	36.0
99	Stbd	77.5	66.2	54.5	38.0
103	Port	75	64.4	50.0	39.4
106	Day	57	54.0	50.9	48.3
107	Port	58	50.6	40.0	30.3
115	Port	52.5	53.3	43.7	17.3
123	Stbd	62.5	68.1	63.5	56.3
126	Irregular	45.5	53.8	48.4	38.3
127	Day	52	53.9	52.2	46.8
128	Day	48.5	51.8	49.5	43.9
129	Day	42.5	46.6	45.0	43.9
131	Day	64.5	73.8	71.1	62.1
134	Night	51.5	60.0	59.0	54.4
136	Day	55	55.8	54.7	51.1
137	Night	39	56.3	54.3	43.0
140	Day	55	56.7	53.8	50.2
141	Day	59	54.3	52.3	48.2
143	Day	48	68.8	64.5	61.1
146	Day	53	52.5	47.7	38.7
147	Day	55	64.1	62.5	58.3
150	Day	60	57.7	55.5	42.1
154	Day	32	54.8	53.1	47.0
163	Day	62	69.6	65.7	49.1
164	Day	51	67.8	63.7	58.6
165	Day	25.5	54.7	53.3	51.9
169	Stbd	62.5	59.9	50.6	42.6
172	Stbd	49	54.5	53.6	49.5
179	Stbd	60.5	77.8	73.1	62.2
184	Day	61.5	66.5	58.9	49.8
189	Day	46.5	41.6	37.1	22.7
190	Stbd	62	59.4	50.0	41.4
191	Day	35	39.7	38.1	36.0
193	Stbd	44.5	60.6	56.1	50.3
199	Port	58	77.5	69.2	58.9
204	Port	50	59.5	55.5	53.9
207	Stbd	73.5	58.0	47.6	38.0
212	Stbd	60	59.4	51.7	36.7

Where:

logslp-tot = total sleep in 8 days which was obtained from the log data.

The actigraph data files are located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\GetActigraphData\PVT files updated

The Matlab code and the excel files for this analysis are located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\SelfReportedActigraphSleepSummary

Table 2 can be found in the "sleep duration Summary.xlsx" file located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\SummaryExcelFiles

2.2 Model 1 – Two-Process Model of Sleep

This model was developed by Acherman and Borbley [2] and includes two main components: a circadian system and a sleep homeostatic system. The homeostatic sleep pressure as a function of time is as follows:

$$S_t = 1 - e^{\frac{-\Delta t}{t_r}} \times (1 - S_{t-\Delta t}) \quad \textit{during wake} \qquad \textbf{Equation 1}$$

$$S_t = e^{\frac{-\Delta t}{td}} \times S_{t-\Delta t} \quad \textit{during sleep} \qquad \textbf{Equation 2}$$

Where Δt is the time step; and t_r (18.2 h) and t_d (4.2) are time constants for the rise and decay of the homeostatic process during wakefulness and sleep, respectively.

The circadian rhythm as a function of time is as follows:

$$C = A \sum_{k=1}^{5} a_k \times sin \frac{2k\pi}{\tau}(t - t_0) \qquad \textbf{Equation 3}$$

Where

- A = amplitude of skewed sine wave (0.12)
- τ = period of C (24 hours)
- t_0 = the circadian phase at the beginning of the simulation (8.6 h)
- a_1 = 0.97
- a_2 = 0.22
- a_3 = 0.07
- a_4 = 0.03
- a_5 = 0.001

The following initial conditions were used in the simulation: t = 24; S= 0.49.

When **S > 0.67+C** during rest period, it is time to sleep; when **S < 0.17+C** it is time to wake up.

2.3 Model 2 – Three-Process Model of Alertness

The Three-Process Model of Alertness was developed by Akersted and his group [3] and has had several revisions. The results of Model 2 from References [1 and 5] were in a good agreement with the empirical data. Thus this version of Model 2 was used in the present analysis.

A brief description of Model 2 [3] is provided below:

$$S = la + (sw - la) \times e^{(d \times taw)} \quad \textbf{Equation 4}$$

$$S' = ha - (ha - ss) \times e^{(g \times tas)} \quad \textbf{Equation 5}$$

The original process S' (Equation 5) was modified with "break function" that splits process into S'b1 (Equation 6) for the part of sleep with high homeostatic pressure and S'b2 (Equation 7) for the last part of sleep with lower pressure [2]. The "brake point" in time asleep (bt) is defined a switch from S'b1 to S'b2 and calculated as follows:

$$bt = (bl - ss)/(g \times (bl - ha)) \quad \textbf{Equation 6}$$

If tas ≤ bt , the process S'b1 is as follows:

$$S'b1 = ss + tas * (g \times (bl - ha)) \quad \textbf{Equation 7}$$

In the case dt ≥ bt, the following algorithm is used:

$$S'b2 = ha - (ha - bl) \times e^{(g \times (\mathrm{tas} - bt))} \quad \textbf{Equation 8}$$

$$C = m1 + \alpha_1 \times cos\left(\frac{\pi}{12} \times (t - p)\right) \quad \textbf{Equation 9}$$

$$U = m2 + \alpha_2 \times cos(\pi/6 \times (t - (p + 3)) \quad \textbf{Equation 10}$$

Where

la	= low asymptote (2.4);
sw	= S at waking up;
d	= decay in alertness (-0.0353);
taw	= time since waking up, in decimal hours;
tas	= time since falling asleep, in decimal hours;
ha	= high asymptote (14.3);
ss	= S at falling asleep;
g	= recovery in alertness which is calculated as $\ln(\frac{ha-14.0}{ha-7.96})/8 \approx$ -0.381;
bl	= 12.2;
m1	= mesor (0);
α_1	= amplitude (2.5);
α_2[2]	= amplitude (0.5);
p	= acrophase (16.8 Reference [2]);
m2	= mesor (-0.5);

S+C+U < 8.38 – threshold for falling asleep
S+C+U > 11.38 – threshold for waking up

The initial conditions were as follows:

1. t = 24
2. S'(24) = 8.76

[2] Note that the α_2 value was unintentionally omitted in Reference [1] and [5].

3 Results

3.1 Accuracy

A new approach was introduced in Reference [5] and the model's accuracy was calculated as follows:

$$accuracy_i = \frac{\sum_{i=1}^{N} match_i}{\sum_{i=1}^{N} match_i + \sum_{i=1}^{N} missMatch_i}$$

Where

$match_i$ = 30 minutes if there is a match between predicted and experimental sleep for the time interval "i";

$missMatch_i$ = 30 minutes if the predicted sleep of the time interval "i" does not match the experimental sleep of the time interval "i";

N = total number of time intervals (Δt = 30 minutes in presented calculation).

A 30 minute time step was used in the mathematical models due to the 30 minutes time step in the log data. In addition, different time steps (Δt = 1 min, 15 min, and 30 min) were used to investigate their effects on the accuracy.

The comparison of model results versus both the experimental log and the actigraph data was performed for Model 1 and Model 2 respectively.

3.1.1 Model 1

The accuracy, the predicted sleep and the number of sleep episodes were calculated using the default parameters for Model 1. The predicted and experimental log sleeps were compared at every 30-minute interval.

The Model 1 files including the MATLAB code are located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model1 vs SelfReported

In addition to the log comparison, the predicted sleep was analyzed versus the actigraph data with a Δt of 1 min, 15 min, and 30 min.

The Model 1 files including the actigraph analysis code are located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model1 vs Raw Actigraph (step 1 min) and C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model1 vs Actigraph (step 1 min)

3.1.2 Model 2

The accuracy, the predicted sleep and the number of sleep episodes were calculated using the default parameters for Model 2. The predicted and experimental log sleeps were compared every 30 minutes.

The Model 2 files including the MATLAB code are located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 vs SelfReported

The actigraph analysis files can be found in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 vs Raw Actigraph (step 1 min) and C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 vs Actigraph (step 1 min)

3.1.3 Models and Comparison Results

The comparison of the predicted results from Model 1 and Model 2 versus the log data and actigraph data are summarized in **Tables 3** to **5** for Day workers, Port Watch and Starboard Watch respectively.

