NATIONAL TECHNICAL UNIVERSITY OF ATHENS
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LABORATORY FOR MARITIME TRANSPORT

A BAYESIAN NETWORK APPLICATION FOR THE PREDICTION OF HUMAN FATIGUE IN THE MARINE INDUSTRY

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TABLE OF CONTENTS

LIST OF FIGURES 6
LIST OF TABLES 9
AKNOWLEDGEMENTS 10
ΠΕΡΙΛΗΨΗ 11
SYNOPSIS 14
1 THESIS PURPOSE 18
1.1 BACKGROUND 18
1.2 GENERAL GOAL 18
2 HUMAN FACTORS AND RELIABILITY 21
2.1 HUMAN FACTOR AND HUMAN ERROR 21
2.2 THE EMERGENCE OF HFE 24
2.3 HUMAN RELIABILITY ANALYSIS AND HUMAN ERROR PROBABILITY 26
2.4 HUMAN FACTOR IN MARITIME TRANSPORTS 27
2.5 FATIGUE AS AN IMPORTANT HUMAN FACTOR 30
3. FATIGUE 33
3.1. WHAT IS FATIGUE IN TERMS OF PHYSIOLOGY 33
3.1.1 PHYSICAL FATIGUE 35
3.1.2 MENTAL FATIGUE 35
3.1.3 CENTRAL FATIGUE 36
3.1.4. PERIPHERAL FATIGUE 36
3.2. FATIGUE IN MEDICAL TERMS 37
3.3 FATIGUE RISK FACTORS 38
3.3.1 SLEEP & SLEEP QUALITY 39
3.3.2 CIRCADIAN RHYTHMS 47
3.3.3 SECONDARY RISK FACTORS 50
3.4. EFFECTS OF FATIGUE 54
3.4.1. WORK PERFORMANCE 54
3.4.2 MICRO SLEEPS 55
3.4.3 HEALTH EFFECTS 56
3.5 FATIGUE-RELATED ACCIDENTS 57
3.5.1 COSTS ASSOCIATED WITH FATIGUE 58
3.6 MEASURING FATIGUE 59
3.6.1 PHYSIOLOGICAL MEASURES 60

3.6.2 BEHAVIORAL MEASURES ... 61
3.6.3 SELF REPORT MEASURES ... 62
3.6.4 PERFORMANCE MEASURES ... 64
3.6.5 OTHER FATIGUE MEASURMENTS TOOLS ... 65
3.7 FATIGUE COUNTERMEASURES ... 67
4 FATIGUE IN TRANSPORTATION ... 72
4.1 GENERAL OVERVIEW ... 72
4.1.1 FATIGUE IN AVIATION ... 73
4.1.2 RAILWAY OPERATIONS FATIGUE ... 74
4.1.3 FATIGUE IN DRIVING ... 75
4.2 LEGISLATION REGARDING FATIGUE IN TRANSPORT ... 77
4.3. FATIGUE IN MARITIME TRANSPORT ... 79
4.3.1 MARITIME FATIGUE RISK FACTORS ... 80
4.3.2 THE IMPACT OF STRESS ON MARINER'S FATIGUE ... 93
4.4 RESEARCH REGARDING FATIGUE IN MARITIME TRANSPORATION ... 94
4.4.1 ITF SEAFARER FATIGUE: Wake up to the dangers (1997) ... 94
4.4.2 THE NEW ZEALAND MARITIME SAFETY ... 95
4.4.3 THE CARDIFF PROGRAMM ... 95
4.4.4 MAIB BRIDGE WATCHKEEPING SAFETY STUDY (2004) ... 96
4.4.5 THE TNO REPORT (2005) ... 96
4.4.6 NTUA'S IDENTIFYING AND ASSESSING NON-TECHNICAL SKILLS ON GREEK MARITIME OFFICERS (2010) ... 97
4.4.7 CREW ENDURANCE MANAGEMENT SYSTEM ... 98
4.4.8 FATIGUE AT SEA - A FIELD STUDY IN SWEDISH SHIPPING ... 99
4.5 LEGISLATION ON FATIGUE IN THE MARITIME SECTOR ... 100
4.5.1 IMO & THE ISM CODE ... 100
4.5.2 IMO AND STCW ... 101
4.5.3 ILO 180 ... 102
5 INTRODUCTION TO BAYESIAN NETWORKS ... 104
5.1 AN INTRODUCTION TO UNCERTAINTY AND GRAPHICAL MODELS ... 104
5.1.1 UNCERTAINTY ... 104
5.1.2 PROBABILISTIC GRAPHICAL MODELS ... 105
5.2 BAYESIAN NETWORKS AND BAYESIAN INFERENCE ... 105
5.2.1 WHAT IS A BAYES NET? ... 105
5.2.2 CONDITIONAL PROBABILITIES AND INDEPENDENCE IN BAYESIAN NETWORKS ... 107

5.2.3 BAYESIAN INFERENCE 111
5.3 PRESENTATION OF A BAYESIAN NETWORK 112
5.3.1 TYPICAL PRESANTATION OF A PROBLEM OF UNCERTAINTY 112
5.3.2 USE OF BAYESIAN NETWORKS IN A TYPICAL EXAMPLE 113
5.3.3 USING GENIE 116
5.3.4 NOISY OR GATES 120
5.4 COMMON BAYESIAN NETWORK APPLICATIONS 121
5.4.1 GENERAL 121
5.4.2 MARITIME 123
5.4.3 FATIGUE 123
5.5 WHY BAYESIAN NETWORKS ARE SO HELPFUL TO THESIS THESIS. ADVANTAGES DISADVANTAGES 124
6 A BAYESIAN NETWORK FOR PREDICTING FATIGUE IN MARITIME TRANSPORT 128
6.1 MODEL PRESENTATION 128
6.1.1 TARGET NODE 128
6.1.2 PARENT NODES 129
7 BAYESIAN NETWORK APPLICATION FOR FATIGUE IN MARITIME SCENARIOS AND ACCIDENTS 155
7.1 THE IMPACT OF DYNAMIC FACTORS ON FATIGUE PREVALENCE 156
7.1.1 SUFFICIENT SLEEP AND SLEEP DEPRIVATION 156
7.1.2 WEATHER AND SEA STATE 158
7.2 MARITIME ACCIDENTS 161
7.2.1 EXXON VALDEZ 161
7.2.2 MFV BETTY JAMES 166
7.2.3 ANTARI (GENERAL CARGO 2446 G.T.) 172
7.3 HYPOTHETICAL SCENARIO OF 30000 G.T. CONTAINERSHIP 176
7.3.1 PROPOSED EVIDENCE 178
7.3.2 CALCULATING THE PROBABILITY FOR THE HYPOTHETICAL SCENARIO 180
8 SENSITIVITY ANALYSIS 185
8.1 INTRODUCTION 185
8.2. BAYESIAN NETWORK SENSITIVITY ANALYSIS 185
8.2.1 PARAMETER DESICION 185
8.2.2 SENSITIVITY ANALYSIS 187
8.2.3 NAVAL ARCHITECT OPTIMAL AND WORST SCENARIO 192
9 CONCLUSIONS 197

9.1 GENERAL LITERATURE 197
9.2 CONCLUSION FROM OUR BAYESIAN NETWORK APPLICATION ON MARITIME SCENARIOS 200
9.3 SUGGESTIONS 202
REFERENCES 204

LIST OF FIGURES

Chapter 2

Figure 2. 1: Types of Human Error........22
Figure 2. 2: Three steps to Human Error avoidance........23
Figure 2. 3: The Swiss Cheese Model for Human Error........24
Figure 2. 4: A common example of Applied Ergonomics........25
Figure 2. 5: Human Factors Engineering Pyramid........26
Figure 2. 6: The disasters of Exxon Valdez and Herald of Sea Enterprise........27
Figure 2. 7: Maritime Human Factor Statistics........28

Chapter 3

Figure 3. 1: The Chernobyl nuclear accident........35
Figure 3. 2: Central and Peripheral fatigue........37
Figure 3. 3: Muscle impairment and rejuvenation process........38
Figure 3. 4: The effect of sleep deprivation on alertness,(Sirois, 1998.)........41
Figure 3. 5: Average hours of sleep needed per day-Age........42
Figure 3. 6: Examples of hazardous and healthy sleeping environments........44
Figure 3. 7: Body temperature during a regular day (Sirois, 1998)........45
Figure 3. 8: Sleep deprivation and alertness (Sirois, 1998)........46
Figure 3. 9: Biological clock and Circadian Rhythms........48
Figure 3. 10: Circadian Rhythms and Alertness........48
Figure 3. 11: Fatigue-fitness connection (Ruby & Gaskill, 2002)........51
Figure 3. 12: Driver experiencing a microsleep........56
Figure 3. 13: Three Mile Island nuclear power plant........59
Figure 3. 14: The Multiple Sleep Latency Test........60
Figure 3. 15: Fatigue measurement tools. PERCLOS and EEG........61
Figure 3. 16: A common behavioral measure, the Actigraph........62
Figure 3. 17: The Epworth Sleeping Scale for sleepiness measurement........63
Figure 3. 18: A typical sleeping diary........64
Figure 3. 19: Fatigue Severity Scale, (FSS)........67
Figure 3. 20: The Fatigue Avoidance Scheduling Tool........69
Figure 3. 21: Effectiveness, feasibility and duration of effect for common Fatigue Countermeasures........70

Chapter 4

Figure 4. 1: The air crash of American Airlines, MD-82 at Little Rock, AR........74
Figure 4. 2: A driver about to experience a microsleep........76
Figure 4. 3: The first, most significant and most recently revised regulations........77
Figure 4. 4: Legislation regarding Fatigue in Transportation........79
Figure 4. 5: Sleep difficulties at sea, ashore and at home........82

Figure 4. 6: Vigilance though improved ship's design....85
Figure 4. 7: The lack of sunlight in a vessel's Engine Room....86
Figure 4. 8: ABS lighting Guidelines....87
Figure 4. 9: ABS Guidelines regarding Noise levels aboard ships....89
Figure 4. 10: Transmission of vibration throughout the human body....90
Figure 4. 11: Vibrations effects to human body and movement....92
Figure 4. 12: Factors that affect the Marine's endurance (CEM)....98
Figure 4. 13: Factors that affect Fatigue according to Crew Endurance Management 99
Figure 4. 14: The Karolinska Sleepiness Scale....100

Chapter 5

Figure 5. 1: The difference between non-acyclic and acyclic graphs....106
Figure 5. 2: A casual network and its Conditional Probabilities Table....107
Figure 5. 3: Serial Connection....109
Figure 5. 4: Diverging Connection....109
Figure 5. 5: Converging Connection....109
Figure 5. 6: Graphical presentation of the 'wet grass' example....112
Figure 5. 7: Noisy OR Gates example....120

Chapter 7

Figure 7. 1: Fatigue Acceptance Scale....155
Figure 7. 2: Fatigue - Hours Awake....157
Figure 7. 3: The Beaufort Scale....159
Figure 7. 4: Fatigue - Weather....160
Figure 7. 5: The Exxon Valdez oil spill....161
Figure 7. 6: Exxon Valdez actual incident....164
Figure 7. 7: Exxon Valdez alternate scenario....165
Figure 7. 8: Exxon Valdez scenario comparison....166
Figure 7. 9: The grounding of Betty James....167
Figure 7. 10: Betty James actual incident....169
Figure 7. 11: Betty James alternate scenario....171
Figure 7. 12: Betty James scenario comparison....171
Figure 7. 13: The Antari Grounding....172
Figure 7. 14: Antari actual incident....174
Figure 7. 15: Antari alternate scenario....176
Figure 7. 16: Antari scenario comparison....176
Figure 7. 17: A unfortunate incident aboard a containership....177
Figure 7. 18: Containership accident friendly scenario....181
Figure 7. 19: Containership optimal scenario....182
Figure 7. 20: Containership scenario comparison....183

Chapter 8

Figure 8. 1: Noise sensitivity analysis 188
Figure 8. 2: Light sensitivity analysis 189
Figure 8. 3: Vessels Motions sensitivity analysis 190
Figure 8. 4: Vibrations sensitivity analysis 191
Figure 8. 5: Management Demands sensitivity analysis 192
Figure 8. 6: Naval Architect optimal scenario 193
Figure 8. 7: Naval Architect worst scenario 194
Figure 8. 8: Naval Architect scenario comparison 195

LIST OF TABLES

Chapter 3

Table 3. 1: Factors that affect the overall sleep quality 40
Table 3. 2: Sleep architecture stages 42

Chapter 5

Table 5. 1: P (W/R) and P (H/R, S) 113
Table 5. 2: Prior probability table for P (H,R,S) 114
Table 5. 3: P (H,R,S) with entries H= n eliminated 114
Table 5. 4: Calculation of P*(H,R,S) = P(H,R,S/ H=y) 114
Table 5. 5: Calculation of P*(W,R)= R(W/R)*P*(R) =P(W,R) P*(R)/ P(R)
Table 5. 6: P**(W,R) =P(W,R /W=y, H=y) 115
Table 5. 7: P**(R,S) =P(R,S /H=y,W=y) 115

Chapter 7

Table 7. 1: Fatigue - Hours Awake 157
Table 7. 2 : Fatigue -Weather 160
Table 7. 3: Exxon Valdez Actual 163
Table 7. 4: Exxon Valdez Alternate scenario 165
Table 7. 5: Betty James Actual incident 169
Table 7. 6: Betty James Alternate scenario 170
Table 7. 7: Antari actual incident 174
Table 7. 8: Antari alternate scenario 175
Table 7. 9: Containership accident friendly scenario 180
Table 7. 10: Containership optimal scenario 182

Chapter 8

Table 8. 1: Noise sensitivity analysis 187
Table 8. 2: Light sensitivity analysis 188
Table 8. 3: Vessel Motions sensitivity analysis 189
Table 8. 4: Vibrations sensitivity analysis 190
Table 8. 5: Management Demands sensitivity analysis 191
Table 8. 6: Naval Architect Optimal scenario 193
Table 8. 7: Naval Architect worst scenario 194

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ΠΕΡΙΛΗΨΗ

Τα τελευταία χρόνια η επιστήμη του ανθρώπινου παράγοντα έχει ξεκινήσει να κάνει σιγά σιγά την είσοδο της στο χώρο της παγκόσμιας ναυτιλίας. Παρόλο που από άποψη τεχνογνωσίας και έρευνας βρίσκεται αρκετά πίσω από άλλες προηγμένες βιομηχανίες, οι εφαρμογές του κάνουν μικρά αλλά σταθερά βήματα προς την εδραίωση τους στο χώρο. Ήδη έρευνες και στατιστικά δεδομένα δείχνουν πως το 80% των ναυτικών ατυχημάτων είναι συνδεδεμένα, είτε έμμεσα είτε άμεσα, με το ανθρώπινο σφάλμα.

Ένα από τα σημαντικότερα στοιχειά με τα οποία σχετίζεται το ανθρώπινο λάθος είναι αναμφισβήτητα η ανθρώπινη απόδοση. Με τον όρο αυτό εννοούμε το εύρος των δυνατοτήτων ενός ατόμου, καθώς και των περιορισμών που θέτει η ανθρώπινη φυσιολογία στα πλαίσια της διεκπεραίωσης ενός καθήκοντος. Είναι σαφές πως ο ανθρώπινος οργανισμός είναι σχεδιασμένος με τέτοιο τρόπο έτσι ώστε να αμύνεται σε περίπτωση που τα παραπάνω όρια ξεπερνιούνται.

Η κόπωση αποτελεί το μήνυμα του ανθρώπινου σώματος όταν τα όρια αυτά έχουν ξεπεραστεί, είτε τείνουν να ξεπεραστούν. Αποτελεί μια κατάσταση κατάπτωσης κατά την οποία περιορίζεται μεταξύ άλλων, η ικανότητα της αντίληψης, της προσοχής, της σωματικής κίνησης καθώς και της αντίδρασης ενός ατόμου σε φυσικά ερεθίσματα. Η αντίδραση του σώματος στην κόπωση είναι μια παρατεταμένη περίοδος ξεκούρασης η οποία είναι απαραίτητη ώστε η λειτουργικότητα του οργανισμού να επανέλθει σε φυσιολογικά επίπεδα και οποιαδήποτε δραστηριότητα να είναι εφικτή.

Είναι σαφές λοιπόν πως η κόπωση αποτελεί αναπόσπαστο κομμάτι της ανθρώπινης απόδοσης και κατ' επέκταση της επιστήμης που μελετά ο ανθρώπινος παράγοντας. Μερικές από τις μεγαλύτερες καταστροφές στην ιστορία της ανθρωπότητας ήταν άμεσα η έμμεσα συνδεδεμένες με το αποτέλεσμα μιας σειράς ατυχών συμβάντων που ξεκίνησαν από ένα ανθρώπινο σφάλμα. Σε πολλές από αυτές τις περιπτώσεις δε, τα ατυχήματα προέκυψαν από τις πράξεις και τις επιλογές ενός ατόμου που δρούσε υπό την επήρεια της κόπωσης. Ο κόσμος ακόμα θυμάται τον πυρηνικό όλεθρο του Τσερνομπίλ, την τεραστία οικολογική καταστροφή που προκάλεσε η προσάραξη του Exxon Valdez καθώς και τα αμέτρητα αεροπορικά δυστυχήματα που κόστισαν τη ζωή σε εκατοντάδες ανθρώπους.

Στο πλαίσιο αυτής της διπλωματικής εργασίας θα εξετάσουμε το φαινόμενο της κόπωσης στα ναυτικά πληρώματα, καθώς και την επίδραση αυτής σε ατυχήματα πλοίων. Στη συνεχεία, θα παρουσιάσουμε ένα πιθανολογικό μοντέλο βασισμένο στη θεωρία πιθανοτήτων του Bayes, κατασκευασμένο υπό τη μορφή ενός δικτύου πίστεως το οποίο εκτίμα την πιθανότητα της κόπωσης ενός ναυτικού ανάλογα με το εργασιακό περιβάλλον του, τη φύση του καθήκοντος του, τη φυσική του κατάσταση και κυρίως την ποιότητα της ξεκούρασης του οργανισμού του (κυρίως ποιότητα ύπνου) πάνω στο πλοίο.

Τα δίκτυα πίστεως ή Bayesian Networks παρέχουν ένα σύγχρονο εργαλείο για την εκτίμηση πιθανοτήτων πολύπλοκων συστημάτων σε περιβάλλον αβεβαιότητας. Αποτελούν ένα συνδυασμό της κλασσικής θεωρίας πιθανοτήτων του Bayes και της θεωρίας γραφών, αντλώντας πλεονεκτήματα και δυνατότητες και από τους δυο χώρους. Στις μέρες μας παρά πολλοί επιστημονικοί κλάδοι έχουν επωφεληθεί από τις εφαρμογές τους με κυριότερα παραδείγματα αυτών την ιατρική και την πληροφορική. Ένα απλό αντιπροσωπευτικό παράδειγμα των εφαρμογών τους είναι η εκτίμηση της πιθανότητας της εμφάνισης μιας νόσου δεδομένου των πιθανοτήτων μιας σειράς συμπτωμάτων της.

Στο $1^{ο}$ κεφάλαιο αυτής της εργασίας παραθέτουμε τους λογούς που μας οδήγησαν στο να ασχοληθούμε με το συγκεκριμένο αντικείμενο καθώς και το γενικότερο σκοπό αυτής. Έπειτα στο $2^{ο}$ κεφάλαιο κάνουμε μια σύντομη αναδρομή στην ιστορία του ανθρώπινου παράγοντα καθώς και της εφαρμογής του στο χώρο των μεταφορών μέσω του Human Factors Engineering. Αργότερα, γίνεται αναφορά στην ανάλυση ανθρώπινης αξιοπιστίας (Human Reliability Analysis) που αποτελεί το βασικότερο εργαλείο του ανθρώπινου παράγοντα για την εκτίμηση των σφαλμάτων. Το κεφάλαιο ολοκληρώνεται με μια σύντομη ανασκόπηση της εργονομίας στο χώρο των θαλασσίων μεταφορών τονίζοντας τη σημαντικότητα του φαινομένου της κόπωσης των ναυτικών πληρωμάτων.