Table 3 illustrates that the best agreement of 80.09% between model predictions and log data for Day Shift workers was observed for Model 2 with a Δt of 30 min. The average accuracy of the predicted results versus the actigraph data is 72.45% which is ~8% lower compared to the log data accuracy. The average model prediction for Model 1 (with log data) is 77.34% which is ~3% lower compared to Model 2. Therefore, Model 2 fits the experimental data (actigraph and log data) more accurately than Model 1.

Table 4 shows that Model 2 has the best average model predictions (63.91%) for Port Watch. This value is ~16% less than for Day Shift Workers. The average model prediction versus the log data for Model 1 is 63.44%. The average accuracy versus the actigraph data is also less for Model 1.

Table 5 shows that the best average model predictions of 46.56% for Starboard watch is obtained by Model 2. This value is ~33% less than for Day Shift Workers. The average model prediction versus the log data for Model 1 is 42.97%.

Overall, the average correct estimate for Port and Starboard Watch is about 16% and 33% less than for Day Shift Workers. The least accurate predictions are made for participants whose work shifts are a combination of day and night schedules and these results are consistent with the study in Reference [5]. Model 1 and Model 2 perform well for day workers; however, the models' accuracies are much lower for Port and Starboard Watch workers.

Next step is to optimize the model's parameters to improve the agreement between the predicted and experimental sleep for various types of work schedules.

Table 3 – Accuracy in (%) of Sleep Predictions from Model 1 and Model 2 for Day Shift workers

Subject #	Model 1 vs log data (Δt=30min)	Model 1 vs slp 1 (Δt=1min)	Model 1 vs slp 2 (Δt=1min)	Model 2 vs log data (Δt=30min)	Model 2 vs slp 1 (Δt=1min)	Model 2 vs slp 1 (Δt=15min)	Model 2 vs slp 2 (Δt=1min)	Model 2 vs slp 2 (Δt=15min)	Missing Data (h)
8	94.02	92.52	92.34	93.97	92.18	92.17	92.22	91.67	0
13	83.87	71.31	73.46	83.06	70.76	69.66	73.02	72.66	0
31	78.03	73.65	71.56	79.55	74.03	73.31	72.85	72.87	0
73	92.05	73.04	72.08	92.05	73.04	72.54	72.08	71.73	0
75	71.67	65.73	65.10	74.58	68.83	68.91	66.76	67.23	0
106	86.40	79.52	76.94	86.29	79.18	78.88	77.27	76.61	0
127	84.48	80.86	81.08	81.03	81.16	80.42	81.70	81.97	0
128	84.96	86.50	84.99	87.39	87.16	87.28	85.48	84.89	0
129	72.64	60.56	60.05	73.83	64.76	65.25	64.30	64.50	0
131	84.44	79.12	81.99	89.23	78.55	78.11	81.52	81.12	0
136	85.95	83.34	82.39	83.47	80.21	80.32	79.88	79.76	0
140	75.61	45.56	47.33	95.54	54.05	53.79	56.30	55.91	0
141	62.41	52.84	52.76	76.74	68.54	69.11	68.08	68.36	0
143	61.19	62.82	64.76	67.19	68.62	66.34	69.52	67.01	0
146	76.00	77.93	73.49	80.33	80.28	80.82	74.90	74.79	0
147	76.19	68.64	69.88	75.20	73.51	73.29	74.88	74.54	0
150	74.07	71.37	71.51	75.19	74.81	73.96	74.57	73.75	0
154	62.14	57.02	57.71	63.37	57.57	56.67	59.05	58.17	0
163	79.55	67.99	67.39	83.21	77.54	77.43	79.98	80.00	0.5
164	60.47	54.43	54.35	64.57	61.34	61.26	62.39	63.07	0
184	81.95	66.04	63.61	85.38	66.91	66.11	62.22	63.76	0
189	77.98	67.69	63.43	80.19	68.82	68.84	64.51	64.93	5.5
191	72.83	67.55	67.52	70.83	64.56	64.45	64.48	64.73	0
AVG	77.34	69.83	69.38	80.09	72.45	72.13	72.09	71.91	
STD	9.26	11.10	10.78	8.62	8.88	9.00	8.79	8.64	

Table 4 – Accuracy in (%) of Sleep Predictions from Model 1 and Model 2 for Port Watch

Subject #	Model 1 vs log data (Δt=30min)	Model 1 vs slp 1 (Δt=1min)	Model 1 vs slp 2 (Δt=1min)	Model 2 vs log data (Δt=30min)	Model 2 vs slp 1 (Δt=1min)	Model 2 vs slp 1 (Δt=15min)	Model 2 vs slp 2 (Δt=1min)	Model 2 vs slp 2 (Δt=15min)	Missing Data (h)
18	55.35	54.14	54.13	55.35	54.88	54.28	54.91	54.45	2
26	49.33	55.82	52.55	49.33	56.35	56.03	53.07	52.76	0
36	61.54	46.10	46.55	61.54	46.79	46.64	47.29	46.85	0
41	70.49	61.20	60.35	69.92	60.75	60.73	59.89	59.09	0
48	75.41	70.93	72.31	75.41	70.99	71.20	72.38	71.55	0
49	45.45	48.36	46.58	45.77	48.96	49.13	47.17	47.52	5.5
63	50.00	48.15	47.23	50.74	48.56	48.08	47.51	48.20	0
68	58.43	46.21	45.57	58.43	46.38	46.41	45.74	45.40	0
78	66.12	64.80	66.75	66.12	64.80	65.25	66.75	66.67	0
80	70.54	57.06	55.91	74.42	62.81	63.22	61.02	60.78	1.5
82	79.84	67.09	63.63	79.84	68.22	67.19	64.74	63.11	0
84	85.59	73.02	72.62	85.59	73.66	72.83	73.26	72.11	0
87	63.01	62.43	60.53	63.01	62.73	63.16	60.83	61.15	0
91	51.57	45.22	43.52	51.57	45.26	45.30	43.56	43.36	0
96	56.00	59.60	59.02	56.00	59.80	58.76	59.25	58.49	0
103	63.58	60.35	48.84	66.89	63.98	64.64	52.66	51.89	0
107	70.59	56.77	50.85	72.73	58.37	57.84	52.39	51.79	0
115	64.17	71.56	60.80	64.17	71.56	70.09	60.80	59.73	0
199	62.70	47.91	49.19	62.20	47.84	47.89	49.12	49.35	1
204	69.16	60.80	57.93	69.16	60.80	60.40	57.93	57.79	0
AVG	63.44	57.88	55.74	63.91	58.67	58.45	56.51	56.10	
SD	10.22	8.69	8.51	10.40	8.80	8.68	8.43	8.15	

Table 5 – Accuracy in (%) of Sleep Predictions from Model 1 and Model 2 for Starboard Watch

Subject #	Model 1 vs log data (Δt=30min)	Model 1 vs slp 1 (Δt=1min)	Model 1 vs slp 2 (Δt=1min)	Model 2 vs log data (Δt=30min)	Model 2 vs slp 1 (Δt=1min)	Model 2 vs slp 1 (Δt=15min)	Model 2 vs slp 2 (Δt=1min)	Model 2 vs slp 2 (Δt=15min)	Missing Data (h)
1	50.41	39.01	39.62	56.25	44.50	44.11	44.77	43.90	0
2	50.48	44.58	47.33	59.63	52.29	50.75	55.62	54.88	2
17	46.71	44.47	41.44	52.23	44.55	43.13	42.62	41.58	0
25	40.14	44.06	44.83	45.10	45.76	44.52	43.20	41.36	0
29	48.59	42.32	42.81	45.33	47.49	47.06	41.30	41.16	0
32	33.33	45.15	44.62	36.20	38.85	38.07	39.05	37.92	0.5
42	35.95	45.35	47.45	39.10	46.39	46.18	39.11	38.89	0
53	40.16	41.99	41.84	29.93	35.99	33.77	35.55	33.68	0
60	40.69	42.84	44.53	43.79	49.76	48.14	52.30	50.76	0.5
61	40.58	43.51	44.28	44.14	46.82	45.24	45.11	43.66	0
71	45.83	46.05	46.73	52.78	52.30	51.03	49.45	47.90	0
72	46.77	35.77	34.24	54.96	46.76	45.02	37.49	36.25	0
79	39.69	43.93	41.68	39.72	39.68	38.08	40.84	39.70	2.5
86	35.29	45.47	46.37	38.75	41.94	39.86	39.43	37.02	0
90	42.86	48.88	41.97	51.35	53.32	52.58	58.47	57.59	0
99	46.58	44.50	41.75	44.97	47.38	46.71	46.52	45.79	0
123	38.78	42.11	41.51	38.71	46.54	45.51	46.10	44.67	0
169	47.14	43.80	35.96	49.30	47.90	47.00	50.86	50.00	0
179	32.87	37.25	35.25	38.16	43.47	43.57	43.78	43.64	0
190	48.46	38.62	34.59	57.46	49.99	48.38	48.79	44.35	0
193	51.02	40.83	39.57	58.25	53.06	51.94	53.61	52.44	0
207	38.22	42.95	37.77	46.58	45.65	44.68	43.47	42.67	0
212	47.73	38.24	35.82	48.20	51.96	51.09	53.54	53.63	0
AVG	42.97	42.68	41.39	**46.56**	**46.62**	45.50	45.69	44.50	
SD	5.55	3.08	4.08	**7.79**	**4.51**	4.64	6.06	6.19	

Table 3 to **Table 5** can be found in the "AccuracySummaryActigraphSelfReported.xlsx" file located at C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\SummaryExcelFiles

Based on this information and discussions with DRDC, the sensitivity analysis of Model 2 was performed and is provided below.

3.2 Sensitivity Analysis of Model 2

The lowest accuracy was observed for Starboard Watch Workers based on the results shown above. To improve the agreement between the predicted and experimental data, a sensitivity analysis was performed.

The following parameters were selected for the sensitivity analysis:

1. Acrophase (p) (default value is p = 16.8 hours);
2. Recovery in alertness (g) (default value is g = -0.381);
3. Decay in alertness (d) (default value is d = -0.0353);
4. Upper and lower thresholds (default values are 11.38 and 8.38 respectively).

The analysis was performed as follows:

- Only one parameter was modified at a time, fixing the three others at their default values;
- parameters range was defined as [default_value - default_value*20%] to [default value + default_value x 20%];
- step was defined as one percent of default value;
- average accuracy was calculated for every step as follows:
    a. the accuracy for each subject was calculated using the modified parameters.
    b. the overall average of all subjects' accuracies was then computed.

3.2.1 Acrophase Analysis

As described above, a series of calculations with the acrophase value ranged from 13.44 to 20.16 hours with a step of 0.168 h were run for STBD. The results are shown in **Figure 1**.

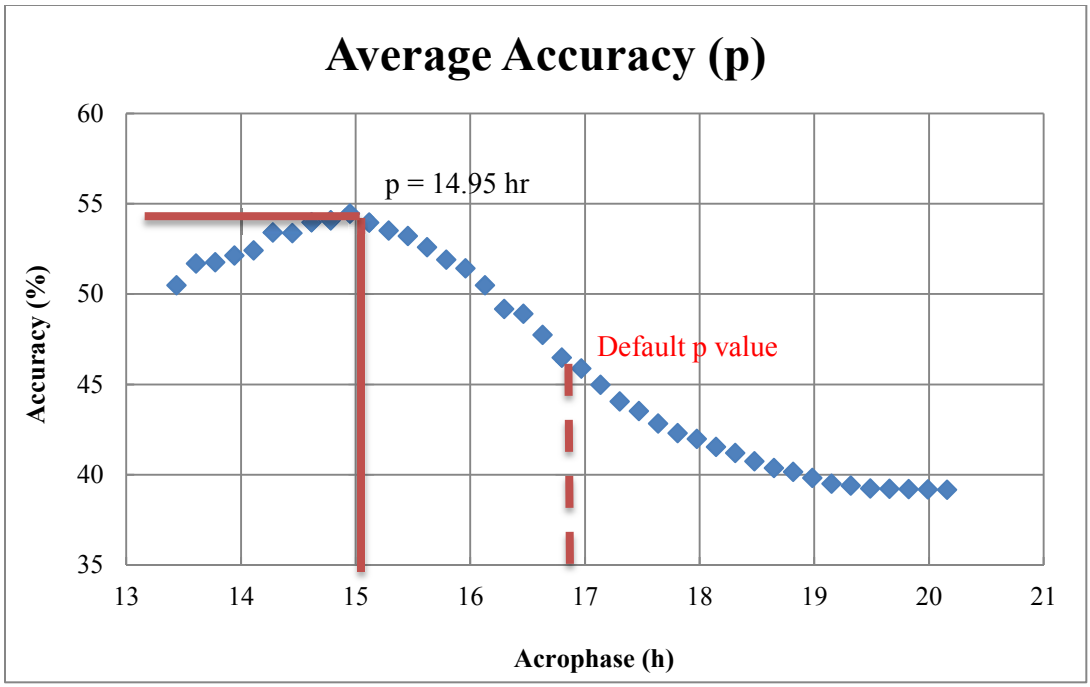

Figure 1 – Average Accuracy as a function of acrophase

The maximum accuracy with the acrophase as a variable parameter is 54.4% which corresponds to an acrophase value of 14.95 h.

The Matlab code and the excel files for this analysis are located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD\Acrophase

Figure 1 can be found in the file named "sensitivity analysis Summary.xlsx" which is located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD

3.2.2 Logarithm Analysis

The parameter ***g*** in Equations 6, 7 and 8 was calculated using the following equation: $\ln(\frac{ha-14.0}{ha-7.96})/8$. The denominator corresponds to sleep duration of 8 hours.

The model was tested with the logarithm values ranging from 6.40 to 9.6 h with a step of 0.08 h. The results are summarized in **Figure 2**.

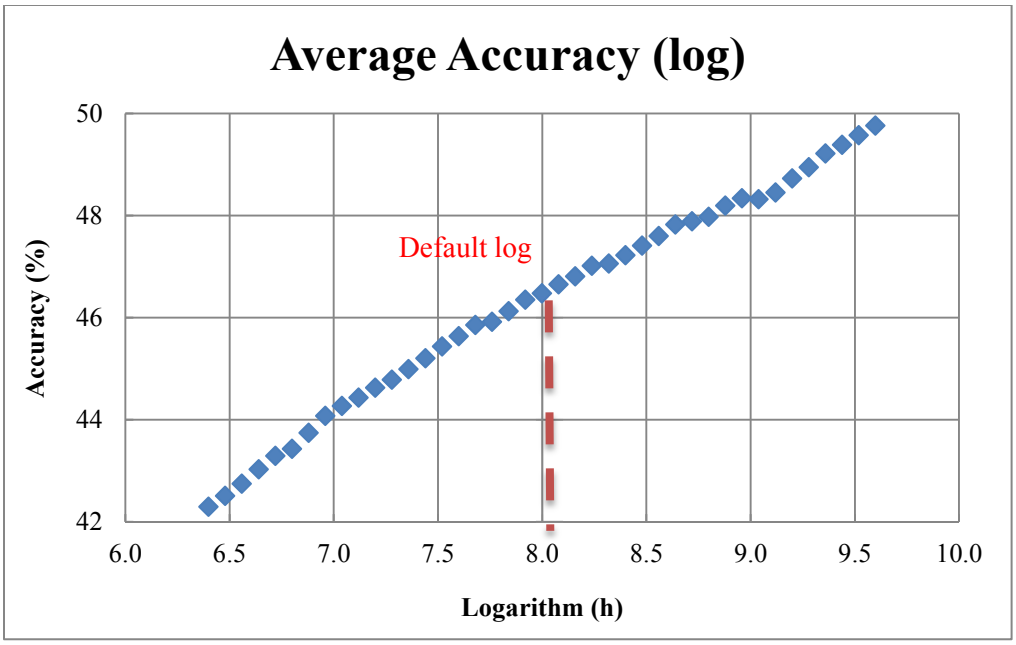

Figure 2 – Average accuracy as a function of the logarithm denominator to calculate g

The maximum accuracy with a variable logarithm is 49.76% with a logarithm value of 9.6. As observed in Reference [1] increasing the logarithm value in Equations 7 and 8 gives a lower value of homeostatic function S'(t) during sleep (Equations 7 and 8). As a result, the conditions for waking up (S+C+U >11.38) are met later compared with the default log value.