Το $3^{ο}$ κεφάλαιο αποτελεί μια εκτεταμένη βιβλιογραφική επισκόπηση πάνω στο γενικότερο πλαίσιο του φαινομένου της κόπωσης ως κομμάτι της ευρύτερης ανθρώπινης φυσιολογίας. Παράγοντες όπως ο ύπνος, οι κιρκάδιοι ρυθμοί και το στρες που οδηγούν στην κόπωση αναλύονται σε βάθος ενώ τελικά γίνεται αναφορά στις συνέπειες της, σε μέτρα αντιμετώπισης της καθώς και σε επιστημονικούς τρόπους μέτρησης και ποσοτικοποίησης της.

Στη συνεχεία, το $4^{ο}$ κεφάλαιο αναφέρεται αποκλειστικά στη παρουσία φαινομένων κόπωσης στο χώρο των μεταφορών. Αφού κάνουμε μια σύντομη αναφορά του αντικείμενου σε άλλες βιομηχανίες, όπως οι αερομεταφορές και οι οδικές συγκοινωνίες, παραθέτουμε του παράγοντες που προκαλούν κόπωση στα ναυτικά πληρώματα συμφώνα με τον IMO. Ιδιαίτερη έμφαση δίνεται σε εκείνους τους παράγοντες μέσω των οποίων ο Ναυπηγός Μηχανολόγος Μηχανικός μπορεί να δημιουργήσει ένα υγιές και εργονομικό περιβάλλον, απαλλαγμένο από τις βλαβερές επιπτώσεις της κούρασης των πληρωμάτων. Τέλος, γίνεται μια σύντομη βιβλιογραφική επισκόπηση σε αντίστοιχες έρευνες που έχουν γίνει στο παρελθόν στο χώρο της ναυτιλίας καθώς και στους υπάρχοντες θεσμοθετημένους κανονισμούς και νομοθεσίες.

Το $5^{ο}$ κεφάλαιο αποτελεί μια μίνι-εισαγωγή στην αβεβαιότητα, τα πιθανολογικά γραφικά μοντέλα και τις βασικές αρχές της θεωρίας πιθανοτήτων. Δίνονται αντιπροσωπευτικά παραδείγματα, μέσω των οποίων γίνεται επεξήγηση του ορισμού ενός δικτύου πίστεως, ενώ με τη χρήση ενός μίνι-tutorial προσπαθούμε με συνοπτικό τρόπο να δείξουμε τις βασικότερες λειτουργίες και δυνατότητες του λογισμικού που χρησιμοποιήθηκε. Στη συνέχεια παραθέτοντας τα κυριότερα πλεονεκτήματα των δικτύων πίστεως, εξηγούμε για ποιους λόγους καταλήξαμε στην επιλογή τους για την εργασία μας. Τελικά, στο κεφάλαιο που ακολουθεί παρουσιάζουμε αναλυτικά τη δομή του μοντέλου μας, παραθέτοντας τους κόμβους που το αποτελούν, τις σχέσεις μεταξύ αυτών (υπό τη μορφή πινάκων εξαρτημένων πιθανοτήτων) καθώς και τις αρχικές κατανομές των πιθανοτήτων των κόμβων-γονέων.

Στο 7^{o} κεφάλαιο, το οποίο αποτελεί το βασικό μέρος της εργασίας μας, γίνεται εφαρμογή του πιθανολογικού δικτύου μας σε πραγματικά ναυτικά ατυχήματα, αλλά και σε ρεαλιστικά υποθετικά σενάρια. Η ανανέωση του δικτύου για τον υπολογισμό της τελικής πιθανότητας της κόπωσης γίνεται μέσω της εισαγωγής αποδείξεων. Οι αποδείξεις αυτές αποτελούν προϊόν είτε επιθεωρήσεων ναυτικών ατυχημάτων υπό τη μορφή γραπτών αναφορών, είτε αποτελέσματα εκτιμήσεων που προήρθαν από πραγματικές μαρτυρίες ναυτικών αλλά και την εκτεταμένη έρευνά μας πάνω στο θέμα. Από την παραπάνω διαδικασία προέκυψαν αντιπροσωπευτικά διαγράμματα και πινάκες, τα οποία με τη σειρά τους βοήθησαν στην καλύτερη κατανόηση του εξεταζόμενου θέματος.

Στο 8^{o} κεφάλαιο πραγματοποιήσαμε μια ανάλυση ευαισθησίας (Sensitivity Analysis) με σκοπό να ελέγξουμε την γενικότερη αξιοπιστία και συμπεριφορά του μοντέλου μας καθώς και το κατά πόσο τα αποτελέσματα αντανακλούν την πραγματικότητα. Έπειτα, θελήσαμε να δώσουμε μια ρεαλιστική εκτίμηση του ποσοστού που μπορεί να συνεισφέρει ο Ναυπηγός Μηχανολόγος Μηχανικός στην βελτίωση των συνθηκών διαβίωσης πάνω στο πλοίο και κατ’ επέκταση στην αντιμετώπιση φαινομένων κόπωσης στα ναυτικά πληρώματα.

Κλείνοντας, η εργασία μας παρουσιάζει τα κυριότερα ευρήματα που προέκυψαν τόσο από την βιβλιογραφία όσο και από την εφαρμογή του μοντέλου. Έπειτα, παραθέτουμε τα σημαντικότερα συμπεράσματα μας πάνω στο θέμα σε αντιστοιχία με προτάσεις που πιστεύουμε ότι θα οδηγήσουν στην αποτελεσματικότερη καταπολέμηση φαινομένων κόπωσης στις θαλάσσιες μεταφορές.

SYNOPSIS

In the past few years, human factors science has begun to make steps towards its entrenchment in the global maritime domain. Even if the shipping world is at an early stage in terms of technical know-how and research, compared to other advanced industries, human factors applications are in the process of their consolidation in the field. Both researches and statistical data show that 80% of total maritime accidents are connected, indirectly or directly, to the human fault.

One of the fundamental elements related to the human error is undeniably an individual's performance. By using this term we define the breadth of possibilities of an individual as well as the limitations that places human physiology in terms of performing of duty. It is explicit to indicate that the human body is structured in such way that defense mechanisms are activated when the preceding limits are exceeded.

Fatigue constitutes the signal of the human body that serves as an alert when the bodily limitations are surpassed or tend to be exceeded. It is describe by medicine, as a condition of collapse during which awareness, attention, bodily movement and reaction time to stimuli are severely diminished. The organism's answer to fatigue is the need for an extended period of rest which is essential for the human body in order for any ordinary activity to be feasible in the future.

It is explicit therefore that fatigue constitutes an integral factor of human performance thus being an extension of science that studies human factors. Some of the notable dissasters in the history of humanity were directly or indirectly connected with the sequence of mishaps that began from a human fault. In many of these cases, the accidents resulted from the actions and the choices of a certain individual that acted under the influence of fatigue. The world still remembers the nuclear havoc of Chernobyl, the enormous ecological destruction that caused the grounding of Exxon Valdez as well as the innumerable aviation accidents that cost the life of hundreds of people.

In this thesis, we examine the phenomenon of fatigue amongst shipping crews as well as its effect on maritime accidents. Later, we will present a probabilistic model based on Bayesian probability theory, constructed under the form of a belief network which assesses the mariner's fatigue, given information depending his work environment, the nature of his duty, his physical condition and primarily the rest quality (mainly sleep quality) that a seafarer has the chance to amass onboard.

Belief networks or Bayesian Networks, as they are commonly known, provide a state of the art tool for the probabilities inference calculus of complex and sophisticated systems, in an uncertainty environment. They constitute a marriage of traditional Bayesian theory and Graph theory, drawing advantages and capabilities from both fields. Nowadays many scientific domains have profited from their applications, with medicine and the computer science being the most typical examples. A simple representative example of their applications is the probability inference for the prevalence of a disease, given the probabilities for a plethora of its symptoms.

In the 1st chapter of this study we indicate the reasons that led us to research this particular subject, as well as the general purposes of this thesis. Then in the 2nd chapter we make short reference in the history of human factors as well as its incorporation in the transportation field via the implementation of Human Factors Engineering. Later, we discuss the principles of Human Reliability Analysis (HRA) which constitutes the fundamental tool that Human Factor science uses for the prediction of the human error. Finally, we make a brief introduction to ergonomic principles in maritime transport while we highlight the significance of fatigue amongst seafarers.

The 3rd chapter is an extensive bibliographic review on the prevalence of fatigue as part of general human physiology. Risk factors such as sleep, circadian rhythms and stress, all of which lead to lassitude, are analyzed in-depth while references are made regarding fatigue consequences, countermeasures as well as scientific tools for fatigue measurement and quantification.

Furthermore, the 4th chapter is dedicated exclusively to fatigue in the field of global transports. After a short review of fatigue prevalence in industries such as air transportations and railways, we indicate the factors that cause fatigue in the maritime domain in accordance to the guidelines provided by IMO. Particular emphasis is given in those factors through which the Naval Architect and Marine Engineer can create a healthy and ergonomic environment, exempted from the damaging repercussions of tiredness amongst crews. Finally, we provide a brief review of related researches and projects as well as of existing enacted regulations and legislation.

The 5th chapter constitutes a mini-introduction to uncertainty, probabilistic graphic models and the basic principles of probabilities theory. Though the use of representative examples, the definition of Bayesian Networks is explained, while a mini-tutorial is provided in order to demonstrate the basic functions and overall capabilities of the GeNie (software used). Furthermore, the primary advantages of Bayesian networks are listed in order to highlight the reasons that led us in their choosing as the instrument of our research. Finally, in the next chapter we present the structure of our model in depth, introducing the participating nodes, the relations between them (in the form of conditional probabilities tables) as well as the initial prior probabilities distributions of the parent-nodes.

In the 7th chapter, which constitutes the main part of our thesis, we apply our network to real maritime accidents as well as in realistic hypothetical scenarios. Each time, we import evidence to our network and through BN updating the posterior fatigue probability is calculated. This evidence was product either of inspections of actual accidents in the form of official reports, or results of estimations from seamen's' testimonies and our own extensive research on the subject. The preceding process provided several representative figures and tables which in turn helped us in to achieve better comprehension of fatigue in the shipping word.

In the 8th chapter we performed a Sensitivity Analysis in order to test the overall reliability and behavior of our model as well as its reflection of the ‘real world’. Then, we try to give a realistic estimate of percentage of the Naval Architect’s possible contribution in the improvement of the living conditions aboard ships; a contribution that can help can mitigate fatigue phenomena amongst seafarers.

Finally, we present our major findings that resulted both from our extensive bibliographic review and the application of our model. In addition, we summarise our conclusions on the subject in equivalence with proposals that we believe will lead into more effective countermeasures and thorough knowledge about fatigue at sea.

CHAPTER 1

THESIS PURPOSE

1 THESIS PURPOSE

1.1 BACKGROUND

In the last 30 years, the maritime industry has suffered many losses, both in terms of human lives and ecological disasters, caused by the hazardous effects of the prevalence of fatigue aboard ships. Even if the principles of Human Factors are becoming more and more incorporated into the shipping world, the occurrence of fatigue amongst shipping crews is rather underrated and often neglected. Furthermore, the contemporary tendency to reduce operating costs has resulted in lower manning levels, exhaustive workloads and badly planned shift rotation. In addition, regular port calls, adverse weather conditions and intensive paperwork lead mariners in adjusting to a rather hazardous lifestyle which makes them vulnerable to the obnoxious consequences of fatigue.

The consequences of fatigue amongst mariners lead in dangerous outcomes both in terms of the vessel's overall safety but the individual's well being as well. Common examples of fatigue include injuries that were the result of lack of alertness, or even major ecological catastrophes, such as the grounding of the Exxon Valdez, that was the outcome of the actions of a sleep deprived watchkeeper. Additionally, taking into consideration the number of people aboard a regular passenger vessel, a possible fatigue-related incident could result in the loss of thousands of human lives.

While searching existing literature, interesting but rather unsettling facts can be found. Not only has there been relatively little research on the subject but the mariner's knowledge regarding fatigue ranges from limited to none. It is clear that if shipping crews were more aware of fatigue prevalence and its mechanisms, they would have been more careful in their choices and actions aboard ships. Consequently, fatigue perception and knowledge is an integral part in the effort of mitigating fatigue related incidents in the maritime domain.

1.2 GENERAL GOAL

The general goal of this thesis can be summarized in the following paragraphs:

At first, we tried to provide a thorough literature framework regarding the subject of fatigue and its overall nature. While circumventing on the physiological part of the issue, we present the basic biological mechanisms of fatigue as well as the mental and body-motor effects on a human organism. Furthermore, the most important factors that lead to fatigue were highlighted and described in order to indicate their significance on its prevalence. Through this procedure we acquired sufficient knowledge which was later used in the structure of our probabilistic graphical model.

However, our main purpose in aggregating all this information is to grant the reader the opportunity to develop fatigue perception and attain substantial knowledge about the subject.

Later in this thesis, we propose the use of a probabilistic graphical model for the prediction of fatigue, given evidence regarding the environment and the individual's physiological background. The primary purpose of our model (and the thesis as well) can be subcategorized in two main goals:

- To provide the opportunity to predict the posterior fatigue probability in a real maritime accident. Through this procedure we are able to identify the importance of fatigue prevalence in an actual maritime mishap and the significance of the contributing factors that led to it

- To provide an efficient auditing tool that will help mariners and investigating parties to evaluate fatigue in the future. Through proper use and further improvement of our model surveyors can benefit from fatigue related findings, such as extreme noise and vibrations levels that are rarely mentioned in an actual accident report. The primary advantage of our model is that it provides the opportunity to predict fatigue prevalence and its importance, given information regarding workload, environment and ergonomic factors, prior to the occurrence of the accident.

CHAPTER 2

HUMAN FACTORS AND RELIABILITY

2 HUMAN FACTORS AND RELIABILITY

2.1 HUMAN FACTOR AND HUMAN ERROR

The concept of *human error*, whether intentional or unintentional, is defined as (Lorenzo, 1990):

Any human action (or lack thereof) that exceeds or fails to achieve some limit of acceptability, where limits of human performance are defined by the system.

Human error has been the main contributor in numerous modern disasters such as the factory explosion in Bhopal, the railway accidents at Paddington and Southall, the shipwrecks of Herald of Free Enterprise and Exxon Valdez, the nuclear catastrophes in Chernobyl and in Three-Mile Island, the accident of the Challenger Shuttle and many more. What these disasters had in common was that they were exposed at a daily basis and finally affected by the impact of human factor/error. Many of these incidents resulted in loss of life or multiple injuries but apart from that, the environmental and monetary costs were even greater [108].

Managing and preventing human error has become a top priority for most of the advanced industries such as aviation and nuclear. Initially, researchers focused on the technical part of the problem, a common practice that has been dominant ever since. However, since contemporary technology has provided extremely intelligent and reliable systems, scientists also focused on the interplay between these systems and human performance. Moreover, while investigating accidents that included equipment and operator failure, researchers agree that there should be more available knowledge (in terms of training) regarding safety culture.

The following are some of the many ways to categorize human error [I].

- exogenous versus endogenous
- situation assessment versus response planning and related distinctions in
  - errors in problem detection
  - errors in problem diagnosis (problem solving)
  - errors in action planning and execution
- By level of analysis; for example, perceptual versus cognitive versus communicational versus organizational.

Figure 2.1 shows a logical sequence resulting in human error. It is obvious that human error can occur in each one of these steps.

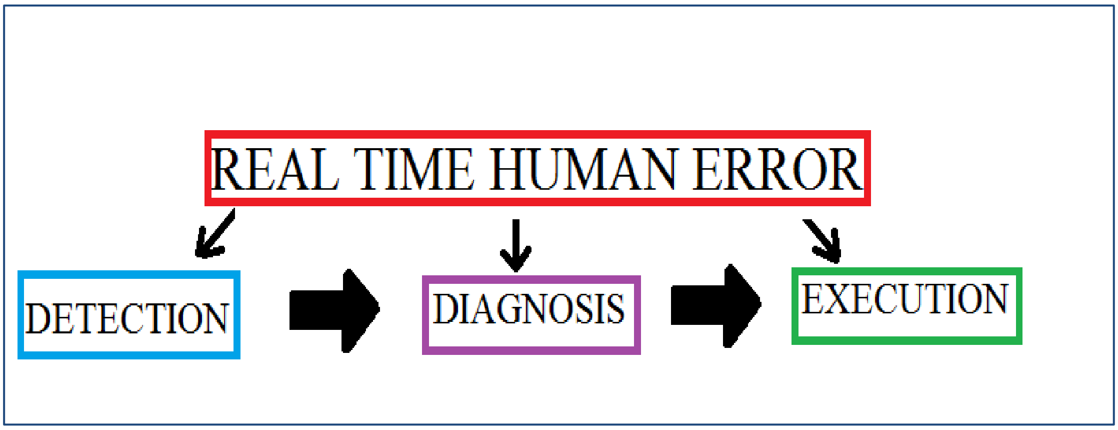


Figure 2. 1: Types of Human Error

Recent statistical data prove that over 80% of the accidents that take place globally are entirely or partly connected to human error or underperformance (HSE, 1999). For example, a study has shown that the human error is the main contributor to 60% of total maritime accidents, with the organizational and management omissions to constitute 15%, while the rest 25% to be part of technical problems (Tangen, 1987).

In the search for mitigating the hazardous effects of human error, the field of Human Factors came into prominence. According to Dr.Rothblum [80] the principle of Human Factors is the instrument for understanding and managing human potential in terms of capabilities and limitations. Human factors can prove helpful in applying its knowledge to equipment, work environments, procedures, and policies in order to enhance their interaction with human performance. By integrating applied ergonomics in technology HF guarantees a type of informal *'alliance'* between individuals and their overall working environment. The idea of adapting complex systems to human performance has been widely described by scholars as the *human-centered* approach. This practice can provide several beneficial elements to individuals such as increased efficiency and effectiveness, reduced error probability, lower costs, decreased personnel injuries and above all increased morale and well being [80].

Human factors science has provided applications for various domains such as engineering, statistics, medicine, operations research and psychology. It is a term that covers (Figure 2.2):

- The science of understanding the properties of human capability (Human Factors Science).
- The application of this understanding to the design, development and deployment of systems and services (Human Factors Engineering).
- The art of ensuring successful application of Human Factors Engineering to a program (Human Factors Integration). It can also be called ergonomics [I].

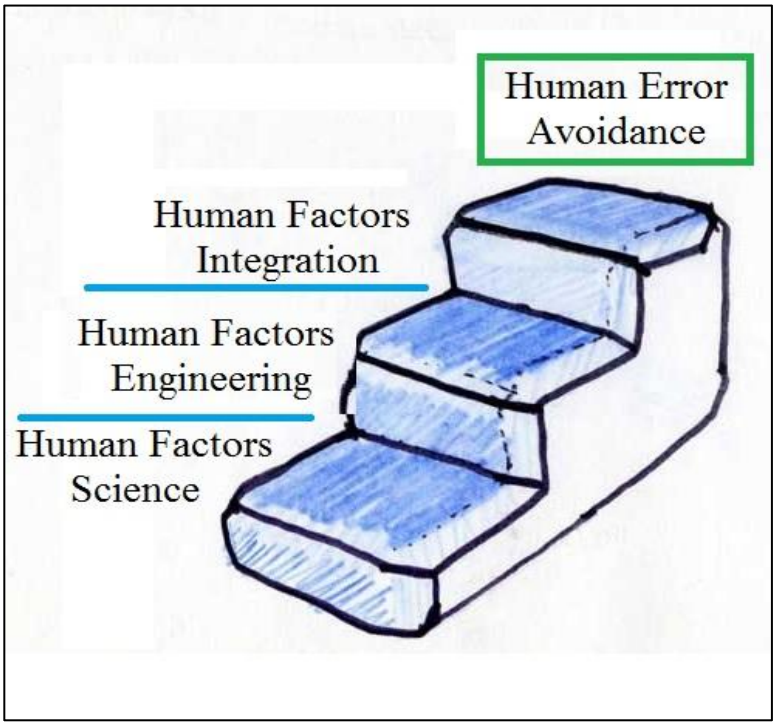


Figure 2. 2: Three steps to Human Error avoidance

Some more specializing approaches of Human Factors include:

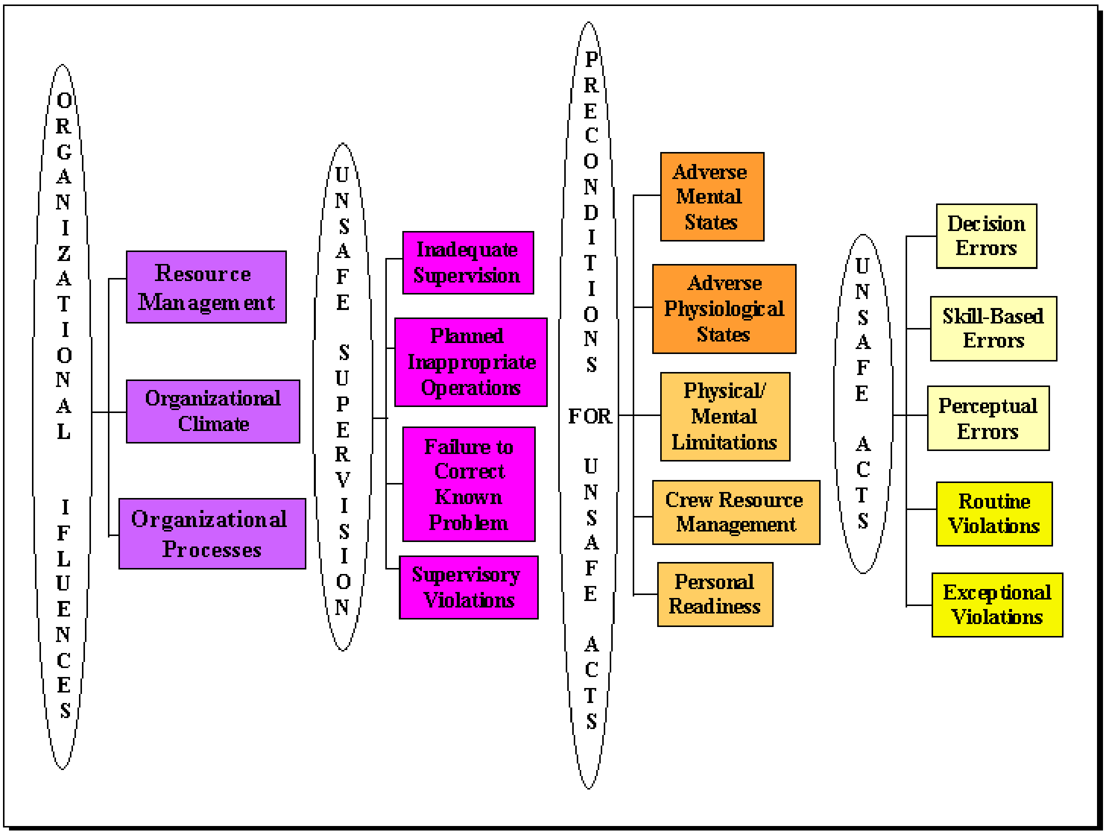
- Cognitive ergonomics
- Usability
- Human computer interaction
- Human machine interaction
- User experience engineering.

In the past 20 years Human Factors has been a very active research field. Specific focus has been given in researching memory capacity. Another field that has also benefited from the use of Human Factors practices is decision making in terms of preventing human error probability. Furthermore, conversation analysis has used several HF patterns in order to develop a productive human communications framework.

In an attempt to formally classify various types of human error, Dr Scott Shappell and Dr Doug Wiegmann of the University of Illinois, developed the Human Factors Analysis and Classification System (HFACS). HFACS is a useful tool in identifying the human causes of an accident and providing assistance in the investigation process, target training and prevention efforts, (Kirwan and Ainsworth 1992). It is based in the "Swiss Cheese" model of human error which looks at four levels of human failure, including unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences. It is a comprehensive human error framework that folded

Reason's ideas into the applied setting, defining 19 causal categories within four levels of human failure [AA].

Figure 2.3 gives a visual representation of the Swiss Cheese Model.



<u>Figure 2. 3:</u> The Swiss Cheese Model for Human Error

2.2 THE EMERGENCE OF HFE

Human Factors science has been the spark for further and more multifaceted studies regarding human potential and performance. In the wake of the 21^{st} century, a new engineering field was introduced in order to integrate Human Factors knowledge to modern engineering.

"Human Factors Engineering (HFE) is the discipline of applying what is known about human capabilities and limitations to the design of products, processes, systems, and work environments. It can be applied to the design of all systems having a human interface, including hardware and software. Its application to system design improves ease of use, system performance and reliability, and user satisfaction, while reducing operational errors, operator stress, training requirements, user fatigue, and product liability. HFE is distinctive in being the only discipline that relates humans to technology." [I]

Human Factors engineering activities include:

1. Usability assurance
2. Determination of desired user profiles
3. Development of user documentation
4. Development of training programs [I].

An example of HFE integration is figure 2.4. Human Factors science and HFE have pinpointed the parameters that affect directly a computer operator's compliance to the system. In order for the operator to achieve maximum performance, HFE has provided the optimum distances and angles ranges in a casual workplace environment.

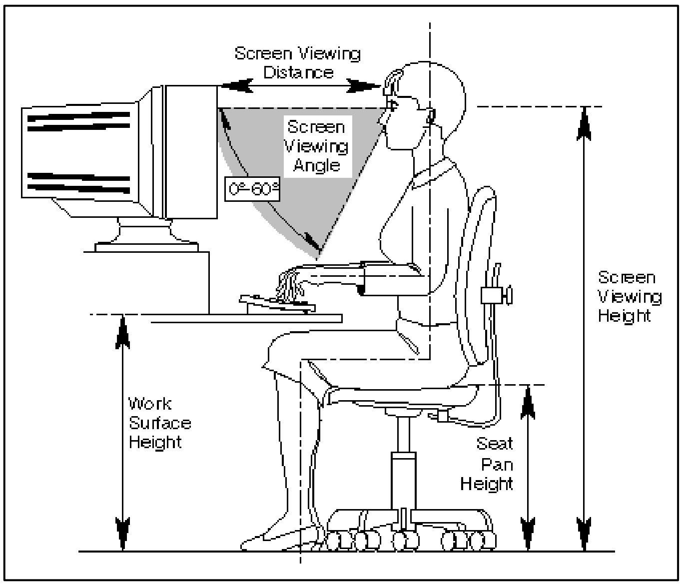


Figure 2. 4: A common example of Applied Ergonomics

Furthermore, Human Factors Engineering has provided guidelines in integrating its principles in ship design as well. Some of the most common suggestions include [14]:

- identifying the individuals part in a complex system
- workload simulation and modeling
- enhancement of man-machine interfaces in order to increase overall safety
- advanced human centered ship design methods
- techniques to enhance ship crew productivity thereby reducing manning requirements.

In figure 2.5 HFE suggests, in the form of a pyramid, the most important steps for successfully integrating its principles in modern industries. The bottom of the pyramid points the fact that before any action is taken, the management has to realize that following this procedure can be beneficial to the personnel but to the whole company/industry as well.

Figure 2. 5: Human Factors Engineering Pyramid

2.3 HUMAN RELIABILITY ANALYSIS AND HUMAN ERROR PROBABILITY

The most popular method for assessing human error probability in human/machine environment is the Human Reliability Analysis (HRA), a state of the art tool based on the principles of Probabilistic Risk Assessment (PRA). It can be best described as an analysis of the potential failure arising from human performance which emphasizes on system risk and reliability.

Human reliability analysis grew up in the 1960s with the intention of modeling the likelihood and consequences of human error. Initially, humans were considered as typical system component no different than equipment or procedures. The main part of an HRA is the assessment of the operator's error probability. Over the years, methods have been developed that recognize human potential to recover from a failure, on the one hand, and the effects of stress and organizational culture on the likelihood of possible errors, on the other. However, no method has yet been developed that incorporates all our understanding of individual, team and organizational behavior into overall assessments of system risk or reliability [2].

Some of the most popular HRA's include:

- A Technique for Human Error Analysis (ATHEANA)
- Cognitive Reliability and Error Analysis Method (CREAM)
- Human Cognitive Reliability Correlation (HCR)
- Human Error Assessment and Reduction Technique (HEART)
- Influence Diagrams Approach (IDA)
- Success Likelihood Index Method (SLIM)
- Technique for Human Error Rate Prediction (THERP)

2.4 HUMAN FACTOR IN MARITIME TRANSPORTS

In the past three decades, the maritime industry has suffered from incidents and accidents that were associated directly or indirectly with the prevalence of human error at sea. Maritime disasters such as the Exxon Valdez or the Herald of Sea Enterprise led both the scientific world and various organizations (e.g. classification societies) to conduct further investigation on the subject. While investigating the reports of most of these incidents, mariners' fatigue, human error, and human performance are recorded on a regular basis. International groups such as the International Maritime Organization (IMO) have established new legislation and proposed guidelines in order to address human error. Flag State safety, enforcement agencies and international treaties have implemented new laws and proposed several programs and strategies to reduce human error at sea. Moreover, high-risk ships can now be identified while conducting port state controls practices at a regular basis (e.g. mini bulkers).

Figure 2. 6: The disasters of Exxon Valdez and Herald of Sea Enterprise

Moreover, the whole maritime community, including IACS and national coast guards, has tried to isolate specific risk factors that increase human error probability. This fact has forced shipping companies to comply with existing regulations and embrace any human error related guidelines [53].

Rothblum [80] states that the maritime system is a *people* system, and human errors figure prominently in casualty situations. About 75-96% of marine casualties are caused, at least in part, by some form of human error. Studies have shown that human error contributes to:

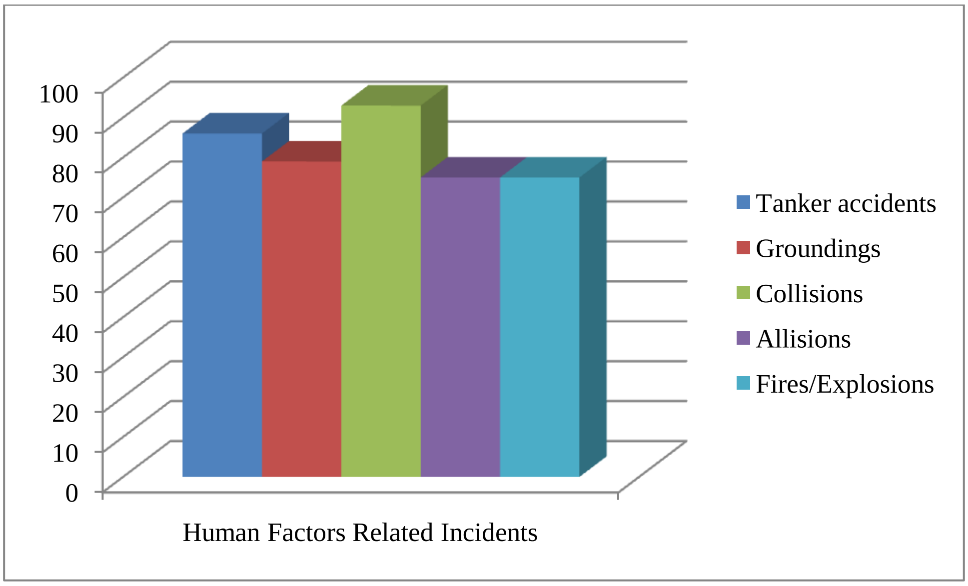
• 84-88% of tanker accidents

• 79% of towing vessel groundings

• 89-96% of collisions

• 75% of allisions

• 75% of fires and explosions



<u>Figure 2. 7:</u> Maritime Human Factor Statistics [80]

Some typical examples of the measures taken to mitigate human error on board was the establishment of the Integrated Bridge Systems (IBS), the improvement of the vessel's habitability and several applications of applied ergonomic in the engine room and the engine control room.

However, the most crucial measures to battle human error have been the introduction of the International Safety Management code (ISM) and several amendments on the Standards for Certification and Training of Watchkeepers (STCW) in the 2010 Manila convention. The fact that over 80% of accidents at sea are directly or indirectly a result of human error is primarily the reason for further research, investigation and guidance.

Pomeroy and Sherwood Jones of Lloyd's Register of shipping [70] indicate that the operational context is changing while the mariner population is changing in terms of background, culture and skills. The need to reduce overall costs has forced shipping companies to minimize crew complements. Moreover, seafarers have to adapt to high tech equipment and complex systems, results of the contemporary technological evolution and dominance of computer based machinery. While it is not obvious that these independent developments are compatible to human capabilities, the shipping industry remains in a transitional phase between a goal-setting approach and several regulation based and prescriptive trends.

IMO, in order to formally address the human element in the maritime domain, has established the *IMO HUMAN ELEMENT GROUP*. This group was formed in 1991 by the fifty-ninth session of the Maritime Safety Committee (MSC) and the thirty-first session of the Marine Environment Protection Committee (MEPC).

The fact that the working group was established jointly by both major IMO committees, as listed above, is in recognition of the case that the human element is a key factor in both safety and pollution prevention issues. The working group meets concurrently with meetings of the MSC or MEPC, as necessary.

Nowadays the group has several separate parties that address each specialized task through correspondence. Furthermore, the Human Element Working Group collaborates directly with the group that deals with Formal Safety Assessment (FSA). The FSA group aims to generate a new approach for developing international regulations with emphasis on risk and hazard assessment. This approach also gives full attention to the human element in ship operations.

The most important issues addressed by the Human Element Working Group include:

- safety management, through the ISM Code;
- human element principles and goals for the Organization;
- human element analyzing process tool for addressing the human element in the regulatory process;
- the problems associated with fatigue;
- a taxonomy of terms used in human element analysis; and
- review of studies related to ship operations and management.

Consideration of the human element has become a standing subject within the Organization. The Organization has adopted Human Element Vision, Principles and Goals and has developed the Human Element Analyzing Process tool, which provided a strategic plan and a structured systematic framework for addressing the human element [K].

In her paper regarding maritime Human Factors, Dr. Rothblum [80] summarizes the most common Human Factors Issues in the Marine Industry:

- *Fatigue.* 16% of the vessel casualties and 33% of the injuries are fatigue related.

- *Inadequate Communications.* 70% of major marine collisions and allisions occurred while a State or federal pilot was directing one or both vessels

- *Inadequate General Technical Knowledge.* In one study, this problem was responsible for 35% of casualties

- *Inadequate Knowledge of Own Ship Systems.*The lack of ship-specific knowledge was cited as a problem by 78% of the mariners surveyed.

- *Poor Design of Automation. Decisions Based on Inadequate Information.*

- *Faulty standards, policies, or practices*

- *Poor maintenance*

- *Hazardous natural environment.*

2.5 FATIGUE AS AN IMPORTANT HUMAN FACTOR

In our search for significant human factors in the maritime domain we concluded that one the most important ones is human physiology. It is rather logical that when a piece of machinery is badly maintained the probability of the system's failure is significantly high. The same rule occurs while investigating human performance.

Fatigue is the primary factor of human underperformance since it prevents the human body and cognitive skills to perform at an optimum level. While it is generally researched in the maritime industry, most studies have failed to indentify its importance and long term effect that may come with it. The underreporting of fatigue and the difficulties in measuring and analyzing it have made this task even harder.

According to Dr. Paula Sind-Pruiner of United States Coast Guard Research and Development center [14] there are a number of factors that have been recognized concerning human factors and fatigue in the maritime industry. Some of them are listed below:

- When stressed, fatigued, overworked, etc., trained methods usually fail.
- Fatigue is alive and well in the maritime industry.

- There are competitive economic pressures to maximize vessel utilization.
- There are competitive economic pressures to minimize crew size.
- Failure to recognize the dangerous performance effects of fatigue.
- Lack of knowledge concerning fatigue, and
- System lifecycle training costs often greatly exceed the incremental design costs.[14]

Hethrighton et al. [31] state that contemporary research has shown that there are potentially disastrous outcomes from fatigue in terms health and performance.

In the wake of the twenty first century, the seafarer's job has become more demanding than ever due to a combination of minimal manning, sequences of rapid turnarounds and short sea passages, adverse weather and traffic conditions, long working hours with insufficient opportunities for recuperative rest [94].

Despite the introduction of work rest mandates by IMO (2001) and STCW (1995) many seafarers have to work for more than 12 hours a day with a maximum of 5-6 hours break. In addition, in a report by the National Transportation Safety Board (1999), seafarers were identified out of the occupational groups included to be second in highest number of continuous working time, close behind rail workers.

Moreover, the seafarers themselves recognized that the impact of fatigue has been significantly greater in the past 10 years than it used to be. In a certain survey, out of 1000 participating officers, 84% felt that stress and fatigue were widely prevalent aboard ships, (Cole-Davies 2001).

In addition, Dr. Rothblum [80] indicates that the NTSB has identified fatigue to be an important cross-modal issue, being just as pertinent and in need of improvement in the maritime industry as it is in the aviation, rail, and automotive industries. Several studies, some of which were mentioned earlier, have cited fatigue as the primary factor for mariner's underperformance.

In conclusion, the importance of fatigue lays on the fact that even communications or incompetency errors can be the result of a fatigued individual. For example, a sleep deprived operator can make a wrong judgment in an emergency situation. The probability of this *judgment* error would be significantly lower if the operator had slept enough since fatigue affects directly an individual's cognitive skills. However, this error would be recorded as decision issue rather than a fatigue related one (due to the underreporting of fatigue) thus creating a trend to focus on the enhancement of decision making culture rather than mitigation of fatigue aboard.

CHAPTER 3

FATIGUE

3. FATIGUE

3.1. WHAT IS FATIGUE IN TERMS OF PHYSIOLOGY

Fatigue can be described as the feeling of tiredness or weakness that reduces the ability to perform ordinary tasks. Fatigue affects everyone differently. It can result into an intensive feel of tiredness resulting in a great urge for sleep. Pain can sometimes come along with fatigue as well. In general, it is the human body's way of signaling its need for rest and sleep. If there is a persistent feeling of tiredness or exhaustion present, which goes beyond normal sleepiness, it is usually the ‘alarm’ that something serious is amiss.

Physically, fatigue is characterized by a profound lack of energy, feelings of muscle weakness, and slowed movements or central nervous system reactions. Fatigue can also trigger serious mental exhaustion. Persistent fatigue can cause a lack of mental clarity, difficulty concentrating, and in some cases, even lack of memory. Chronic fatigue syndrome (CFS) is a long-term fatigue that may occur with other symptoms, such as recurrent sore throats, muscle pain, multi-joint pain, tender lymph nodes, new patterns of headaches, and complaints such as impaired memory or concentration [BB].

According to *handicapsupport.com* (L) fatigue can be dangerous when the tasks to be performed require great deal of concentration. When an individual is sufficiently fatigued, he or she may fall asleep for a small period while on duty, a common fatigue effect known as microsleep. However, objective cognitive testing should be done to pinpoint the difference between the neurocognitive deficits of brain disease from those attributed to fatigue.