The Matlab code and the excel files for this analysis are located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD\Logarithm

Figure 2 can be found in the file named "sensitivity analysis Summary.xlsx" which is located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD

3.2.3 Lower and Upper Threshold Analysis

The lower threshold (LThreshold) values ranged from 6.7 to 10.06 with a step of 0.0838 and the upper threshold (UThreshold) values ranged from 9.1 to 13.66 with a step of 0.1138. The results are shown in **Figures 3** and **4**.

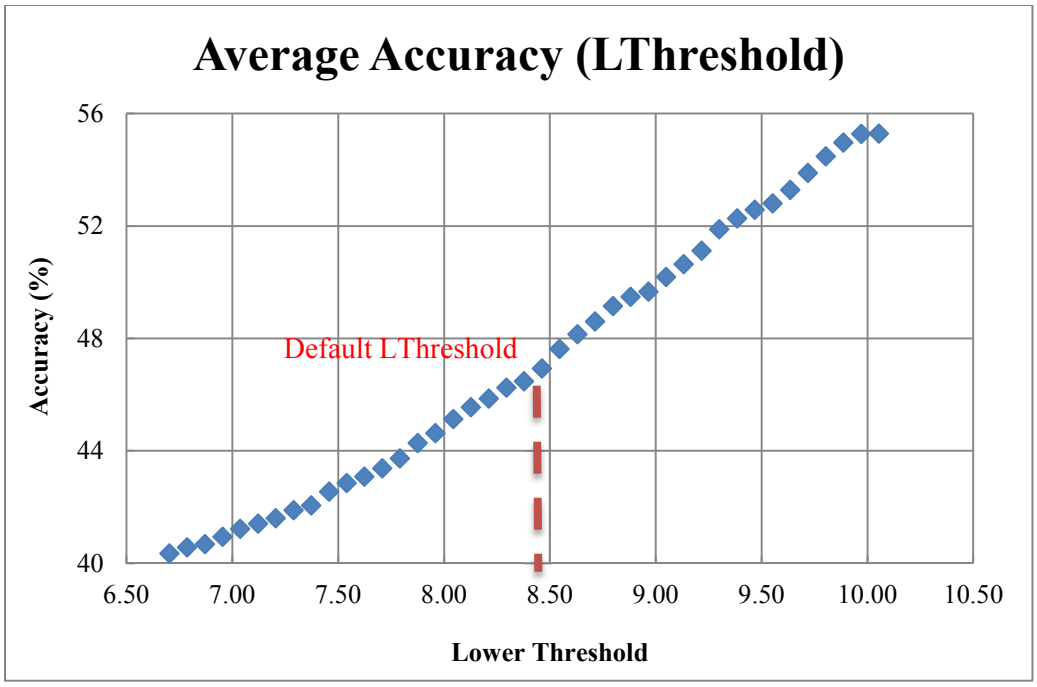

Figure 3 – Average Accuracy as a function of Lower Threshold

The maximum accuracy with a variable lower threshold is 55.28% which corresponds to a lower threshold value of 10.06. The accuracy improves due to increasing duration of evening sleep, furthermore, some extra sleep episodes can be observed compared with the default values.

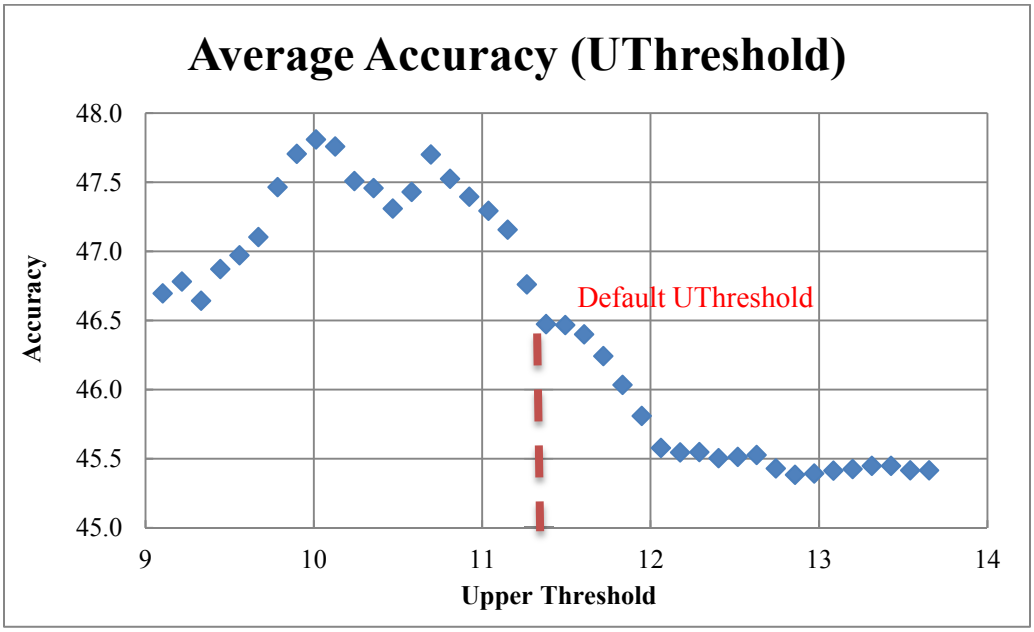

Figure 4 – Average Accuracy as a function of Upper Threshold

The maximum accuracy with a variable upper threshold value is 47.81% corresponds to an upper threshold value of 10.01. The accuracy improves due to increasing duration of evening sleep.

The Matlab code and the excel files for this analysis are located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD\LThreshold and C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD\UThreshold

Figures 3 and **4** can be found in the file named "sensitivity analysis Summary.xlsx" which is located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD

3.2.4 Decay Analysis

The decay values ranged from -0.0424 to -0.0282 with a step of 0.000353. The results are summarized in **Figure 5**.

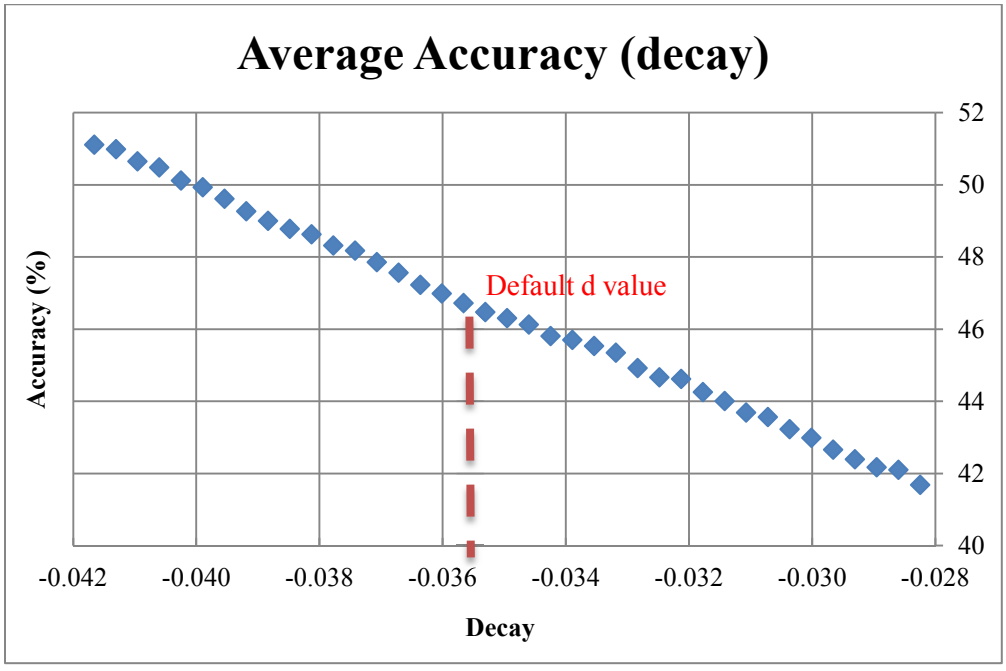

Figure 5 – Average Accuracy as a function of decay

The maximum accuracy with a variable decay is 51.53% which corresponds to a decay of -0.0424. The lower decay value causes a decrease of S(t) function in Equation 4. Therefore, the conditions to fall asleep (S+C+U < 8.38) are met earlier than if it was with the default decay.