Fatigue can be found in literature by various aliases such as

- Exhaustion
- Lethargy
- Languidness
- Languor
- Lassitude or Littleness

Fatigue is divided in two subcategories and two types

- 1. Physical fatigue
- 2. Mental fatigue
  And
- A) Central fatigue
- B) Peripheral fatigue

Smith et al. [90] indicate that the technical use of the term fatigue is imprecise. The variety of fatigue inducing situations, time courses and outcomes suggests that it is unlikely that we are considering a single set of processes leading to a specific underlying state. An individual that is affected by fatigue will experience possible performance deterioration and a probable physiological malfunctioning. Therefore, acute fatigue can be recognized as the main source of the symptoms that come with it. Reporting of fatigue and presence of symptoms is the first step in assessing the issue. Moreover, Smith pinpoints that fatigue is heavily dependent on which aspect of the fatigue process one uses as the indicator of its presence. For example, if one assumes that doing shift work is a risk factor for fatigue one might simply use the number of workers doing shift work as an indicator of prevalence. However, this is based on the assumption that shift work automatically leads to fatigue which one finds is not always the case. Similarly, fatigue may be measured by the presence of negative outcomes, but the extent of the problem will often depend on the indicator chosen. There is no single “right” approach: all aspects of the fatigue process must be assessed and considered [90].

The main question that remains is: Why is fatigue so important?

In their recent research regarding Human Factors, HSE [C] indicated that poorly designed shift-working arrangements and long working hours that do not balance the demands of work with time for rest and recovery can result in fatigue, accidents, injuries and ill health.

Consequently, fatigue can often be synonymous to excessive working time, poorly designed shift patterns and continuous lack of sufficient rest. It may come more easily if the tasks to be performed are complex, tedious and machined paced so it is deeply connected to the nature of the workload.

Fatigue has played an integral part in numerous accidents, ill-health and injury, and reduced productivity. Major disasters or near misses such as Herald of Free Enterprise, Chernobyl, Texas City, Clapham Junction, Challenger and Exxon Valdez have all been related to fatigue presence and outcomes.

HSE statistical data show that Fatigue has been implicated in 20% of accidents on major roads and is said to cost the UK £115 - £240 million per year in terms of work accidents alone. These costs might be an overestimation but if we take fatigue underreporting into consideration, the actual monetary damage could be even greater. For example, the restoration of a large oil spill (that can easily be the result of fatigue in the maritime domain) may cost more than a billion U.S. $.

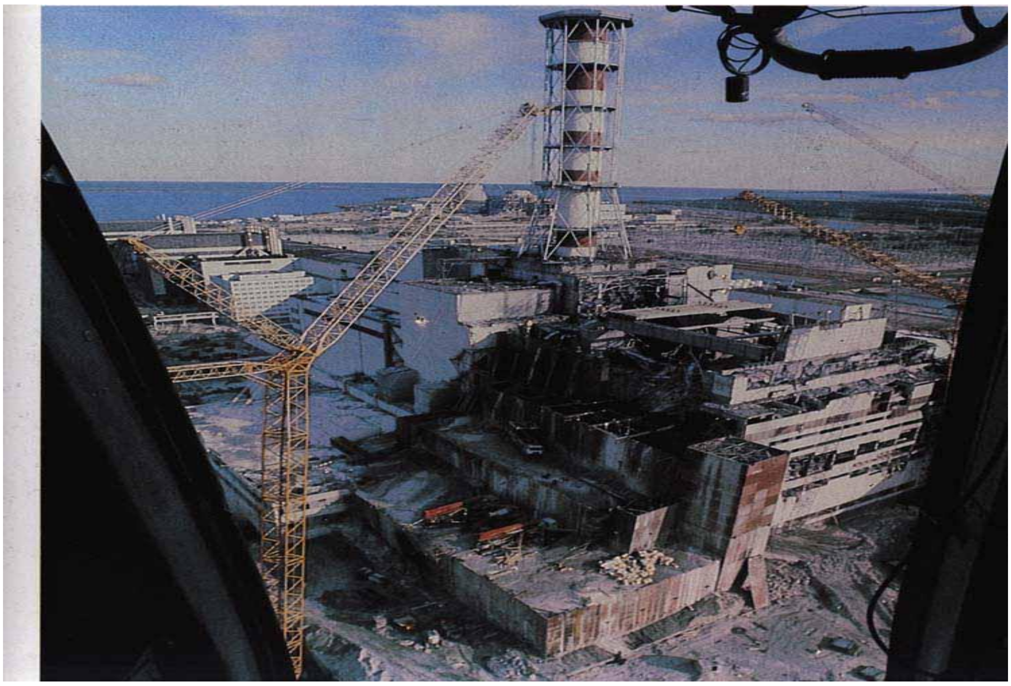


Figure 3. 1: The Chernobyl nuclear accident

3.1.1 PHYSICAL FATIGUE

Physical fatigue or muscle weakness is a direct term for the inability to exert force with one’s muscles to the degree that would be expected given the individual’s general physical fitness. A test of strength is often used during a diagnosis of a muscular disorder before the actual etiology can be identified. Such etiology depends on the type of muscle weakness, which can be true or perceived as well as central or peripheral. True weakness is substantial, while perceived rather is a sensation of having to put more effort to do the same task. On the other hand, central muscle weakness is an overall exhaustion of the whole body, while peripheral weakness is an exhaustion of individual muscles [M].

3.1.2 MENTAL FATIGUE

In addition to physical, fatigue also includes mental fatigue, not necessarily including any muscle fatigue. Mental fatigue describes the effect that people experience during and following prolonged periods of cognitive activity that requires work efficiency. Such a mental fatigue, in turn, can manifest itself either as decreased wakefulness or just as a general lack of attention, not necessarily including sleepiness. It may also be described as a more or less decreased level of consciousness. In any case, this can be dangerous when performing tasks that require constant concentration, such as driving a vehicle or paroling.

To summarize, mental fatigue refers to the state caused by extended period of demanding cognitive activity. The effect of mental fatigue on cognitive skills and mental performance are rather profound. However, the impact of mental fatigue on physical performance is often neglected and not sufficiently researched.

An interesting comparison between physiological and psychological fatigue is made by Shen et al. [86]. In this essay, physiological fatigue is described as a loss of maximal force generating capacity during muscular activity or a failure of the functional organ. It may be induced by excessive energy consumption or the depletion of hormones, neurotransmitters or essential physiological substrates. Physiological fatigue may be associated with fever, infection, anemia, sleep disturbances, and pregnancy. Psychological fatigue, in contrast, has been defined as a state of weariness related to lack of motivation. Psychological fatigue has been associated with stress and other intense emotional experiences and may accompany depression and anxiety [86].

3.1.3 CENTRAL FATIGUE

The central component to fatigue is generally described in terms of a reduction in the neural drive or nerve-based motor command to working muscles that result in a decline in the force output. It has been suggested that the reduced neural drive during exercise may be a protective mechanism to prevent organ failure if the work was continued at the same intensity [M].

3.1.4. PERIPHERAL FATIGUE

Fatigue during physical work is considered an inability for the body to supply sufficient energy to the contracting muscles to meet the increased energy demand. This is the most common case of physical fatigue-affecting a national average of 72% of adults in the work force in 2002. This causes contractile dysfunction that is manifested in the eventual reduction or lack of ability of a single muscle or local group of muscles to do work. The insufficiency of energy, i.e. *sub-optimal aerobic metabolism*, generally results in the accumulation of lactic acid and other acidic anaerobic metabolic by-products in the muscle, causing the stereotypical burning sensation of local muscle fatigue.

The fundamental difference between the peripheral and central theories of fatigue is that the peripheral model of fatigue assumes failure at one or more sites in the chain that initiates muscle contraction. Peripheral regulation is therefore dependent on the localized metabolic chemical conditions of the local muscle affected, whereas the central model of fatigue is an integrated mechanism that works to preserve the integrity of the system by initiating fatigue through muscle derecruitment, based on collective feedback from the periphery, before cellular or organ failure occurs. Therefore the feedback that is read by this central regulator could include chemical and mechanical as well as cognitive cues. The significance of each of these factors will depend on the nature of the fatigue-inducing work that is being performed [CC].

The following image shows a typical example of central (left) and peripheral fatigue (right). Peripheral fatigue, as shown in figure 3.2, can be the result of a specific type of exercise such as working out the biceps. The red zone represents the impaired part of the body that needs to rest, in order to perform the same task effectively.

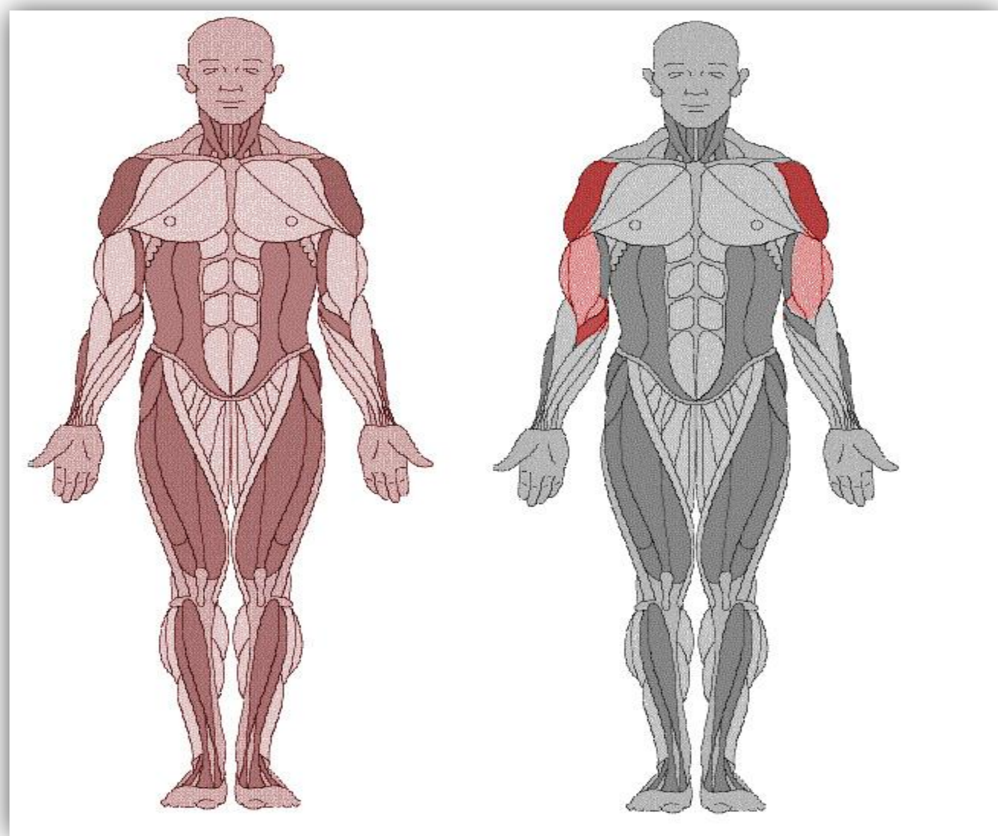


Figure 3. 2: Central and Peripheral fatigue

In a similar comparison to that between physiological and psychological fatigue Shen, Barbera et al [90] state that central models of fatigue imply a malfunction of the CNS (central nervous system), such as impaired transmission between the CNS and the peripheral nervous system, or dysfunction of selected areas of CNS such as the hypothalamic region. Peripheral models of fatigue, in contrast, view fatigue as resulting from dysfunction of the peripheral nervous system, such as impaired neuromuscular transmission at the motored-plate. While dualistic approaches have proven to be popular, such definitions fail to capture the multidimensional nature of the fatigue. A number of other definitions for fatigue have been proposed [90].

3.2. FATIGUE IN MEDICAL TERMS

In medical physiology, fatigue is the inability to perform reasonable and necessary physical or mental activity. When the metabolic reserves of the body are exhausted and the waste products increased, as for example after prolonged exertion, the body finds it difficult to continue its function and activity. The accumulation of *lactic acid* in muscle tissue and the depletion of glycogen (stored glucose) results in muscle fatigue. The contractile properties of muscle are reduced, and continued exertion is impossible unless the muscle is allowed to rest. In the normal body a period of rest permits redistribution of nutritive elements to the muscles and tissues and elimination of accumulated waste products; the body is then ready to resume activity. There are some persons in whom fatigue is a chronic state that does not necessarily result from activity or exertion. In some instances this abnormal fatigue may be associated with systemic disorders such as anemia, a deficiency of protein or oxygen in the blood, addiction to drugs, increased or decreased function of the endocrine glands, or kidney disease in which there is a large accumulation of waste products. If excessive fatigue occurs over a prolonged period, exhaustion (marked loss of vital and nervous power) may result. In most persons with chronic fatigue, however, the condition seems to be associated with manic-depressive disorder. Thorough medical and psychiatric examination may be required [N].

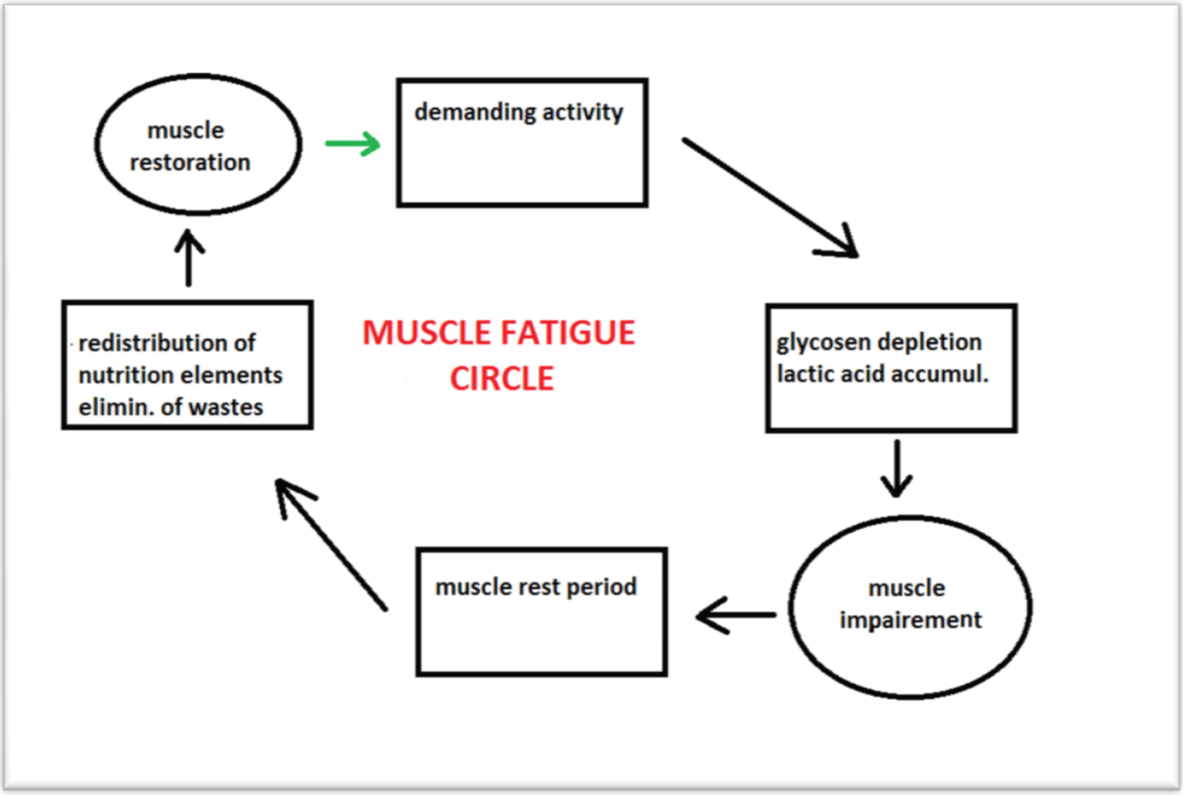


Figure 3. 3: Muscle impairment and rejuvenation process

3.3 FATIGUE RISK FACTORS

In their research regarding seafarer's fatigue Smith et al. [94] summarize t that fatigue may be the result of a great number of factors: lack of or poor quality sleep, long working hours, working at times of low alertness, prolonged work, insufficient rest between work periods, excessive workload, noise and vibration, motion, medical conditions and illnesses. Chronic fatigue can either be the result of continuous exposure to acute fatigue or can represent a failure of rest and recuperation to remove fatigue. Many working patterns induce acute fatigues which in time lead to chronic fatigue. For example, working at night is associated with reduced alertness during the shift and may also produce cumulative problems because of poor sleep during the day. Risk factors for fatigue have been deeply connected with problems related to sleep quality and deprivation as well as day-time sleep following a night shift.

In addition, Smith et al. [94] state that risk factors for fatigue have been categorized by researchers into factors that reflect the work environment (e.g. working hours, task nature, the physical surroundings) and aspects related to the individual (both stable traits, and current state). It is of the outmost importance to recognize that it is the interplay of these risk factors that is significant; fatigue is most likely to appear when a large number of these factors are present. It is a common fact that most regulatory bodies have, until recently, focused their research and legislation regarding fatigue on work schedules. On the other hand, the role of psychological and emotional factors is rather neglected resulting in insufficient research on their sources and impact. Moreover, Smith et al. recognizes that only few studies have examined how risk factors might interact in terms of their effects, or attempted to pinpoint the different risk factors (e.g. what are the relative contributions of factors such as sleep deprivation, long working hours and high job demands to fatigue levels?). Recent studies regarding fatigue have indicated that psychosocial workplace stressors tend to demonstrate cumulative associations with self reports of work stress and poor health outcomes with similar or greater severity to those caused by physical fatigue [94].

A general summary of the most common and influential fatigue risk factors is presented by Calhoun [14]:

- poor sleep quality
- sleep deprivation
- physical/mental exertion
- emotional stress
- disruption of circadian rhythms
- poor physical condition,
- And drug/alcohol use.

3.3.1 SLEEP & SLEEP QUALITY

According to *Macmillan Dictionary (1980)* sleep is a naturally recurring altered state of consciousness with relatively suspended sensory and motor activity, characterized by the inactivity of nearly all voluntary muscles. It is distinguished from quiet wakefulness by a decreased ability to react to stimuli, but it is more easily reversible than hibernation or coma. Sleep is a heightened anabolic state, accentuating the growth and rejuvenation of the immune, nervous, skeletal and muscular systems [O].

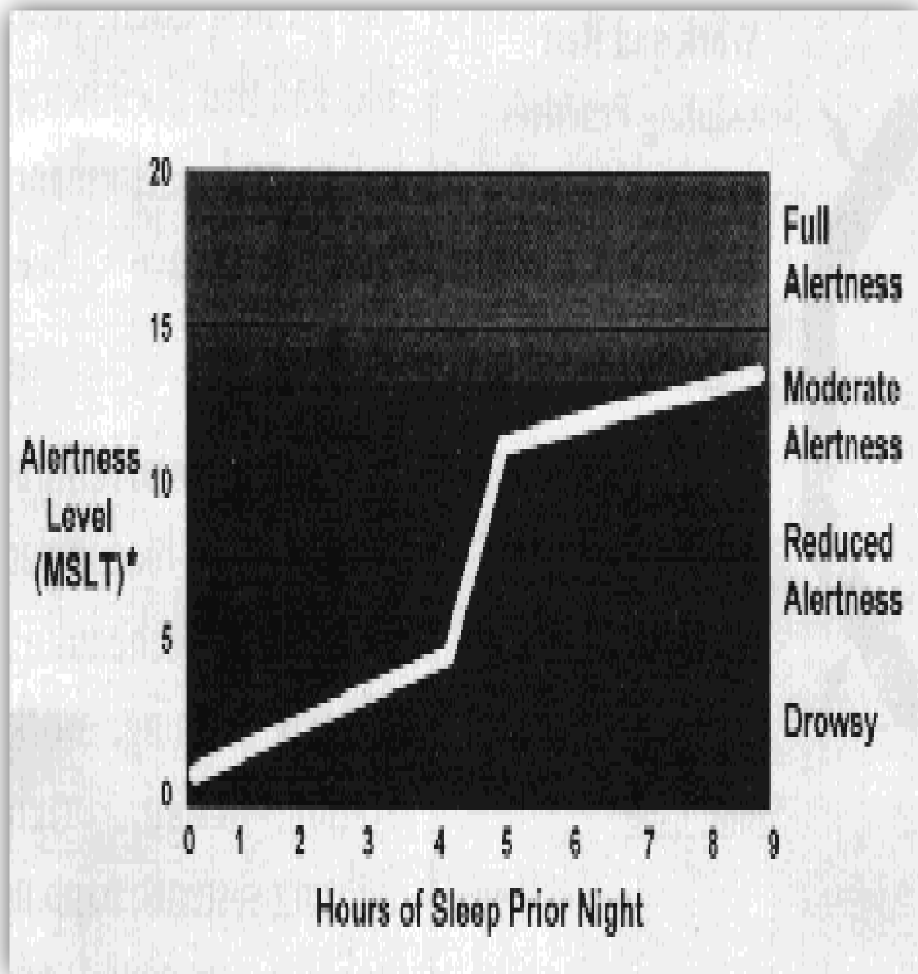
The need for sleep and its physiology have being researched extensively for many years. Research has shown that the human body needs "restorative sleep" in order to remain alert and rejuvenate its *'batteries'*. In order to have restorative sleep four stages of sleep are necessary to take place. Table 3.1 shows four general factors that constitute the overall picture of sleep quality.

<u>Table 3. 1:</u> Factors that affect the overall sleep quality [14]

Component	Description	Notes
1. Duration	Individual requirements are unique; minimum 7 - 8 hours in a 24-hour period.	Sleep loss effects are cumulative.
2. Continuity	Sleep period must be uninterrupted.	Five stages of sleep; cycle throughout the sleep period.
3. Quality	Deep sleep/REM required for recuperation	Five stages of sleep. Each provides differing benefits.
4. Time of Day	Sleep during the day not as high quality as sleep during the night.	Circadian Rhythm is the driving factor.

3.3.1.1. SLEEP DURATION (QUANTITY)

Restorative sleep plays a significant role on individual performance so for avoiding sleep deprivation it is essential for the human body to establish a sleep quantity routine. Individuals have different requirements regarding the hours of sleep needed to feel fresh and renewed the following morning. The vast majority of the human population requires seven to eight hours. Alertness levels in correlation to sleep duration are shown below in Figure 3.4 [14].We can see that the turning point from reduced to full alertness lies within four to six hours of sleep. However, this figure refers to person who had regular sleeping patterns in the past. If an individual sleeps an average of five hours for a week, he is likely to experience lack of alertness due to sleep deprivation.



<u>Figure 3. 4:</u> The effect of sleep deprivation on alertness,(Sirois, 1998.)[1][14]

It is a common fact that if a person sleeps less than five hours, there is a great probability to be drowsy when he gets up the next day. Figure 3.4 also shows that the average person needs eight or more hours of sleep in order to reach peak levels of alertness [14].

Medical research has shown that the sleeping time each person needs depend on various factors, the most important being age. In figure 3.5 we can see an empirical estimation of the sleeping hours needed per day for a number of different age groups. While these needs are representative, each individual might require more or less sleep than the average due to general health, environmental and social issues. For example, research has shown that an individual with a regular smoking habit might need two extra hours of sleep to that of a non-smoking person of the same age.

[1] In the above graph, the measure of alertness is the multiple sleep latency test (MSLT). This is a measure of how quickly a person falls asleep. An alert person takes the most time and a fatigued person takes less time

Average Number of Hours of Sleep Needed

Age	Per Day
Birth	16 to 18 hours
First 6 months	14 to 16 hours
6 to 12 months	13 to 14 hours
12 months to 2 years	12 to 13 hours
2 to 6 years	10 to 13 hours
6 to 12 year	9 to 11 hours
12 to 18 years about	10 hours
Adults about	8 hours

Figure 3. 5: Average hours of sleep needed per day-Age [O]

3.3.1.2 SLEEP ARCHITECTURE

Sleeping quantity is an essential part of the whole sleep quality procedure. While asleep, the human body cycles through different levels of sleep. These levels are known as sleep stages and each serves a different purpose for rejuvenating the body (the purpose of each stage is currently researched). This cyclical pattern of light sleep, deep sleep and rapid eye movement (REM) sleep is called sleep architecture. In the following table we can see the duration, effects and order of all 4 known sleep stages.

Table 3. 2: Sleep architecture stages [14]

Stage	Duration	Description	Effects	Notes
1. Transition	10 mins.	Phase between waking and sleeping	Asleep without knowing it	Microsleep and Automatic Behavior Syndrome (described later)
2. Light sleep	15 mins.	Light level of sleep	Feel briefly alert and refreshed	50% of all sleep is in this stage
3. Delta sleep	15-20 mins.	A deeper sleep		
4. Deep sleep	20-70 mins.	Deepest stage of sleep	Will feel groggy if awoken; occurs early in the night	Sleep Inertia (described later)
5. REM sleep	After 70-80 mins. of sleep	Dreaming state		

The entire cycle normally occurs in 90-minute periods, providing approximately four to five cycles in an 8-hour period. The proportions and duration of each stage are critical to the restorative quality of the cycle. Research has shown that restorative sleep requires three to five uninterrupted sleep cycles.

Experts currently believe that the third and fourth sleep stages are responsible for body restoration and REM for strengthening and organizing memory. The cycle continues throughout the sleep period, with each REM stage increasing in length.

Interruptions while sleeping, such as those caused by light, noise, and excessive vibration, tend to keep the body in the lighter stages. This makes it difficult to transition to deeper sleep, thereby reducing the ability to get the important third, fourth, and fifth stages that are required for sleep to be restorative. It is very probable that even one day of reduced sleep is enough for a person to experience a decline in their alertness levels. The loss of sleep over a week's time causes dangerously low levels of alertness and this is when accidents are likely to occur. These same effects are experienced by those who work late at night and through the early morning hours [14].

3.3.1.3 COMMON CAUSES OF SLEEP LOSS

The Queensland government website [H] indicates that a number of factors in the workplace and in a person's private life can cause sleep loss. Examples from the workplace include:

- Extended working hours
- Irregular and unpredictable working hours
- Time of day when work is performed and sleep obtained
- Shift work
- Having more than one job and
- Stress.

3.3.1.4 SLEEPING ENVIRONMENT

Sleeping environment is an integral part of the overall sleep quality. The idea of a satisfying sleep environment rests on a plethora of factors. The most important factor is the temperature. The brain acts slowly if its temperature is in a comfortable zone. Temperature controls the brain activity and in turn; the body activity. If it is cool it affects the brain to be in rest and one can sleep. Another factor is light - we need darkness or toned light - the mixture of dark and light. The third factor is sound. When we close our eyes we feel comfortable, but if sound is there our eyes will open so we need a quiet environment. The other factor is the surface of the mattress. The smoother the surface is, the better we will sleep. To summarize, the key contributors for a healthy sleeping environment are:

- Light
- Noise
- Temperature

Some other factors that have been known to worsen the overall sleep environment are:

- Humidity
- Vibrations
- Uncomfortable clothing
- Pillows and mattresses
- Smoky environment
- Available space

The following figure (3.6) shows the difference between a healthy and a hazardous environment. It should be mentioned that in hazardous sleeping environment the individual is often vulnerable to the factors that can disrupt sleep continuity and decrease sleep quality.

Figure 3. 6: Examples of hazardous (left) and healthy (right) sleeping environments

3.3.1.5 TIME OF DAY

Many scientists have indicated that the time of the day can also be a contributing factor to the sleep quality. It is a common fact that the human body is not *designed* to operate at night and sleep during the day, so it is rather clear that sleeping during daytime could prove extremely difficult. A graphical depiction of why this is true is shown in Figure 3.7 (Sirois, 1998). The graph shows changes in body core temperature throughout the day, which directly relates to alertness. A drop in temperature naturally causes sleepiness.

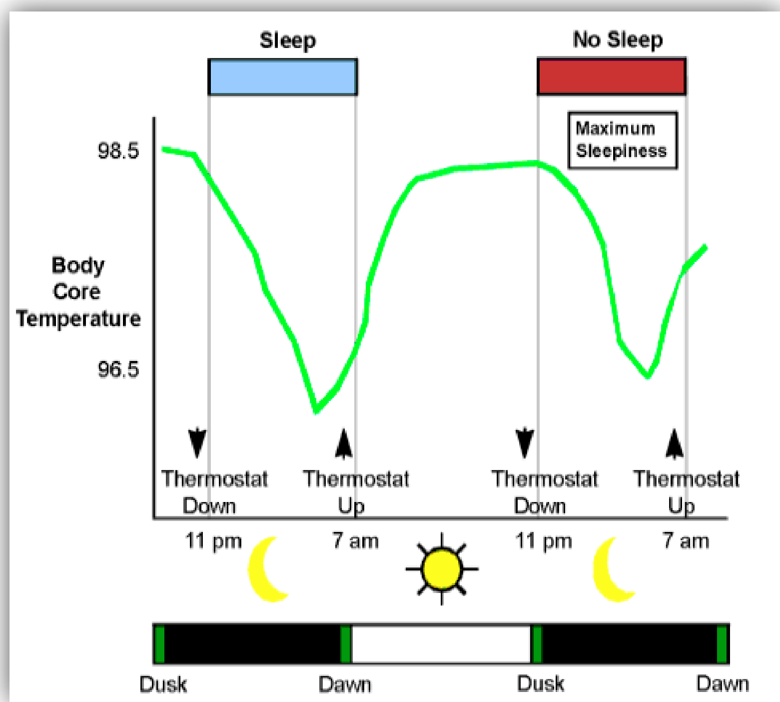


Figure 3. 7: Body temperature during a regular day (Sirois, 1998) [103]

3.3.1.6 NAPPING

A nap is a short period of sleep, usually in the daytime. Naps may be taken when one person becomes drowsy during the day or as a traditional daily practice. It is common for small children and elderly people to take frequent naps. Experts agree that the best way to fight fatigue is to get enough sleep every night. But for some people, especially those who work long hours, have care giving responsibilities or work at night, this can be an ambitious goal. Even people who do get enough sleep regularly may feel the effects of the midday dip, especially after a heavy meal. Studies show that taking a nap is a great way to increase alertness and reaction times, improve mood, and reduce accidents. For many people, napping is also a highly pleasurable experience [*P*].

3.3.1.7 SLEEP DEPRIVATION

Sleep deprivation, a sleep disorder characterized by having too little sleep, can be either chronic or acute. Long-term sleep deprivation causes death to lab animals. A chronic sleep-restricted state can cause fatigue, daytime sleepiness, clumsiness and weight loss or weight gain, [O]. Extended periods between sleep sessions deprive a person of the rest needed to remain alert. Sleep deprivation drastically reduces alertness levels after a person has been awake for more than fourteen hours. Figure 3.8, (Sirois, 1998) [14] illustrates this point:

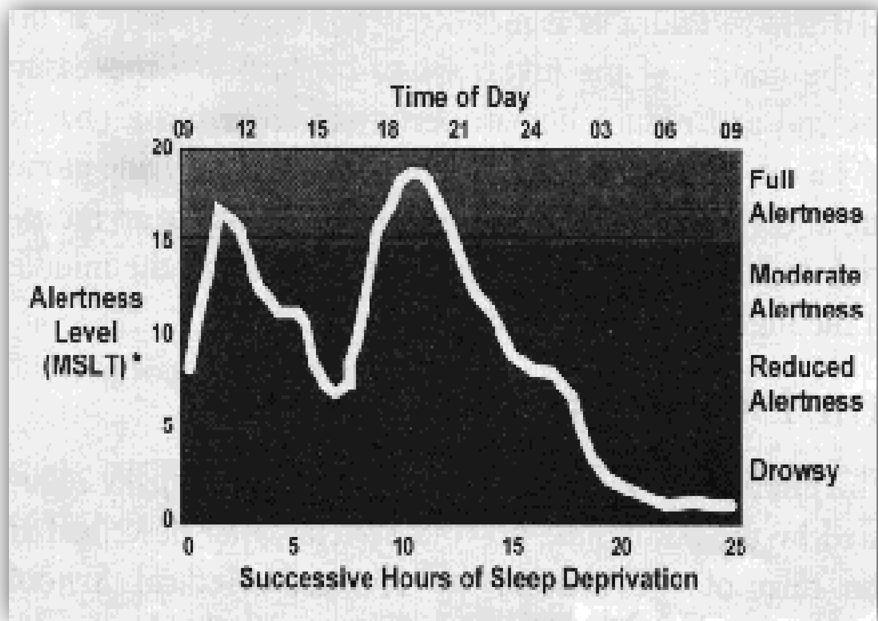


Figure 3. 8: Sleep deprivation and alertness 14]

Common effects of sleep deprivation

The end-your-sleep-deprivation website [Z] categorizes the effects of sleep loss/deprivation in the following:

1. **Decreased Alertness and Ability to Maintain Focus**

   Carrying a sizable sleep debt throughout the day can drastically decrease productivity. Fatigue will compromise your attention, and as a result cognitive performance will suffer. Specifically, learning, memory, and creativity are frequently hampered by a large sleep debt. In a situation such as driving a car this decreased alertness can, and has repeatedly, led to fatal results.

2. **Mood**

   It's not uncommon for sleep-deprived individuals to be subject to extreme emotions and mood swings. A very tired person who is laughing uncontrollably at one moment may be crying or yelling angrily a few minutes later. In addition, sleep deprived individuals tend to be short-tempered and difficult to communicate with while fatigue also results in lack of motivation.

3. **Energy and Motivation**

   A decrease in energy and motivation is probably the most noticeable consequence of sleep deprivation. Individuals who have not received sufficient sleep will feel lethargic and uninspired to work.

4. **Control, Coordination, and Impulsiveness**

   Lack of sleep is often associated with a hindrance of bodily control. Tired individuals often feel enhanced physical impulses, such as an otherwise inexplicable desire to eat.

3.3.2 CIRCADIAN RHYTHMS

According to Dr. Samuel Strauss, "Circadian rhythms" are physiological and behavioral processes, such as sleep/wake, digestion, hormone secretion, and activity that oscillate on a 25 hour basis. Each rhythm has a peak and a low point during every day/night cycle. Time cues, called "zeitgebers" keep the circadian "clock" set to the appropriate time of day. Common zeitgebers include daylight, meals and work/rest schedules. If the circadian clock is moved to a different schedule, for example when crossing time zones or changing from a day work shift to a night shift, the resulting "sleep phase shift" requires a certain amount of time to adjust to the new schedule. This amount of time depends on the number of hours the schedule is shifted, and the direction of the shift. During this transition, the circadian rhythm disruption or *"jet lag"* can produce effects similar to those of sleep loss [Q].

Historically, to differentiate genuinely endogenous circadian rhythms from coincidental or apparent ones, three general criteria must be met: 1) the rhythms persist in the absence of cues, 2) they persist equally precisely over a range of temperatures and 3) the rhythms can be adjusted to match the local time [DD]:

- The rhythm persists in constant conditions (for example, constant dark) with a period of about 24 hours. The rationale for this criterion is to distinguish circadian rhythms from those "apparent" rhythms that are merely responses to external periodic cues. A rhythm cannot be declared to be endogenous unless it has been tested in conditions without external periodic input.
- The rhythm is temperature-compensated, i.e., it maintains the same period over a range of temperatures. The rationale for this criterion is to distinguish circadian rhythms from other biological rhythms arising due to the circular nature of a reaction pathway. At a low enough or high enough temperature, the period of a circular reaction may reach 24 hours, but it will be merely coincidental.
- The rhythm can be reset by exposure to an external stimulus. The rationale for this criterion is to distinguish circadian rhythms from other imaginable endogenous 24-hour rhythms that are immune to resetting by external cues and, hence, do not serve the purpose of estimating the local time. Travel across time zones illustrates the necessity of the ability to adjust the biological clock so that it can reflect the local time and anticipate what will happen next. Until rhythms are reset, a person usually experiences jet lag.

Figure 3.9 gives us a rough representation of the human "biological clock" of an average individual [DD].

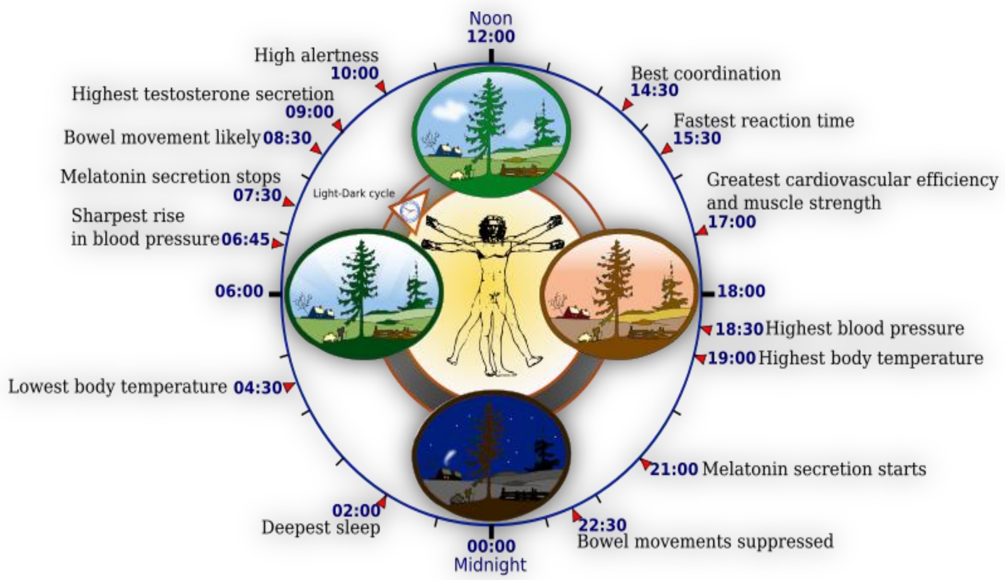


Figure 3. 9: Biological clock and Circadian Rhythms [DD]

This natural rhythm of alertness is illustrated below in Figure 3.10 where we can easily pinpoint the peak and the drowsy periods of the circadian rhythms.

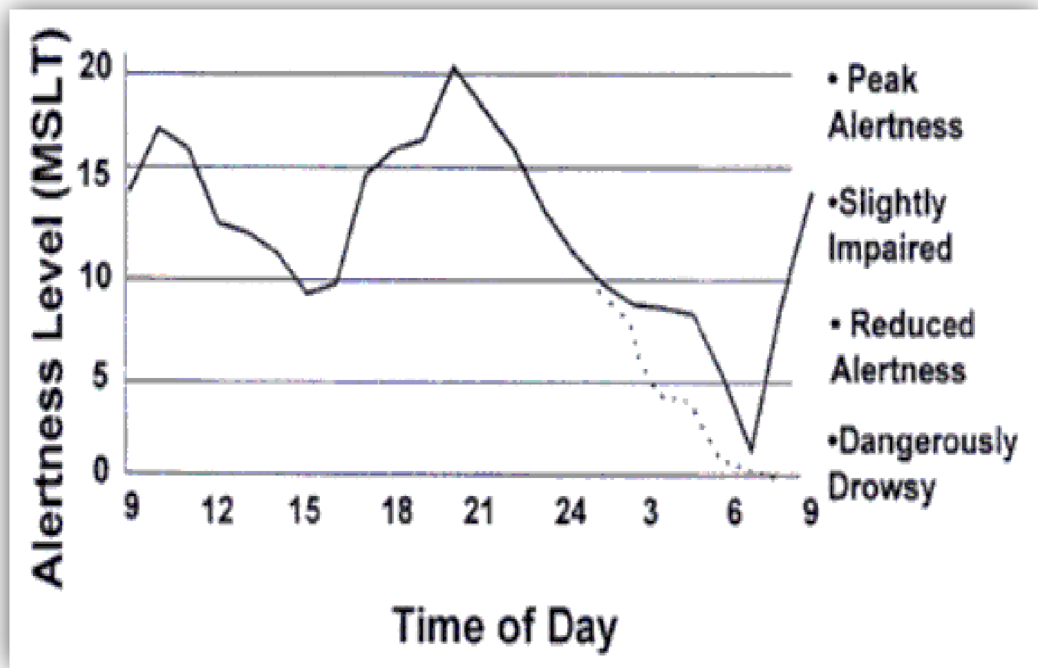


Figure 3. 10: Circadian Rhythms and Alertness [14]

The biological clock regulates energy cycles so that alertness increases after wake-up time, peaks in the mid-morning hours, dips through the late morning and early-afternoon hours, peaks again in the early-evening hours, and then decreases throughout the late-evening and early-night hours, reaching a daily low in the middle of the night. The exact times of these peaks and valleys depend on specific inputs to the biological clock system, namely wake-up times, bedtimes, and daily interval of daylight (or artificial bright light) exposure [103].