The Matlab code and the excel files for this analysis are located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD\Decay

Figure 5 can be found in the file named "sensitivity analysis Summary.xlsx" which is located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD

3.2.5 Results of Sensitivity Analysis

Based on the results described in Sections 3.3.1 - 3.3.4, it was found that the upper thresholds can be eliminated from the sensitivity analysis due to a small impact on the accuracy results and the lower threshold value is kept at the default value as per discussion with DRDC.

A series of calculations has been performed to find the highest accuracy when the acrophase is fixed at 14.95 and the logarithm and decay values are modified one at a time. In addition to that, the number of sleep episodes was checked for every step when the decay parameter was changed.

The following conclusion can be drawn:

- the maximum average accuracy of 76.83% can be achieved when the decay value is -0.085 and the logarithm value is kept at 8 h;
- two sleep episodes were observed for an acrophase value of 14.95 and a logarithm value of 8 when a decay value is equal or lower than -0.0381

The Matlab code and the excel files for this analysis are located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD\DecayLogAnalysis and C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD\VirtualSTBD\FindTwoSleepEpisodesDecay

The results can be found in the file named "decay log sensitivity analysis.xlsx" which is located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD

3.3 Model 2 Parameters Optimization

In addition to the sensitivity analysis described in Section 3.2, a series of computations were performed to optimize some of the parameters of Model 2 for STBD. Based on the sensitivity analysis described above; the following parameters were selected for optimization:

1. Acrophase (p);
2. Decay in alertness (d);
3. Recovery in alertness (g) by modifying the logarithm value.

The optimization has been performed for these three parameters using two sets of data (i.e., test and validation data sets) from two randomized groups of starboard. The MATLAB optimization functions

"fminsearchbnd" and "fmincon" with bound constraints were used for parameter optimization. The optimization was performed with different initial points in order to avoid local minima.

3.3.1 Results of Optimization

Cases 1-5 Opt I were calculated using the Matlab function "fminsearchbnd" while Cases 1-2 Opt II were calculated using the Matlab function "fmincon". The different cases correspond to the different initial points used in the optimization algorithms. Also different initial points were applied. A summary of the optimization results is presented in **Table 6**.

Table 6 – Parameter Optimization Results

Case #	Initial Point for p, logarithm value, decay	Lower Bound Vector [p logarithm value decay]	Upper Bound Vector [p logarithm value decay]	Optimized Acrophase p hour	Optimized Logarithm value	Optimized Decay	Accuracy (%) after optimization - Data Set 1	Accuracy(%)after optimization - Data Set 2 (validation)
Case 1 Opt I	14.95; 8; -0.085	[13 8 -0.1]	[18 13 -0.0353]	14.629	8.004	-0.086	**77.45**	**77.10**
Case 2 Opt I	16.8; 9; -0.0353	[13 8 -0.1]	[18 10 -0.0353]	14.253	9.974	-0.035	**63.76**	**60.14**
Case 3 Opt I	14.95; 8; -0.0353	[13 8 -0.1]	[18 10 -0.0353]	14.518	8.036	-0.085	**77.33**	**77.49**
Case 4 Opt I	16.8; 9; -0.0085	[13 8 -0.1]	[18 10 -0.0353]	14.350	8.279	-0.080	**77.47**	**77.03**
Case 1 Opt II	14.95; 8.9; -0.085	[13 8 -0.1]	[18 10 -0.0353]	14.156	8.717	-0.076	**77.52**	**77.06**
Case 2 Opt II	16.8;9;-0.085	[13 8 -0.1]	[18 10 -0.0353]	13.003	9.955	-0.093	**74.52**	**75.42**

The Matlab code and the excel files for this analysis are located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD\STBD Optimization and C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD\STBD Optimization II.

Table 6 can be found in the file named "optimization Summary – final.xlsx" which is located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\STBD\STBD Optimization.

The following conclusions can be made from the optimization analysis:

- The accuracy for a group of STBD can be improved significantly with parameters' optimization as summarized in Table 6. The results demonstrate that the best accuracy with the optimized parameters is ~ 77.5% showing a 30% improvement compared to the accuracy calculated with the default parameters;
- The results from both MATLAB optimization functions (fminsearchbnd and fmincon) depend on initial points because no optimization technique is guaranteed to return global minima. It was found that the minimum which was determined by these two functions is a local minima;
- Case 1 Opt I was selected for further analysis.

3.4 Night and Day Shift Analysis

As it can be observed from the accuracy results, the current model needs to be adjusted for the crew members with an irregular work schedule. The accuracy of the model is also lower for the crew members whose working hours fall at night in comparison to the day workers. The next step is to assign day or night parameters for workers based on the work schedule. The night shift was arbitrarily defined from 20:00 to 8:00 of the next day.

In order to find the subjects with night working hours in the current data and data from Reference [1], the following approaches were analyzed:

- "full cycle" title corresponds to the case where parameters are defined based on the total period of the experiment;
- "daily cycle" title corresponds to the case where parameters are defined based on the "daily cycle" of the experiment;
- "Δt daily cycle" title is defined as follows:
    a. For the hours where a subject is working, night parameters are used if the current time interval is within the night shift; otherwise day parameters are used. Time intervals are defined to be 15 minutes in duration;
    b. For the hours where a subject is not working, the set of parameters is defined based on the "daily cycle" approach.

In addition, the "day" title corresponds to the case with the default parameters and the "night" case corresponds to the case with the optimized parameters from **Table 6** (i.e., Case 1 Opt I).

The accuracy of Model 2 was calculated for the current data and data from Reference [1] using the approaches listed above. Note that the data sets are called "Data 1" and "Data 2" for the previous study and the current study, respectively.

3.4.1 Results of Night and Day Shifts Analysis

The results are summarized in **Table 7** and presented in detail in **Tables A1** to **A9**.

Based on the computed results, the following conclusions can be made:

- The use of night parameters decreased the average accuracy for Day Workers for Data 1 by ~16% and for Data 2 by ~15%;
- Night parameters improved the average accuracy for Starboard Workers for Data 2 by 30%;
- "Δt daily cycle" algorithm to define the shift schedule and select the set of parameters based on the analysis of a time step works well for all cases as demonstrated in **Table 7**.

Table 7 – Average Accuracy in (%) of Sleep Predictions

Shift	Data Set	Model 2 - Day parameters vs log data	Model 2 - Night parameters vs log data	Model 2 (full cycle) vs log data	Model 2 (daily cycle) vs log data	Model 2 (Δt daily cycle) vs log data
Day	Data 1	80.38	63.66	80.38	80.38	79.53
	Data 2	79.97	64.78	79.97	80.06	78.61
Port[3]	Data 1	67.19	70.86	73.20	72.38	72.25
	Data 2	62.82	64.75	62.82	63.40	63.12
STBD	Data 1	72.42	72.94	72.42	72.71	75.52
	Data 2	46.47	77.18	76.06	75.40	75.98
Irregular	Data 1	39.47	43.91	48.37	48.37	48.97
	Data 2	65.73	65.57	65.73	66.56	68.40

The MATLAB code and the excel files are located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\Model 2 day night and C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\Model 2 old data

All Tables can be found in the excel file named "day night parameters Analysis.xlsx" which is located in C:\Users\Peng Contractor\Documents\ndPhaseII\NewData\ExperimentalDataAnalysis\Analysis\Model2 Sensitivity Analysis\Analysis Excel Files

3.5 Additional Analysis of the Starboard Watch

A supplementary analysis was performed for a better comprehension of the model behaviour using a virtual worker whose work hours are a combination of day and night working hours. The initial work shift used in the analysis was the starboard shift with two work episodes from 0:30 – 7:30 and 12:30 – 17:30 (from the current study). Twenty four cases were analyzed when the work schedule was shifted by an increment of one hour from the initial shift. Different sets of parameters (either day or night shift

[3] Note that Port and Starboard schedules are different compared to Reference [1].

parameters) were applied to the model at each increment depending on whether work time is during the day or during the night. The following sets were used in the analysis:

- "day parameters" corresponds to the case with the default published parameters;
- The night hours were defined as being from 8 pm to 8 am;
- "night parameters" corresponds to the case with the optimized parameters (Case 1 Opt I from **Table 6**);
- "Δt daily cycle" title corresponds to the case with day/night parameters at each time step (15 min) depending on whether work time fails under the day or the night hours. For the rest of the day without work, the parameters are defined based on a daily cycle approach.

The results are summarized in **Table 8**.

Table 8 – Summary of the Starboard Analysis

Case	Work Schedule		Night Parameters			Day Parameters			Δt daily cycle		
		Night hours	Predicted Sleep Duration (h)	Predicted # of Sleep Episodes	Average sleep per day (h)	Predicted Sleep Duration (h)	Predicted # of Sleep Episodes	Average sleep per day (h)	Predicted Sleep Duration (h)	Predicted # of Sleep Episodes	Average sleep per day (h)
1	00:30-7:30; 12:30-17:30	7	80	17	10.00	47	17	5.88	80	17	10.00
2	01:30-8:30; 13:30-18:30	6.5	82	17	10.25	48	17	6.00	82	17	10.25
3	02:30-9:30; 14:30-19:30	5.5	80	17	10.00	44	9	5.50	44	9	5.50
4	03:30-10:30; 15:30-20:30	5	78.75	17	9.84	47.25	9	5.91	56	9	7.00
5	04:30-11:30; 16:30-21:30	5	77.25	17	9.66	51.5	9	6.44	56	9	7.00
6	05:30-12:30; 17:30-22:30	5	72	17	9.00	56	9	7.00	56	9	7.00
7	06:30-13:30; 18:30-23:30	5	71.5	17	8.94	56	9	7.00	56	9	7.00
8	07:30-14:30; 19:30-00:30	5	73.5	16	9.19	56	8	7.00	56	8	7.00
9	08:30-15:30; 20:30-01:30	5	76	16	9.50	52	8	6.50	56	8	7.00
10	09:30-16:30; 21:30-02:30	5	78	16	9.75	50	8	6.25	56	8	7.00
11	10:30-17:30; 22:30-03:30	5	79	16	9.88	48	8	6.00	56	8	7.00
12	11:30-18:30; 23:30-04:30	5	79.5	16	9.94	48	16	6.00	57	16	7.13
13	12:30-19:30; 00:30-05:30	5	77.75	17	9.72	49	17	6.13	59	17	7.38
14	13:30-20:30; 01:30-06:30	5.5	76	17	9.50	50	17	6.25	78	17	9.75
15	14:30-21:30; 02:30-07:30	6.5	74	17	9.25	49	15	6.13	74	17	9.25
16	15:30-22:30; 03:30-08:30	7	72	17	9.00	47.5	12	5.94	72	17	9.00
17	16:30-23:30; 04:30-09:30	7	70.25	17	8.78	42.75	10	5.34	70.25	17	8.78
18	17:30-00:30; 05:30-10:30	7	68.25	16	8.53	40	8	5.00	68.25	16	8.53
19	18:30-01:30; 06:30-11:30	7	66	16	8.25	40	8	5.00	66	16	8.25
20	19:30-02:30; 07:30-12:30	7	66.5	24	8.31	40	8	5.00	66.5	24	8.31
21	20:30-03:30; 08:30-13:30	7	70.25	16	8.78	40	8	5.00	70.25	16	8.78
22	21:30-04:30; 09:30-14:30	7	72.25	16	9.03	40	8	5.00	72.25	16	9.03
23	22:30-05:30; 10:30-15:30	7	75.75	16	9.47	42.5	16	5.31	75.75	16	9.47
24	23:30-06:30; 11:30-16:30	7	78	16	9.75	46	16	5.75	78	16	9.75

The average sleep per day is shown in **Figure 6**.

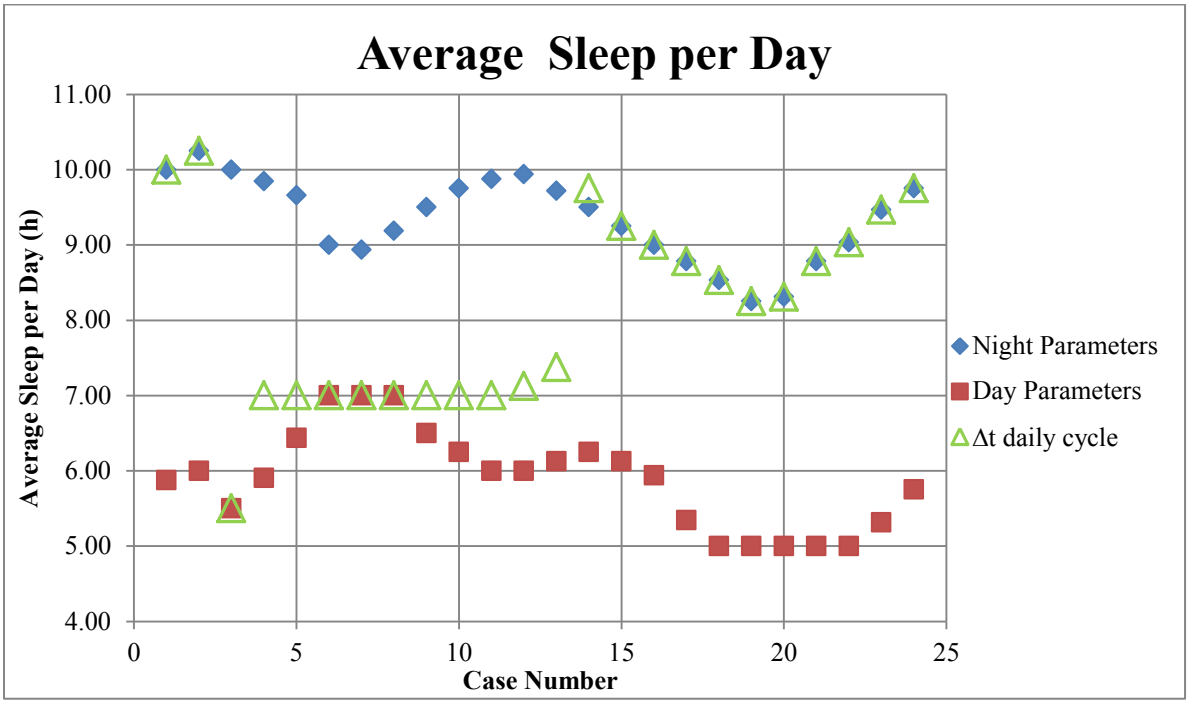

Figure 6 – Average Sleep per Day for the 24 Cases

The starboard analysis was performed for the 24 cases using "day", "night" and "Δt daily cycle" sets of parameters. The following conclusion can be drawn from the analysis:

- "Δt daily cycle" results are similar to the "night parameters" results when the night work hours are equal to or greater than half of the total work hours. This is observed for cases 1, 2 and 14-24;
- "Δt daily cycle" results are greater compared to the "day parameters" results when part of the work is performed during the night hours but the rest of the day is defined by the "day parameters". This difference is observed for the following cases: 4, 5 and 9-13.

4 Conclusion and recommendations

Based on the analysis, the following conclusions can be drawn:

- "Δt daily cycle works well in both sets of experimental data;
- Sleep predictions are more accurate when the log data is used;
- Since the total sleep duration is less for actigraph data the sleep predictions appears to be less accurate in comparison with the log data.

The following is recommended for the next step:

- Perform day parameters optimization;
- Apply the results and the findings to other watch systems (such as the 1-in-3).

References

[1]. N. Doubova (2016), Sleep Models Validation and Selection for SCORE-Fatigue Model Integration, April 2016, Contract Report

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[3]. M. Ingre, W. Van Leeuwen, T. Klemets, C. Ullvetter, S. Hough, G. Kecklund, D. Karlsson & T. Akerstedt, (2014), Validating and Extending the three process model of alertness in airline operations, PLoS ONE 9, e108679.

[4]. D. Darwent, D. Dawson & G.D Roach, (2010), Prediction of Probabilistic Sleep Distributions Following Travel across Multiple Time Zones, Sleep 33, 185-195.

[5]. N. Doubova, (2017) "Final Report 2016-17: Sleep Models Optimization", April 2017, Contract Report: DRDC-RDDC-2017-C122

Appendix A

This Appendix provides accuracy values for different groups of workers for the shift analysis described in Section 3.4. Note that the data sets are called "Data 1" and "Data 2" for the previous study and current study from Reference [1], respectively.