The circadian rhythms most dominant attribute is its effect on the human sleep cycle; this combined with its influence on body temperature regulation, hormone production and adrenal gland output, cause the body to desire sleep. Sleep is desired and initiated at preferred times relative to the circadian rhythm of core body temperature (Monk, 1987). In general, the longest and best quality sleep episodes are initiated several hours prior to the body temperature minimum. Humans are most productive when their body temperature is at its highest and logically at its least efficient, when temperature is lowest. Human performance degradation at circadian lows is one of the major challenges for the aviation industry [A].

The NASA Ames Fatigue Countermeasures Program has underlined the fact that sleep loss, and circadian disruption lead to significant decrements in alertness and performance, (Neri et al., 2002). A 1995 Airbus report highlights Human performance decrements include problems with:

- Vigilance
- Alertness
- Irritability
- Loss of mental agility
- Ability to multi-task
- Decision making
- Perceptive skills

The challenge facing flight crews is the need to maintain vigilance during long, highly-automated, and often boring night flights. Traditionally most accidents and incidents occur during the approach and landing phase of flight [A].

The most common causes of circadian disruption are:

- Jet Lag: The need to adjust ones biological clock to global time changes in a short period. This issue is very common in aviation and truck drivers.
- Routine change or shift change: When the daily sleep routine is altered due to various circumstances. Airline pilots and seafarers often ‘swallow’ shift changes which do not allow them to establish a healthy daily sleep routine thus disrupting their ‘biological clock’.

To conclude, circadian rhythms are responsible for coordinating the following physiological aspects.

- Sleepiness/wakefulness
- Body temperature
- Digestion
- Cardiovascular responses
- Digestion
- Alertness/Vigilance

3.3.3 SECONDARY RISK FACTORS

Apart from sleep and circadian rhythms, there are numerous other fatigue risk factors. It is rather clear that their impact is of lesser impact of the two factors discussed above. However, these factors are not to be ignored since their effects and interaction with each other favor high levels of fatigue. Moreover, most of them have interplay with both sleep quality and the disruption of circadian rhythms, increasing indirectly fatigue presence in work and domestic environments.

Some of the most common secondary fatigue risk factors are discussed in the following paragraphs.

3.3.3.1 PHYSICAL CONDITION

The level of fatigue increases as physical condition drops. Fitness, which is directly associated with physical condition can be an important factor in reducing the presence and effects of fatigue.

Figure 3.11 shows the work done by a hotspot crew in a 9-day period. The crew was divided in fitter and less fit groups. The fitter group did more work per day. It can be inferred that the effect of fatigue was greater on the less fitter group thus effecting their performance.

Aspects that have impact on physical condition are:

1. Exercise
2. Sufficient and healthy nutrition
3. Illness
4. Alcohol
5. Medication(per scripted)
6. Substances (drugs etc.)
7. Smoking habits
8. Sleep disorders

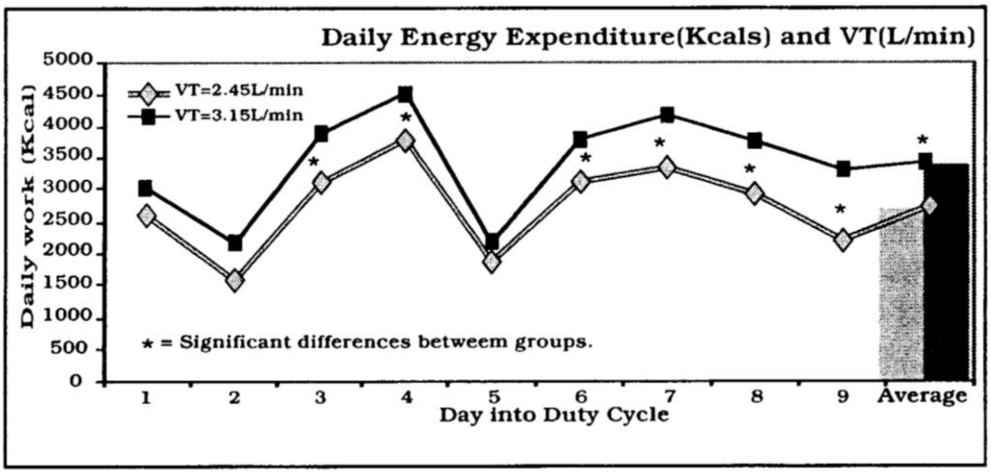


Figure 3—This graph shows the work (kilocalories per day) done by a hotshot crew over a 9-day period. The crew was divided into fitter and less fit groups. The fitter group did more work per day than the less fit group.

<u>Figure 3. 11:</u> Fatigue-fitness connection [105]

3.3.3.2 ENVIRONMENT

Fatigue is deeply connected to the environmental surroundings. A hazardous and non-ergonomic environment can decrease the performance and endanger the safety of an individual. A very common example of this assumption is the idea of performing a certain task in the presence of extreme heat. Heat has a severe impact on body temperature causing an outburst of fatigue. Fatigue factors that are linked to the environment are:

1. Temperature
2. Noise
3. Weather phenomena
4. Humidity
5. Lighting
6. Vibrations (moving environments aircrafts, ships etc.)
7. Ventilation

3.3.3.3 WORK WONDITION

Recent research has shown that job demands and overall nature play a key role in the emergence of fatigue. Statistical data and scientific expertise agree that job-specific fatigue is affected by:

1. Workload: The amount of workload is logically connected to fatigue. Heavy workload often means limited time for rest and an inevitable concentration of fatigue. Moreover, workload, by means of shift

change, can possibly disrupt the circadian rhythms as mentioned in paragraph 3.3.2.

2. Type of work: Type of work in terms of job ‘attractiveness’ can often result in fatigue problems. A tedious and repetitive task can provoke tiredness and even sleepiness. On the other hand, a pleasant and interesting activity could reduce potential signs of fatigue, especially mental.

3.3.3.4 STRESS

According to Selye (1956) stress is a term in psychology and biology, first coined in the biological context in the 1930s, which has in more recent decades become a commonplace of popular parlance. It refers to the consequence of the failure of an organism – human or animal – to respond appropriately to emotional or physical threats, whether actual or imagined.

Stress symptoms commonly include a state of alarm and adrenaline production, short-term resistance as a coping mechanism, and exhaustion, as well as irritability, muscular tension, inability to concentrate and a variety of physiological reactions such as headache and elevated heart rate [T].

The *Université Laval occupational health and safety management department* [U] states that the transactional model of Lazarus defines stress as an imbalance between the demands of the environment and the individual's resources. According to this model, the individual makes a primary appraisal of the situation or the demand with which he is confronted. The demand may be perceived as a challenge or even a threat if the individual thinks that it may give rise to negative consequences-and-extent. The individual then makes a secondary appraisal where he attempts to determine what resources are available to meet the demand. Thus, workplace stress implies that work-related demands exceed the employee's ability to adapt to these demands. The effects of stress may therefore be positive and provide the motivation, energy and creativity needed to accomplish a task if the individual thinks that he has the abilities and resources needed to succeed at it. The effects of stress will be negative when there is a discrepancy between the individual's resources and the demand.

Here are many causes (stressors) of stress in life including:

- Death: of spouse, family, friend
- Health: injury, illness, pregnancy
- Crime: Sexual molestation, mugging, burglary, pick-pocketed
- Self-abuse: drug abuse, alcoholism, self-harm
- Family change: separation, divorce, new baby, marriage
- Sexual problems: getting partner, with partner
- Argument: with spouse, family, friends, co-workers, boss

- Physical changes: lack of sleep, new work hours
- New location: vacation, moving house
- Money: lack of it, owing it, investing it
- Environment change: in school, job, house, town, jail
- Responsibility increase: new dependent, new job.

UK's HSE lists six key stress factors (stressors) at work [C]:

1. The demands of the job
2. The control staff have over how they do their work
3. The support they receive from colleagues and superiors
4. Their relationships with colleagues
5. Whether they understand their roles and responsibilities
6. How far the company consults staff over workplace changes.

In addition, *Universite Laval* website [U] states some common symptoms of stress:

Physical symptoms

- Cardio-vascular disorders
- Allergies
- Dermatological disorders
- Migraines
- Respiratory disorders
- Sleep disorders
- Gastrointestinal disorders

Psychological symptoms

- Depression
- Anxiety
- Boredom
- Frustration/Irritability
- Isolation
- Difficulties concentrating or making decisions
- Memory lapses

Behavioural symptoms

- Aggressivity
- Alcohol or drug abuse
- Eating disorders
- Conflicts
- Absenteeism
- Decreased productivity

- Decision to leave job
- Accident proneness

The Consequences of Stress for the individual

It is rather obvious that stress affects fatigue in many different ways. The direct consequences of stress can be summarized in the following categories.

1. Mood disorders
2. Anxiety disorders
3. Burn out (unhealthy relationship with work environment)
4. Survivor syndrome

3.4. EFFECTS OF FATIGUE

Cumulative fatigue can have numerous various effects in everyday life. In this paragraph the most considerable results of fatigue will be presented. The complex nature of fatigue and its causes makes the number of consequences too great to count. However, scholars and researchers have categorized these effects in three greater categories

3.4.1. WORK PERFORMANCE

3.4.1.1 GENERAL

High levels of fatigue cause reduced performance and productivity, and increases the risk of accidents and injuries. Fatigue affects the ability to think clearly. As a result people who are fatigued are unable to gauge their own level of impairment, and are unaware that they are not functioning as well or as safely as they would be if they were not fatigued. Performance levels drop as work periods become longer and sleep loss increases. Staying awake for 17 hours has the same effect on performance as having a blood alcohol content of 0.05%. Staying awake for 21 hours is equivalent to a blood alcohol content of 0.1% [H].

The most common effects associated with fatigue are:

- Desire to sleep
- Lack of concentration
- Impaired recollection of timing and events
- Irritability
- Poor judgement
- Reduced capacity for communicating with others
- Reduced hand-eye coordination
- Reduced visual perception
- Reduced vigilance

- Reduced capacity to judge risk and
- Slower reaction times.

Not only do these effects decrease performance and productivity within the workplace, but they simultaneously increase the potential for incidents and injuries to occur. People working in a fatigued state may place themselves and others at risk, most particularly:

- When operating machinery (including driving vehicles)
- When performing critical tasks that require a high level of concentration and
- Where the consequence of error is serious.

3.4.1.2 SLEEP INERTIA

Sleep inertia is that groggy feeling that is experienced for up to a half-hour after waking up. Managers and safety observers must be aware of sleep inertia and should act to prevent someone from performing tasks immediately after waking up. This is a very common problem because it always affects someone who just woke up, whether fatigued or not. Waking up from a deep sleep simply requires time in order to become oriented and to raise awareness [14].

3.4.2 MICRO SLEEPS

A micro sleep is a brief nap that lasts for approximately four to five seconds. People who suffer from micro sleeps are not always aware when a micro-sleep occurs, which can have a significant effect on safety. Micro sleep is the most dangerous and scary effect because the person actually falls asleep for short periods, as long as ten to fifteen seconds. When performing a dangerous task or monitoring safety critical evolutions, falling asleep for any amount of time can be fatal. Micro sleep is what often causes car accidents and results in fatalities on dangerous job sites.

Figure 3.12 shows a driver experiencing a microsleep on the wheel. Fatigue resulting to microsleeps has been a common issue in the maritime industry as well. Many groundings have occurred because of a fatigued watchkeeper who experienced a microsleep or even fell asleep in duty. Moreover, the consequences of microsleep while driving can be fatal. Due to the nature of this activity, the time available to react in such situations is limited. Many tired drivers have found themselves driving in the wrong side of the road or even wake up when their car crashed on an obstacle. Several surveys have pinpointed that accidents related to microsleeps constitute a considerable percentage of all occurring road incidents.

Figure 3. 12: Driver experiencing a microsleep

3.4.3 HEALTH EFFECTS

3.4.3.1 GENERAL HEALTH ISSUES

According to the Queensland Government website [H], the effects of fatigue increase with age. People over 50 years of age tend to have lighter, fragmented sleep; which can prevent them from receiving the recuperative effects from a full night of sleep, and can make them more likely to become fatigued.

Lack of sleep has been indirectly linked with the following health effects:

- Heart disease and high blood pressure
- Stomach disorders
- Mental illnesses and
- Lower fertility.

When the circadian rhythm is disrupted, the treatment of some medical conditions can be affected. Examples of medical conditions which may be affected include:

- Asthma
- Depression and
- Diabetes.

3.4.3.2 CHRONIC FATIGUE SYNDROME

Chronic fatigue syndrome (CFS) is the most common name given to a variably debilitating disorder or disorders generally defined by persistent fatigue unrelated to exertion, not substantially relieved by rest and accompanied by the presence of other specific symptoms for a minimum of six months. The disorder may also be referred to as post-viral fatigue syndrome (PVFS), when the condition arises following a flu-like illness, myalgic encephalomyelitis (ME), or several other terms. The disease process in CFS displays a range of neurological, immunological, and endocrine system abnormalities. Although classified by the World Health Organization under *Diseases of the nervous system*, the etiology (cause or origin) of CFS is currently unknown and there is no diagnostic laboratory test or biomarker [M].

Common symptoms of fatigue include:

- Impaired memory or concentration
- Post-exertional malaise, where physical or mental exertions bring on "extreme, prolonged exhaustion and sickness"
- Unrefreshing sleep
- Muscle pain (myalgia)
- Pain in multiple joints (arthralgia)
- Headaches of a new kind or greater severity
- Sore throat, frequent or recurring
- Tender lymph nodes (cervical or axillary)

3.5 FATIGUE-RELATED ACCIDENTS

Caldwell (2001) [12] makes a historical perspective on select fatigue-related problems in the industrial sector. A typical example of this was in 4 AM on March 28, 1979, Unit No. 2 at the Three Mile Island Nuclear Power Plant shut down as nearly every valve in the feed water cooling system slammed shut, a pump casing ruptured, and numerous pipes shattered. Given the lack of a cooling system, both heat and pressure in the reactor began to build to dangerous levels, and a plant operator's failure to recognize that emergency backup pumps were not functioning began a chain of events that nearly resulted in a nuclear meltdown. Two days of intense effort on the part of plant workers and Nuclear Regulatory Commission personnel ultimately brought the situation under control but not without significant costs. The consequences were that radioactive gases were vented into the air, radioactive water was released into the Susquehanna River, and a reactor whose 36,000 fuel rods ruptured after reaching temperatures of 4300 degrees was lost. Thankfully, a major nuclear catastrophe was avoided.

Another well-known example came seven years later, when the former Soviet Union was not so fortunate. In the early morning hours of April 26, 1986, the sequence of events for the world's first nuclear meltdown began at Chernobyl Unit 4 in Ukraine. During a safety experiment designed to evaluate potential cooling-system backup procedures, plant operators had disabled automatic warning systems, deactivated automatic temperature and pressure-trip systems, and disregarded established plant procedures. Sluggish responses and inattention by plant operators led to a situation in which steam pressure in the reactor core rose uncontrollably, ultimately resulting in an increase in reactor power to 100 times the design value, shattered fuel pellets, ruptured fuel channels, a fire, and two explosions. Eight tons of fuel and other highly radioactive materials were ejected from the reactor, and large quantities of hazardous vapors were released into the atmosphere. The radioactive fallout was detected all over the world, from Finland to South Africa, with the immediate aftermath in the Soviet Union including 300 deaths, a $12.8 billion disruption to the economy, and a host of problems for those living in the vicinity of the plant, including a doubling of birth defects, a 5 to 10 times higher rate of thyroid cancer, and a 2 to 4 times increase in leukemia rates among children in affected areas.

A similar but more immediately deadly disaster occurred in Bhopal, India, 2 years earlier; however, this one involved chemical rather than nuclear contamination. During the night of December 2, 1984, a toxic cloud of methyl isocyanate (MIC) suddenly was released from the Union Carbide pesticide plant. No action was taken to warn the surrounding population until more than an hour after the leak started. The accident was immediately fatal to more than 2000 people living in the vicinity and has since caused more than 300,000 injuries and as many as 6000 additional deaths. While denying liability, Union Carbide agreed to a settlement of $470 million.

But the big question remains: What do all of these catastrophes have in common?

Most share complex interactions between engineering design issues, inadequate or unclear operational processes, less-than-optimal staff competency, and insufficient emergency response systems, among other factors. However, in each case, it is noteworthy that the tragic chain of events involved one or more human errors that occurred in the early morning hours when unintentional sleep episodes have been shown to be more common. Although it cannot be proven with absolute certainty that all these major industrial blunders resulted from sleepiness-related reductions in alertness, decrements in cognitive processing, or poor reaction time, it is more than coincidence that the disastrous mistakes were made at a time of day when human functional capacity is known to be diminished [12].

3.5.1 COSTS ASSOCIATED WITH FATIGUE

Caldwell (2001) [12] continues in examining the relation between fatigue related accident and their costs. In view of what is now known about fatigue, it is not surprising that several studies have shown a significant increase in workplace accidents during late night hours. Although studies aimed specifically at the aviation sector are virtually nonexistent, conservative estimates from other occupational settings suggest that the direct cost of fatigue in terms of injuries and loss of production is at least $2 billion per year. However, the sum total of the overall effects of sleep loss on work performance has been placed at $18 billion annually in the United States alone. According to a recent survey, 40% of adults indicated they were so sleepy during the day that it interfered with their daily activities, and 18% said they suffered from this type of problem several days a week. Furthermore, more than half the people surveyed also reported that chronic sleepiness adversely affected their mood, energy levels, concentration ability, and overall health, as well as their ability to pursue personal interests and maintain quality relationships with their family and friends. Thus, fatigue touches every aspect of life in modern society, including air EMS activities and other aviation sectors in which requirements for unpredictable and extended work episodes often occur at times when alertness tends to be most compromised. Several studies have tried to evaluate the costs to society of alertness related accidents and loss of performance with one estimating costs exceeding 40 billion $ per year .

Figure 3. 13: Three Mile Island nuclear power plant

3.6 MEASURING FATIGUE

Sherry (2000) [87] states that measuring fatigue in the workplace is a complex process. It is common to use both subjective and objective measures of fatigue and alertness to evaluate the impact of a countermeasure, as multiple measures allow the investigator to triangulate the truth and produce a more convincing conclusion. There are four kinds of measures that are typically used in measuring fatigue; physiological, behavioral, subjective self-report and performance measures.

The following parts were taken from Sherry's paper regarding fatigue in the railroad industry where the author describes all four categories of fatigue measures [87].

3.6.1 PHYSIOLOGICAL MEASURES

Physiological measures that have been used to determine fatigue and sleep are the Electroencephalograph (EEG) and the multiple sleep latency test (MSLT). The EEG has been useful in determining the presence of ongoing brain activity. In general, according to Monk (1991), "the onset of sleep has been characterized by decreases in fast, low voltage activity, decreases in the regularity and frequency of alpha activity and increases in slow activities (delta and theta)." For the most part EEG measures have been used as the reference point for calibrating other measures of sleep and fatigue.

The Multiple Sleep Latency Test (MSLT) was developed by Carskadon and Dement in 1977. The test measures the amount of time a test subject falls asleep in a comfortable, sleep-friendly environment.