Table A1 – Shift Analysis Data 1: Accuracy in (%) of Sleep Predictions for Day Shift Workers

Subject #	Model 2 vs log (Δt=15min)	Model 2 set of night parameters vs log	Model 2 (full cycle) vs log (Δt=15min)	Model 2 (daily cycle) vs log (Δt=15 min)	Model 2 (Δt cycle daily) vs log (Δt=15 min)
227	67.51	72.20	67.51	67.51	75.06
228	68.34	52.98	68.34	68.34	70.43
229	80.32	71.54	80.32	80.32	76.83
231	75.94	77.12	75.94	75.94	80.91
232	85.49	51.16	85.49	85.49	85.85
233	82.62	67.07	82.62	82.62	85.11
234	77.52	46.55	77.52	77.52	83.66
235	86.71	54.57	86.71	86.71	84.79
236	80.46	74.93	80.46	80.46	82.92
237	75.08	66.75	75.08	75.08	81.63
247	86.53	55.82	86.53	86.53	84.14
249	68.13	50.11	68.13	68.13	67.07
250	87.32	69.28	87.32	87.32	74.38
251	91.30	79.10	91.30	91.30	85.80
253	80.43	66.75	80.43	80.43	80.83
255	82.07	65.85	82.07	82.07	77.43
256	90.69	60.41	90.69	90.69	75.22
AVG	80.38	63.66	80.38	80.38	79.53
SD	7.29	9.85	7.29	7.29	5.48

Table A2 – Shift Analysis Data 1: Accuracy in (%) of Sleep Predictions for Port Watch[4]

Subject #	Model 2 vs log (Δt=15min)	Model 2 set of night parameters vs log (Δt=15 min)	Model 2 (full cycle) vs log (Δt= 15 min)	Model 2 (daily cycle) vs log (Δt=15 min)	Model 2 (Δt cycle daily) vs log (Δt=15 min)
203	73.03	78.26	78.26	75.00	76.09
209	84.59	60.67	84.59	84.59	82.14
211	69.26	49.63	69.26	69.26	63.19
215	65.31	82.80	82.80	76.21	77.17
217	60.38	75.59	75.59	74.70	74.26
218	59.55	75.06	59.55	59.55	64.00
224	51.35	60.29	60.29	58.88	59.47
240	83.67	73.52	73.52	73.21	73.52
245	65.85	73.57	73.57	75.98	75.98
246	66.43	72.47	72.47	69.94	69.94
248	73.63	72.49	72.49	75.22	75.22
252	53.30	76.00	76.00	76.00	76.00
AVG	67.19	70.86	73.20	72.38	72.25
SD	10.04	8.90	7.25	6.91	6.44

[4] Note that Port and Starboard schedules are different compared to Reference [1].

Table A3 – Shift Analysis Data 1: Accuracy in (%) of Sleep Predictions for Starboard Watch

Subject #	Model 2 vs log (Δt=15min)	Model 2 set of night parameters	Model 2 (full cycle) vs log (Δt=15min)	Model 2 (daily cycle) vs log (Δt=15 min)	Model 2 (Δt cycle daily) vs log (Δt=15 min)
205	87.21	87.16	87.21	87.21	92.99
210	72.58	92.75	72.58	75.81	93.87
213	79.78	79.38	79.78	79.78	86.33
214	84.84	62.93	84.84	84.84	79.59
216	75.96	68.56	75.96	75.96	76.31
219	58.75	86.05	58.75	58.75	63.71
221	56.39	63.29	56.39	56.39	55.86
225	79.61	76.64	79.61	79.61	81.02
238	65.65	55.98	65.65	65.65	62.78
239	67.77	52.38	67.77	67.77	63.30
241	68.08	77.23	68.08	68.08	74.92
AVG	72.42	72.94	72.42	72.71	75.52
SD	9.64	12.66	9.64	9.69	12.23

Table A4 – Shift Analysis Data 1: Accuracy in (%) of Sleep Predictions for Irregular Workers

Subject #	Model 2 vs log (Δt=15min)	Model 2 set of night parameters	Model 2 (full cycle) vs log (Δt=15min)	Model 2 (daily cycle) vs log (Δt=15 min)	Model 2 (Δt cycle daily) vs log (Δt=15 min)
202	37.67	50.21	50.21	50.21	50.21
207	83.40	61.11	83.40	83.40	86.38
208	15.87	26.35	26.35	26.35	26.35
212	35.77	44.28	44.28	44.28	44.28
222	24.64	37.62	37.62	37.62	37.62
AVG	39.47	43.91	48.37	48.37	48.97
SD	23.34	11.69	19.22	19.22	20.32

Table A5 – Shift Analysis Data 2: Accuracy in (%) of Sleep Predictions for Day Shift Workers

Subject #	Model 2 set of day parameters vs log (Δt=30min)	Model 2 set of night parameters vs log (Δt=30min)	Model 2 (full cycle) vs log (Δt= 30 min)	Model 2 (daily cycle) vs log (Δt=30min)	Model 2 (Δt cycle daily) vs log (Δt=30min)
8	93.97	86.92	93.97	93.97	94.17
12	75.36	68.75	75.36	75.36	79.59
13	83.06	96.80	83.06	83.06	97.60
14	87.29	64.20	87.29	87.29	79.55
23	81.25	69.14	81.25	81.25	84.44
31	79.55	75.00	79.55	79.55	82.35
73	92.05	74.77	92.05	92.05	82.65
74	79.51	75.71	79.51	79.51	80.80
75	74.58	54.66	74.58	74.58	68.46
104	68.97	85.33	68.97	68.97	80.14
106	86.29	73.33	86.29	86.29	80.88
122	62.50	77.07	62.50	62.50	64.19
127	81.03	75.18	81.03	81.03	84.43
128	87.39	74.05	87.39	87.39	80.17
129	73.83	62.88	73.83	73.83	71.68
130	90.16	56.98	90.16	90.16	88.19
131	89.23	57.98	89.23	89.23	89.39
133	75.89	54.14	75.89	75.89	73.50
136	83.47	70.51	83.47	83.47	83.06
138	68.13	75.98	68.13	68.13	70.00
139	49.34	45.36	49.34	53.95	53.16
140	95.54	71.24	95.54	95.54	93.16
141	76.74	53.04	76.74	76.74	77.04
142	82.54	37.91	82.54	82.54	82.17
143	67.19	55.42	67.19	67.19	62.41
144	90.00	63.69	90.00	90.00	88.62
146	80.33	59.64	80.33	80.33	71.53
147	75.20	62.96	75.20	75.20	72.46
150	75.19	81.51	75.19	75.19	86.76
151	78.51	71.33	78.51	78.51	83.61
152	86.07	84.67	86.07	86.07	88.98
154	63.37	46.04	63.37	63.37	56.64
156	84.33	60.87	84.33	84.33	85.19
158	82.50	62.20	82.50	82.50	80.31
159	87.10	54.35	87.10	87.10	87.30
160	86.18	63.43	86.18	86.18	82.95
161	73.28	54.49	73.28	73.28	70.73
162	88.24	42.86	88.24	88.24	84.68
163	83.21	55.91	83.21	83.21	81.62
164	64.57	58.39	64.57	64.57	63.24
174	85.07	68.18	85.07	85.07	85.82
177	82.58	43.90	82.58	82.58	77.70
178	85.71	55.79	85.71	85.71	82.86
180	82.40	67.32	82.40	82.40	82.17
182	84.43	60.69	84.43	84.43	83.87

Subject #	Model 2 set of day parameters vs log (Δt=30min)	Model 2 set of night parameters vs log (Δt=30min)	Model 2 (full cycle) vs log (Δt= 30 min)	Model 2 (daily cycle) vs log (Δt=30min)	Model 2 (Δt cycle daily) vs log (Δt=30min)
184	85.38	68.26	85.38	85.38	76.92
187	65.22	49.68	65.22	65.22	57.97
188	82.46	60.99	82.46	82.46	77.42
189	80.19	63.12	80.19	80.19	69.67
191	70.83	60.87	70.83	70.83	66.02
205	64.46	60.81	64.46	64.46	62.60
216	97.65	84.69	97.65	97.65	90.22
217	89.09	74.45	89.09	89.09	85.12
AVG	79.97	64.78	79.97	80.06	78.61
SD	10.70	13.04	10.70	10.48	10.98

Table A6 – Shift Analysis Data 2: Accuracy in (%) of Sleep Predictions for Port Watch