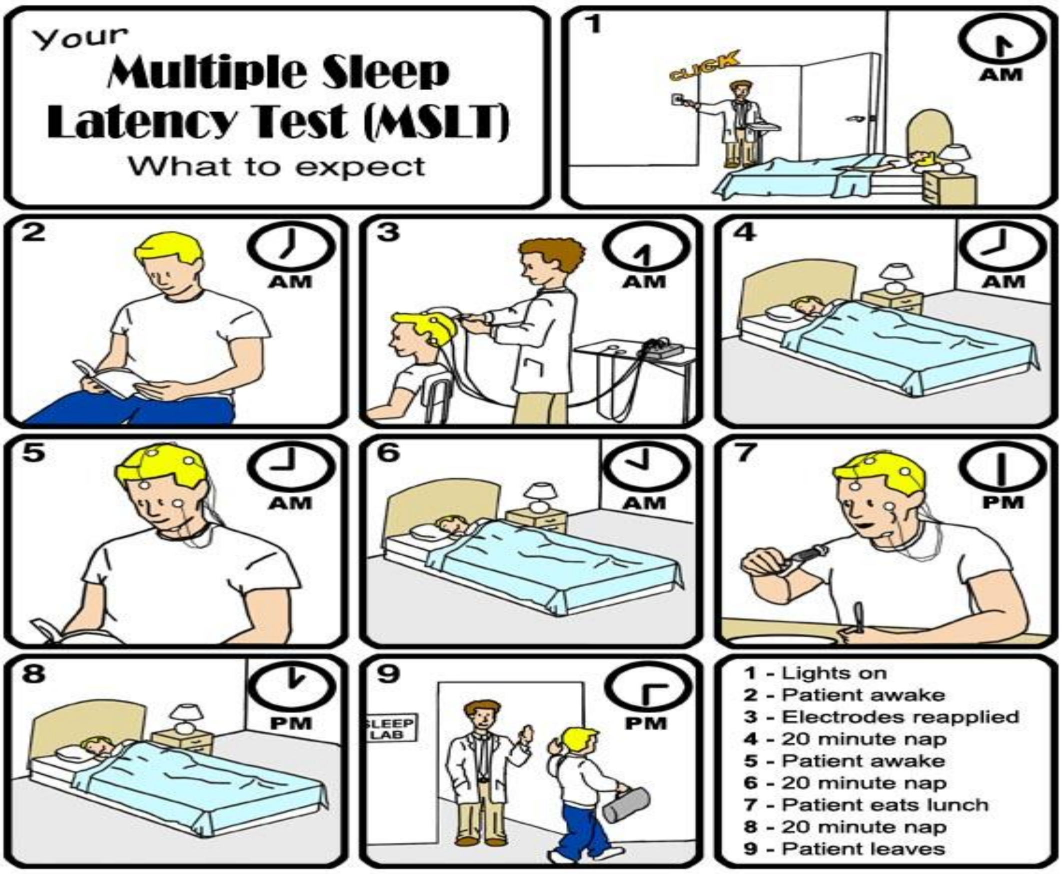


Figure 3. 14: The Multiple Sleep Latency Test

Another physiological measure that has been studied to detect fatigue has been eye-movements. Several studies have looked at the effectiveness of eye movement, (smooth pursuit, and saccadic) as indicators of sleepiness and fatigue. One study used five subjects to complete the Multiple Sleep Latency Test and the Maintenance of

Wakefulness Test (MWT). Results showed that saccadic movement was significantly correlated with increased sleepiness (Porcu, et al., 1998).

Another test used to indicate the presence of fatigue was the psychomotor vigilance test (PVT) developed by Dinges and Powell (1985). This test uses a small yellow light displayed on a computer screen. As soon as the light is displayed the test subject is required to hit a key and stop the reaction time counter.

An increasingly popular method of detecting the presence of fatigue is the use of a measure called PERCLOS (Percentage of Eye Closure). This measure attempts to detect the percentage of eye-lid closure as a measure of real time fatigue. This procedure is achieved by mounting a video camera directed towards the subject's eye. As time progresses the individual's eyelid closure, rate of blinking, and degree of closure is photographed. Subsequently, a variety of indices are computed. Several studies indicate that PERCLOS has significant advantages over EEG algorithms in detecting fatigue and drowsiness.

Figure 3. 15: Fatigue measurement tools. PERCLOS (left) and EEG (right)

A measure that has been studied recently, but for which inconclusive results have been found is the Fitness for Duty (FIT) test by PMI, Inc. This test attempts to detect fatigue through the measurement of the saccadic movements of the eye. Several indices have been calculated such as the extent of smooth pursuit and the saccadic movements.

3.6.2 BEHAVIORAL MEASURES

Behavioral measures of sleep have become popular over the last few years. The most common behavioral measures are the actigraphs, devices that can measure sleep based on the frequency of body movement. The test subject wears a wristwatch-like recording device that detects wrist movements. The number of body movements recorded during a specified time period, or epoch, has been significantly correlated with the presence of sleep. Scientific results have shown a direct connection between actigraph tests and that of the EEG.

<u>Figure 3. 16:</u> A common behavioral measure, the Actigraph

A recent study of NASA astronauts found that on a minute-by-minute basis, there was a good correlation between sleep stage and actigraphic movement counts, with a higher level of counts per minute recorded in epochs with lighter sleep stages. Results showed that actigraphs perform properly at space providing very important data regarding astronaut's sleeping patterns.

3.6.3 SELF REPORT MEASURES

In the scientific community a variety of self-report measures have been developed to study fatigue, sleepiness, and alertness. These measures are easy to administer and readily accepted by study participants. The Stanford Sleepiness Scale (SSS) (Hodes, et al., 1973) consists of seven statements ranging from "wide awake" to "cannot stay awake". The scale has been validated against performance measures as a function of sleep deprivation and is perhaps the most widely used measure of subjective sleepiness.

Another very widely used measure is the Visual Analog Scale (VAS). This type of measure was initially developed for use in educational research (Monk, 1991) while it has also been used in symptom measurement. VAS consists of a single horizontal line presented on a piece of paper. At either end of the line an anchoring descriptor is displayed such as "wide awake" or "about to fall asleep". Study participants are instructed to place an X on the horizontal line between the anchors to indicate the extent to which they are best description of their current state. The user-friendly interface has made VAS very popular to study participants and researchers.

Epworth Sleepiness Scale (ESS)

Situation	Chance of dozing (0–3)			
Sitting and reading	0	1	2	3
Watching television	0	1	2	3
Sitting inactive in a public place—for example, a theater or meeting	0	1	2	3
As a passenger in a car for an hour without a break	0	1	2	3
Lying down to rest in the afternoon	0	1	2	3
Sitting and talking to someone	0	1	2	3
Sitting quietly after lunch (when you've had no alcohol)	0	1	2	3
In a car, while stopped in traffic	0	1	2	3
Total Score				

0 = would never doze 1 = slight chance of dozing 2 = moderate chance of dozing 3 = high chance of dozing

Johns MW. *Sleep*. 1991;14:540.

Figure 3. 17: The Epworth Sleeping Scale for sleepiness measurement

Another type of subjective self-report technique is the mood descriptors. The typical measure of this sort is one in which a series of adjectives that indicate a variety of different mood states are listed. Subjects must then check which adjectives best describe their current state.

Finally, a common self-report measure has been the use of diaries. Several studies have been conducted in which the participants were asked to keep detailed logs of their activities including work and sleep. These diaries were then used to develop descriptions of the sleep wake cycle of the participants and to develop a baseline for further studies. A study of locomotive engineers conducted by Pollard (1996) distributed diaries to over 300 engineers and conductors. While the return rate was low, 24%, results indicated that railroad engineers averaged about seven hours and eight minutes of total sleep per night.

Figure 3.18 shows a typical example of a sleeping diary. It is important to comment that till now, individuals working in fatigue inducing environment have failed to understand the significance of fatigue. This issue is reflected on the fact that few people actually respond or take into serious consideration the importance of such measures as sleeping diaries. Whether there was greater number of participants, the findings that would be provided by this procedure would be an effective instrument for better fatigue knowledge and its counter measuring.

	First day	Second day	Third day	Fourth day
Complete in morning				
Bedtime (date/time)	10:45 p.m. (4/10)			
Rise time (date/time)	7:00 a.m. (4/11)			
Estimated time to fall asleep	30 minutes			
Estimated number of awakenings and total time awake	5 times 2 hours			
Estimated amount of sleep obtained	4 hours			
Complete at bedtime				
Naps (number, time, and duration)	1 at 3:30 p.m. 45 minutes			
Alcoholic drinks (number and time)	1 drink at 8:00 p.m. 2 drinks at 9:00 p.m.			
List stresses of the day	Flat tire Argued with son			
Rate how you felt today 1 = Very tired/sleepy 2 = Somewhat tired/sleepy 3 = Fairly alert 4 = Wide awake	2			
Irritability level 1 = None 2 = Some 3 = Moderate 4 = Fairly high 5 = High	5			
Medications				

Figure 3. 18: A typical sleeping diary

3.6.4 PERFORMANCE MEASURES

A common practice to determine the effects of sleep and sleep deprivation has been the use of performance measures. Various tasks ranging from simple to complex have been examined including reaction time to visual and auditory stimuli and vigilance tests. For example, in one study, twelve male undergraduate students were deprived of sleep for one night and were given a series of cognitive tasks. To explore the effects of short-term sleep deprivation on attention, the following tasks were also administered: a working memory task, a trail-making task, a vowel/consonant discrimination task, and a letter recognition task.

Performance measures that have been used extensively in various studies include the Walter Reed Performance Assessment Battery (PAB) (Thorne, 1985). This battery consists of various measures of neurobehavioral and cognitive performance including: two letter search, six letter search, encoding/decoding, two column addition, serial addition subtraction, logical reasoning, digit recall, pattern recognition, pattern recognition II, visual scanning, mood activation scale, mood scale two, four choice serial reaction time and time estimation. In addition, several tests have been added to the PAB: a visuo-spatial rotation task, interval production. Stroop, repeated acquisition, repeated acquisition, code substitution, delayed recall, running, memory, matching to sample, and the ten-choice reaction time (RT). All of these tests have been demonstrated to have some sensitivity to the effects of sleep deprivation, jet lag, heat stress, physical fatigue, physical conditioning, atropine, hypoxia, and sickle cell disorders.

A variation on the PAB, adapted for Windows based operating systems is the Denver Fatigue Inventory, a computer assisted cognitive test battery. The battery consists of the choice reaction time test, the serial addition subtraction test, the manikin test, the circle target test, and the light response test. These instruments have been used in several studies with locomotive engineers and railroad dispatchers (Sherry, 1998). Results from these uses have demonstrated significant differences between day and midnight shifts. This review has demonstrated that there are a variety of different techniques available for detecting fatigue, sleepiness, drowsiness, and the effects of those conditions which can be sorted into several categories, (Sherry 2000).

However, as Sherry [87] mentioned:

"*There is no objective tool to measure fatigue. It has been proposed that 'fatigability' is an objective inability to sustain power, which can be measured by electrophysiological methods, but to date, attempts to objectively measure fatigue have failed*."

One study compared single-photon emission computed tomography (SPECT) scans between patients with chronic fatigue syndrome (CFS) and healthy persons when performing attention and working memory test. There were no group differences for the performance task, despite the fact that CFS subjects perceived them to require more mental effort to perform the task.

Currently fatigue has typically been identified using a number of subjective scales. More than 30 scales are available for measuring fatigue. Seven of the most frequently used scales are described below [86]

3.6.5 OTHER FATIGUE MEASURMENTS TOOLS

Note: This excerpt was taken directly from [86] in order to present a brief review on additional fatigue measurement tools.

Fatigue severity scale (FSS) this nine-item fatigue severity scale is one of the best known and most used fatigue scales. The FSS items are principally measures of the impact of fatigue on specific types of functioning, relating to the behavioral consequences of fatigue rather than symptoms. The FSS has high internal consistency with Cronbach's alpha between 0.81 and 0.89. Also, it is sensitive to change with time and treatment, and has good test-retest reliability. The FSS is able to distinguish patients with different diagnoses, such as between systemic lupus erythematosus (SLE) and multiple sclerosis (MS), and between chronic fatigue syndrome (CFS), MS and primary depression. Hossain et al. successfully used the FSS to identify the shift workers with high fatigue from those with low fatigue.

Fatigue questionnaire (FQ): The FQ originally consisted of 14 items with a subsequent revision to an 11-item questionnaire. The scale is comprised of two dimensions: Physical Fatigue and Mental Fatigue. This scale was developed for hospital and community studies with CFS and has been used in multiple studies. The FQ was found to be both reliable and valid. There was a high degree of internal consistency with a range of Cronbach's alpha of 0.88 and 0.90. The validity of the FQ, in assessing fatigue, suggests that it is a useful tool for assessing fatigue in a variety of medical disorders. It has been used to assess fatigue in patients with cancer and HIV, and in other medical patients, and Gulf War veterans.

Multidimensional fatigue inventory (MFI-20): The MFI-20 is a 20-item self-report instrument. These items rate the severity of fatigue in the past week. The inventory covers 5 dimensions: General Fatigue, Physical Fatigue, Mental Fatigue, Reduced Motivation and Reduced Activity. It has good internal consistency and test-retest reliability. The MFI-20 was tested for its psychometric properties in cancer patients receiving radiotherapy, patients with CFS, psychology and medical students, army recruits and junior physicians. It was used to discriminate patients who had Parkinson's disease from those who did not. The convergent validity of the MFI-20 was investigated by correlating the MFI subscales with a Visual Analogue Scale measuring fatigue with the correlation co-efficient between 0.22 and 0.79.

Fatigue assessment instrument (FAI): The FAI is a 29-item fatigue assessment instrument that includes four subscales: Fatigue Severity, Situation Specificity, Consequences of Fatigue and Responsiveness to Rest/Sleep. The internal consistencies of the corresponding subscales are good to excellent with Cronbach's alpha values between 0.70 and 0.92.

The Fatigue Severity subscale has 11 items, eight of which correspond highly with the FSS mentioned above, indicating a good convergent validity. Although its test-retest reliability is only moderate, the inventory, in general, has good psychometric qualities. The FAI is used to differentiate normal fatigue from medical disorders commonly recognized to have a large fatigue component and is able to distinguish differences between patients with different diagnoses.

Fatigue impact scale (FIS): This 40-item questionnaire is used to assess the impact of fatigue on different functioning areas, such as cognitive, physical and psychosocial functions. It has good internal consistency and reproducibility. The FIS was validated in a subject sample of patients with MS and hypertension. There were significant differences in the scores of these two groups. A function analysis was carried out in a group of CFS patients and a group of MS patients. The results showed that the FIS correctly classified 80.0% of the CFS group and 78.1% of the MS group when these groups were compared. This validation study indicates that the FIS has considerable merit as a measure of patients' fatigue symptoms. The FIS is also a useful instrument to assess the impact of fatigue on patients' every-day lives.

The brief fatigue inventory (BFI): This nine-item scale was developed for screening and assessing clinical outcome in fatigued patients with cancer and it identified those patients with severe fatigue. The BFI is a reliable instrument. It is used for a rapid assessment of fatigue severity in both clinical screening and clinical trials. The BFI significantly correlated with two previously validated measures, the Profile of Mood States (POMS) Fatigue subscale and the Functional Assessment of Cancer Therapy (FACT), indicating that the BFI has good concurrent validity.

Figure 3.19 presents a depiction of the Fatigue Severity scale.

During the past week, I have found that:	Completely Disagree		Neither Agree Nor Disagree			Completely Agree	
	←	-	-	-	-	-	→
1. My motivation is lower when I am fatigued	1	2	3	4	5	6	7
2. Exercise brings on my fatigue	1	2	3	4	5	6	7
3. I am easily fatigued	1	2	3	4	5	6	7
4. Fatigue interferes with my physical functioning	1	2	3	4	5	6	7
5. Fatigue causes frequent problems for me	1	2	3	4	5	6	7
6. My fatigue prevents sus-tained physical functioning	1	2	3	4	5	6	7
7. Fatigue interferes with carrying out certain duties and responsibilities	1	2	3	4	5	6	7
8. Fatigue is among my three most disabling symptoms	1	2	3	4	5	6	7
9. Fatigue interferes with my work, family, or social life	1	2	3	4	5	6	7

Figure 3. 19: Fatigue Severity Scale, (FSS) [86]

3.7 FATIGUE COUNTERMEASURES

Fatigue is a very common issue both in workplaces and domestic environments. The first step for eliminating fatigue is recognizing the factors that create it. In the past few years, many scholars and professionals from various scientific fields have tried to battle fatigue through research and fatigue management. The recent trend, especially in aviation, is companies and independent professionals that deal exclusively with fatigue countermeasures and fatigue assessment. Their main goal is to reduce fatigue through proper education and arrangements while their primary area of focus is work shifts and work environments in general. However, fatigue is a rather obvious issue so there are a lot of non-complex measures to reduce it.

Queensland government suggests five basic steps in the fatigue risk management process (much similar to IMO’s Formal Safety Assessment):

1. Identifying hazards
2. Assessing risks that may result because of these hazards
3. Deciding on control measures to prevent or minimize the level of risks
4. Implementing control measures and
5. Monitoring and reviewing the effectiveness of control measures.

The USDA Forest Service [105] proposes a rather similar approach:

- Improve your fitness and maintain regular physical activity
- Ensure appropriate rest before assignment or work shift
- Practice work cycling (hard/easy, long/short)
- Adjust your work to conditions (heat and humidity)

A very popular tool for fatigue mitigation is FAST. The Fatigue Avoidance Scheduling Tool (FAST) was developed by the United States Air Force in 2000–2001 to address the problem of aircrew fatigue in aircrew flight scheduling. FAST is a Windows program that allows scientists, planners and schedulers to quantify the effects of various work-rest schedules on human performance. It allows work and sleep data to be entered in graphic, symbolic (grid) and text formats. The graphic input-output display shows cognitive performance effectiveness (y axis) as a function of time (x axis). An upper, green area on the graph ends at the time for normal sleep, 90% effectiveness. The goal of the planner or scheduler is to keep performance effectiveness at or above 90% by manipulating the timing and lengths of work and rest periods. A work schedule is entered as red bands on the time line and sleep periods are entered as blue bands across the time line, below the red bands.

The calculated performance effectiveness represents composite human performance on a number of cognitive tasks, scaled from zero to 100%. The oscillating line in the graph represents expected group average performance on these tasks as determined by time of day, biological rhythms, time spent awake, and amount of sleep, and various confidence limits around the average may be displayed. The graphic display may be cut and pasted into reports and briefing slides. Cognitive effectiveness estimates for work periods of any length may also be cut and pasted in tabular format. While FAST began as an exclusive tool to the Aviation industry, a lot of FAST variations were soon established in other fields of transport and industry in general [GG].