Subject #	Model 2 set of day parameters vs log (Δt=30min)	Model 2 set of night parameters vs log (Δt=30min)	Model 2 (full cycle) vs log (Δt= 30 min)	Model 2 (daily cycle) vs log (Δt=30min)	Model 2 (Δt cycle daily) vs log (Δt=30min)
3	62.14	64.97	62.14	62.14	63.64
4	63.49	66.44	63.49	63.49	62.88
7	66.15	68.24	66.15	66.15	63.70
15	49.72	58.03	49.72	59.22	57.69
16	49.61	53.90	49.61	43.88	47.18
18	55.35	56.74	55.35	55.35	55.42
20	82.40	64.10	82.40	78.63	76.30
26	49.33	49.11	49.33	51.32	51.61
27	57.48	56.67	57.48	57.48	54.41
33	68.07	68.31	68.07	66.94	65.38
34	69.57	65.00	69.57	69.57	67.50
36	61.54	61.11	61.54	61.54	58.28
40	54.25	62.28	54.25	58.44	56.96
41	69.92	78.10	69.92	69.92	71.43
43	62.99	58.28	62.99	62.99	60.15
46	60.51	77.22	60.51	59.87	66.24
48	75.41	75.18	75.41	75.41	75.40
49	45.77	42.11	45.77	45.77	43.71
52	64.71	63.46	64.71	64.71	63.31
55	64.94	71.78	64.94	64.94	64.52
62	72.65	62.84	72.65	72.65	70.25
63	50.74	48.10	50.74	51.45	51.39
67	66.67	62.42	66.67	66.67	65.12
68	58.43	73.60	58.43	58.43	58.43
69	66.94	62.67	66.94	66.94	62.41
76	61.64	69.23	61.64	61.64	61.73
77	59.35	62.13	59.35	61.15	60.38
78	66.12	66.19	66.12	66.12	63.49
80	74.42	72.30	74.42	74.42	75.00
82	79.84	76.71	79.84	79.84	79.84
84	85.59	73.53	85.59	85.59	86.09
87	63.01	62.80	63.01	63.01	62.59
91	51.57	56.25	51.57	54.60	54.55
94	55.63	63.69	55.63	54.84	56.25
96	56.00	67.09	56.00	59.60	59.87
100	68.91	82.22	68.91	74.59	78.57
103	66.89	76.25	66.89	69.74	70.39
107	72.73	63.58	72.73	72.73	67.61
115	64.17	65.00	64.17	64.17	65.08
116	60.39	62.13	60.39	60.39	59.62
166	60.42	65.84	60.42	61.22	62.16
167	45.11	36.26	45.11	45.11	45.32
186	65.93	57.14	65.93	63.12	60.00
194	77.59	97.41	77.59	80.17	94.83
196	59.18	59.04	59.18	60.67	60.39

Subject #	Model 2 set of day parameters vs log (Δt=30min)	Model 2 set of night parameters vs log (Δt=30min)	Model 2 (full cycle) vs log (Δt= 30 min)	Model 2 (daily cycle) vs log (Δt=30min)	Model 2 (Δt cycle daily) vs log (Δt=30min)
197	56.14	68.54	56.14	56.14	55.43
199	62.20	66.89	62.20	62.20	62.12
204	69.16	76.23	69.16	69.16	64.35
209	47.45	55.84	47.45	52.45	53.85
AVG	62.82	64.75	62.82	63.40	63.12
SD	9.25	10.14	9.25	8.94	9.63

Table A7 – Shift Analysis Data 2: Accuracy in (%) of Sleep Predictions for Starboard Watch

Subject #	Model 2 vs log (Δt=30min)	Model 2 set of night parameters vs log (Δt=30min)	Model 2 (full cycle) vs log (Δt= 30 min)	Model 2 (daily cycle) vs log (Δt=30min)	Model 2 (Δt cycle daily) vs log (Δt=30min)
1	56.25	88.06	88.06	80.15	85.61
2	59.63	78.69	78.69	78.51	78.69
17	52.23	85.71	52.23	80.12	81.37
21	40.69	69.62	69.62	69.18	69.18
25	45.10	78.88	78.88	78.40	78.40
29	45.33	80.77	80.77	80.25	80.25
30	52.98	75.00	75.00	77.71	77.71
32	36.20	77.78	77.78	75.15	75.15
35	57.04	84.62	84.62	84.62	84.62
37	41.06	72.78	72.78	72.33	72.33
39	46.54	82.21	82.21	82.32	82.32
42	39.10	71.95	71.95	66.46	68.90
44	46.38	73.83	73.83	69.80	69.80
45	52.03	85.16	85.16	85.81	85.81
53	29.93	65.16	65.16	65.38	65.38
54	41.96	50.35	50.35	50.35	50.35
59	34.97	70.06	70.06	55.76	58.68
60	43.79	84.42	84.42	84.42	84.42
61	44.14	77.42	77.42	76.92	76.92
64	47.45	77.93	77.93	76.87	76.87
70	41.88	80.25	80.25	79.14	80.25
71	52.78	83.23	83.23	83.23	82.69
72	54.96	81.69	81.69	81.69	81.69
79	39.72	67.97	67.97	67.53	67.53
81	55.71	77.85	77.85	77.85	77.85
83	35.71	59.72	59.72	59.31	59.31
85	54.00	84.18	84.18	84.81	84.81
86	38.75	78.75	78.75	79.38	79.38
88	41.18	79.41	79.41	74.71	76.47
90	51.35	88.16	88.16	87.58	87.58
93	55.88	83.89	83.89	82.78	82.78
97	47.47	86.16	86.16	86.16	86.16
98	41.21	81.10	81.10	74.70	74.70
99	44.97	81.76	81.76	77.65	81.66
105	42.76	74.36	74.36	74.36	74.84
109	45.77	63.75	63.75	53.75	58.13
110	45.52	81.62	81.62	80.00	80.88
111	41.73	63.29	41.73	68.00	68.00
119	54.79	91.10	91.10	82.19	82.19
123	38.71	73.13	73.13	72.67	72.67
169	49.30	75.32	75.32	75.95	75.95
172	52.46	64.47	64.47	62.34	62.34
179	38.16	69.14	69.14	68.71	69.33
185	41.67	71.52	71.52	69.33	71.17
190	57.46	88.41	88.41	85.93	85.93

Subject #	Model 2 vs log (Δt=30min)	Model 2 set of night parameters vs log (Δt=30min)	Model 2 (full cycle) vs log (Δt= 30 min)	Model 2 (daily cycle) vs log (Δt=30min)	Model 2 (Δt cycle daily) vs log (Δt=30min)
193	58.25	78.07	78.07	78.07	78.07
203	47.52	76.97	76.97	76.67	76.67
207	46.58	84.47	84.47	77.78	79.63
212	48.20	81.63	81.63	81.63	81.63
AVG	46.47	77.18	76.06	75.40	75.98
SD	6.98	8.22	9.96	8.55	8.30

Table A8 – Shift Analysis: Accuracy in (%) of Sleep Predictions for Night Shifts Workers

Subject #	Model 2 vs log (Δt=30min)	Model 2 set of night parameters vs log (Δt=30min)	Model 2 (full cycle) vs log (Δt= 30 min)	Model 2 (daily cycle) vs log (Δt=30min)	Model 2 (Δt cycle daily) vs log (Δt=30min)
134	55.83	66.92	66.92	66.92	66.92
137	44.64	48.87	48.87	52.80	52.80
AVG	50.24	57.90	57.90	59.86	59.86
SD	5.60	9.03	9.03	7.06	7.06

Table A9 – Shift Analysis: Accuracy in (%) of Sleep Predictions for Irregular Workers

Subject #	Model 2 vs log (Δt=30min)	Model 2 set of night parameters vs log (Δt=30min)	Model 2 (full cycle) vs log (Δt= 30 min)	Model 2 (daily cycle) vs log (Δt=30min)	Model 2 (Δt cycle daily) vs log (Δt=30min)
5	69.57	59.66	69.57	68.75	65.14
6	65.25	51.72	65.25	65.25	63.11
10	57.26	76.12	57.26	60.17	67.50
11	64.46	64.71	64.46	66.41	69.06
126	72.12	75.63	72.12	72.22	77.19
AVG	65.73	65.57	65.73	66.56	68.40
STD	5.08	9.38	5.08	3.99	4.84

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