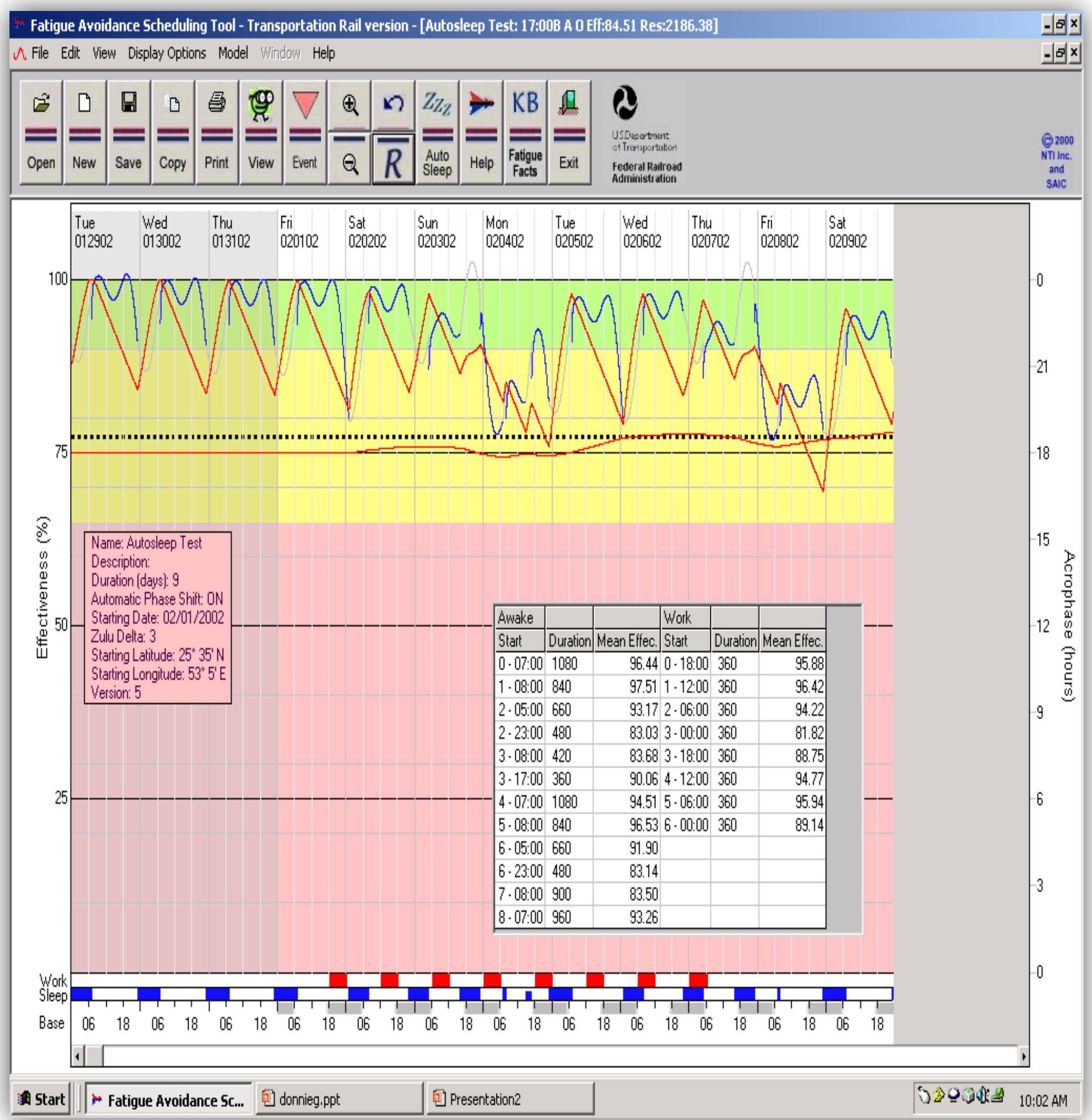


Figure 3. 20: The Fatigue Avoidance Scheduling Tool

The field of fatigue countermeasures is a very rich area for discussion. Strategies for mitigating fatigue in transportation will be thoroughly discussed in the next chapter while our overall perception of the situation and our possible recommendations will be part of the last chapter of this thesis.

In figure 3.21 we provide a summarized representation of the most common fatigue countermeasures in accordance to their effectiveness and their apparent feasibility. It is that certain practices, such as the night/mourning shift rotation, cannot be avoided. On the other hand, listening to music/radio may not be as effective as sufficient sleep but can mitigate fatigue and increase alertness.

Fatigue Countermeasures	Effectiveness	Feasibility	Duration of Effect
Avoidance of night/morning work	High	Low	Several hours
Sufficient sleep	High	High	Several hours
Naps	High	Moderate	Hours (depending on nap length)
Stimulants (noncaffeine)	High	Low	Several hours
Caffeine	Moderate	High	Hours
Rest breaks	Moderate	High	Several minutes
Bright light	Moderate	Low	Used to synchronize rhythms
Melatonin	Low	High	Used to synchronize rhythms
Exercise	Low	Low	Several minutes
Listening to music/radio	Low	High	Several minutes
Exposure to cold air	Low	High	Few minutes (possibly)
Physical fitness	Low	High	Not effective for mental fatigue

Figure 3. 21: Effectiveness, feasibility and duration of effect for common Fatigue Countermeasures

CHAPTER 4

FATIGUE IN TRANSPORTATION

4 FATIGUE IN TRANSPORTATION

4.1 GENERAL OVERVIEW

It is undeniable that fatigue is widely regarded as one of the contributing factors to transportation accidents. The exact impact of fatigue on these incidents remains, even today, a rather difficult and complex task. However, no one can deny its significance although it is usually underestimated. The presence of fatigue in transport has led to thorough research, especially during the past two decades. The main areas of focus are two: a) the issue of fatigue in terms of physiological measures and b) the actual measurement and quantification of fatigue in terms of levels. Unfortunately, the physiological fatigue mechanism has proven to be extremely complex to scientists since it is the result of a plethora of different interacting parties.

Smith, Allen and Wadforth [90] indicate that there is a rather long history of investigating impact of fatigue in other transport sectors. Fatigue investigation has been developed from three different fields, as mentioned below:

- Empirical reports about the impact of fatigue
- Laboratory research about fatigue severity and outcomes
- Extensive research and experiments in military transportation

These types of military transport research have been the first step into a series of related studies, most of whom are solely addressed to driving. Focusing on driver's fatigue seems only logical since driving is regarded as a crucial part of public safety rather than just an issue of a general occupational framework.

Smith et al [90] refers to several International meetings (see Hartley, 1997, Akerstedt and Haraldasson, 2001) that have provided interesting overviews of the area and developed a framework for evidence-based countermeasures. The main problem that has been addressed is that fatigue has severe impact on all areas of transport, an impact which has been overlooked in the past, (Akerstedt and Haraldasson, 2001).

While a lot of regulations and guidelines have been established and made obligatory, none of them achieves to include all eight fatigue related criteria. Those criteria are mostly related to working hours and work environment.

Smith [95] pinpoints a proposition made by many parties for fatigue to be dealt with a hybrid approach incorporating both a prescriptive "hours of service" system and a non-prescriptive, outcomes-based approach.

A general overview of research made on transport fatigue can be found on papers presented at the 2005 *International Conference on Fatigue Management*

Transportation Operations .The papers show the range of issues being studied, issues such as fatigue on fundamental skills required in transport operations or epidemiological studies of fatigue; evaluation of countermeasures; and assessment of fatigue management programs.

4.1.1 FATIGUE IN AVIATION

Due to its complex and demanding nature, aviation has been the spark for many studies regarding fatigue. Statistics indicate that human fatigue has been a contributing factor in a great number of severe aircraft accidents. Generally, it has been estimated that fatigue contributes to 20-30% of transport accidents. In commercial aviation operations, about 70% of fatal accidents are related to human error, therefore the risk of crew fatigue contributes to about 15-20% of the overall accident rate.

Some aircraft accidents that were found to involve fatigue:

- 1993 Kalitta International, DC-8-61F at Guantanamo Bay, Cuba
- 1997 Korean Air, 747-300 at Guam
- 1999 American Airlines, MD-82 at Little Rock, AR
- 2004 MK Airlines, 747-200F at Halifax, Nova Scotia
- 2004 Corporate Airlines, BAE Jetstream31 at Kirksville, USA
- 2004 Med Air, Learjet35A at San Bernadino, CA
- 2005 Loganair, B-N Islander at Machrihanish, UK
- 2006, 27th Aug, Comair, CRJ100 at Lexington, KY
- 2007, 25th June, Cathay Pacific 747F at Stockholm, Sweden
- 2007, 28th Oct, JetX, 737-800TF-JXF Keflavik airport, Iceland

According to Smith et al [90], great concern with fatigue in aviation developed during the Second World War. The NASA-Ames research group has been a pioneer in investigating flight crew fatigue in commercial pilots (Gander, Graeber, Connell, Gregory, Miller and Rosekind, 1998). The area of focus of these projects is mostly circadian disruption, sleep quantity and fatigue before and at the end of flights. As mentioned in Chapter 3, Circadian rhythms are highly affected by jet lag so it is only logical that circadian disruption is a very common issue among flight crews.

In order to present answers to aviation related fatigue, fatigue risk management systems have been developed. Apart from FAST which we discussed earlier Canadian aviation presented the ‘Fatigue Risk Management Toolbox’, a very practical tool, which typically consists of:

- Policy templates and guidelines to assist in the development of global and detailed corporate policies on the management of fatigue.

- Competency-based training and assessment for employees, management and new staff.
- Fatigue audit tools to assess work schedules, verify actual fatigue levels and monitor the fatigue risk management process

Figure 4. 1: The air crash of American Airlines, MD-82 at Little Rock, AR

4.1.2 RAILWAY OPERATIONS FATIGUE

The investigation of fatigue in railway operations has been an active area of research for over five decades. While the general approach of researchers bears a lot of similarities to that regarding drivers-fatigue, the main focus is the interaction of fatigue with specific incidents such as signal misses (Buck and Lamonde, 1993). A series of studies from all around the globe (e.g. Poland - Malgarzeta, 1982; China - Zhou, 1991) have made clear that fatigue is present in the railroad industry and its effects are to not to be neglected [90].

The recent establishment of the Federal Railroad Administration's Fatigue Research Program (Sussman and Coplen (2000) and Pilcher and Coplen (2000) has indicated that risk factors in railways are mainly overall sleep quality and lack of rest breaks. The program's overall approach suggests better data collecting techniques, more sufficient measurement and analysis tools and finally proper and applicable ways of mitigating fatigue.

A rather practical and effective approach for railway industry fatigue was the development of the HSE Fatigue index (Spencer, Robertson and Folkard, 2006)

[35].The fatigue risk factors were recorded via diary entries. Moreover, the research team tried to connect these entries to specific incidents that would cause an accident. At the end of the study Spencer, Robertson and Folkard recommended:

1. Shorter shift duration
2. A maximum of four hours of non-stop
3. Maximum work time during a week
4. Reduction of continuous night shifts
5. Obligatory rest periods
6. Rest breaks between shift changes.

Smith et al [90] agree that the HSE Fatigue Index is probably the most effective option for the fatigue management of rail workers. Consequently, this will have a great impact on forthcoming legislations as a recommendation made by HSE will be taken into consideration so that fatigue levels are reduced in the ranks of rail workers and shift workers in the transport sector in general.

4.1.3 FATIGUE IN DRIVING

Recent studies by the National Transportation Safety Board (NTSB) have indicated that fatigue resulting to sleepiness is a major factor in accidents involving heavy and commercial vehicles.

According to *smartmotorist.com* [EE] the NTSB states that 52 per cent of 107 single-vehicle accidents involving heavy trucks had fatigue playing an important part in their happening. Reports made clear that in nearly 18 per cent of the incidents, the driver actually fell asleep. According to data from US Department of Transportation, the percentage of fatigue-related fatal accidents is estimated to be around 30%. More over statistical data from USDT show that driver fatigue is responsible, among many factors, for approximately 20% of commercial road transport crashes and over 50% of long haul drivers have fallen asleep at the wheel. Recently The National Highway Traffic Safety Administration (NHTSA) estimate that there are 56,000 sleep related road crashes annually in the USA, resulting in 40,000 injuries and 1,550 fatalities.

Several studies in the US have gathered interesting statistics regarding fatigue on the road [EE]:

- 50% of fatal accidents on those roads were fatigue related
- that 30% - 40% of accidents involving heavy trucks are caused by driver sleepiness
- In 2002 alone the Total Cost of Fatigue-Related Crashes exceeded $2.3 billion

The presence of fatigue can cause a serious impairment of an individual's driving skills. High fatigue levels can make reacting much slower, distract concentration on driving and make the surrounding interpretation a difficult task to perform. Fatigue related crashes tend to be more severe because of the limited time available for reaction in order to avoid the accident. The combination of fatigue and alcohol consumption multiplies the probability for a lethal road accident.

Over the period of 2002 to 2006, driver fatigue was identified as being responsible for 256 deaths or twelve percent of fatal crashes, and more than 4,350 injuries in the US. These numbers have convinced scholars and government to address the issue more thoroughly. Recent international research has suggested, due to fatigue under-reporting, the percentage of drivers-fatigue related incidents is significantly greater than it is reported to be. Some rough estimation suggests that the actual percentage is more than double.

The most common signs that can alert a driver are:

- Frequent blinking or yawning

- Difficulty to keep your head up

- Eyes closing

- Inability to focus concentration solely on the road

- Braking too late

- Drifting over the median line unto the other side of the road (which is actually the most alerting sign of all the above).

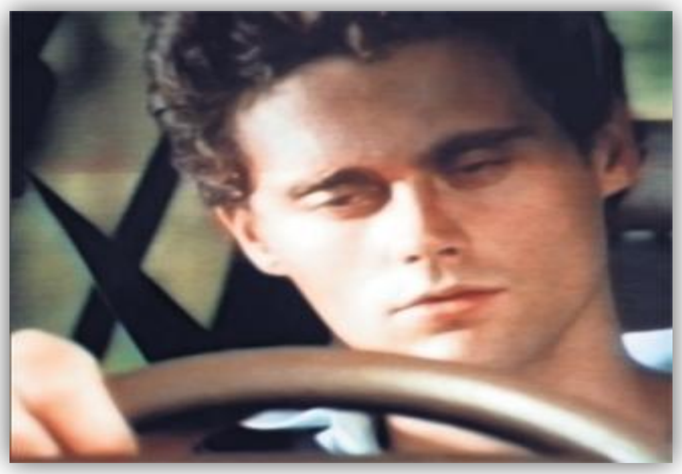


Figure 4. 2: A driver about to experience a microsleep

Smith et al. [90] suggests that the absence of supervision during long distance transport has allowed fatigue *to run more freely on the highways.* Many studies (e.g.

Landstrom, Akerstedt, Bystrom, Nordstrom and Wiborn, 2004) insist that rest breaks and napping are highly recommended to battle fatigue on the road.

Several countries have also convened expert panels to review regulatory options for reducing heavy vehicle driver fatigue (National Road Transport Commission, 2001; Transport Development Centre, Transport Canada, 1998; University of Michigan Transportation Research Centre, 1998) [90].

4.2 LEGISLATION REGARDING FATIGUE IN TRANSPORT

There are several regulations and guidelines regarding fatigue avoidance and mitigation. Jones, Dorrian et al. (2005) [44] have provided some collective figures regarding the issue, in different areas of transportation.

In figure 4.3 we see the first, most significant and most recently revised regulations regarding fatigue and working hours.

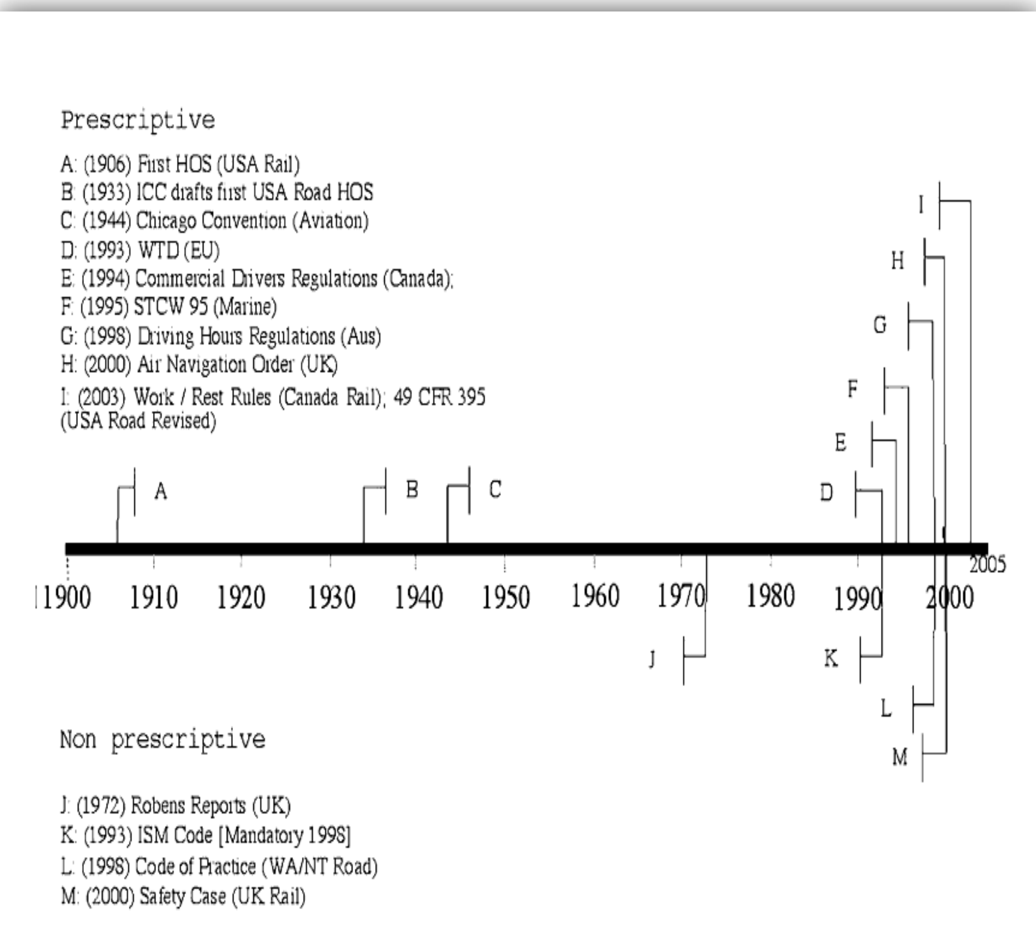


Figure 4. 3: The first, most significant and most recently revised regulations [44]

Most industries have tried to a establish work/rest patterns in order to eliminate the presence of fatigue in the workplace. Smith et al [90] summarize the most common issues that these regulations address:

• **Sleep:** Minimum hours of sleep per day with emphasis on sleep quality, continuity and potential deprivation. The issue of circadian rhythms and disruption is also mentioned by almost all regulations as an integral factor for maintaining alertness levels.

• **The cumulative nature of fatigue and sleep loss:** Repetitive sleep deprivation should be avoided. The cumulative nature of fatigue increases the danger of severe alertness drops.

• **Recovery sleep:** Recovery sleep is essential after long periods of sleep deprivation in order to *recharge the sleep batteries.*

• **Night work:** The human body is not intended to be awake at night. This fact increases the danger of reduced alertness on night shifts even if an individual work at night on a regular basis.

• **Rest breaks:** There should be an equivalent between actual working time and rest time. Most regulations suggest about 10 % of the working time.

• **Duration of working time:** There must be a maximum working time per day or week. Otherwise the danger of fatigue is inevitable.

Many countries advocate the use of fatigue management programs that consist the following:

• Organizational commitment to the requirements of a 'Fatigue Management Program'
• Establishment of a 'Fatigue Management Policy and Process'
• Involvement of all stakeholders throughout the process
• Competency based educational modules
• Effective change to the scheduling, dispatching and compensation processes.
• Objective and subjective measures of fatigue management effectiveness.
• Continual monitoring and improvement [90].

In figure 4.4 provided by Jones et al. (2005) [44], there is a collective representation of how the legislation parties have addressed the eight fatigue related criteria which that were discussed in Chapter 3.

Convention, legislation or subordinate instrument	(A) Time of day	(B) Circadian adaptation	(C) Sleep duration	(D) Sleep quality	(E) Predictability	(F) Sleep debt recovery	(G) Time on task	(H) Short breaks
SCTW 95 (IMO)	NS	NA	S	NA	NS	NA	NA	NA
C 180 (ILO)	NA	NA	S	NA	NA	NS	NS	NA
C 147 (ILO)[b]	–	–	–	S	–	–	–	–
WTD/HAD (EU)	S	NA	S	NA	S	NS (S for aviation)	NS	S
Road Traffic (Driving Hours) Regulations (SA) 1999	NA	NA	S	NA	NA	NS	S	S
Rail Safety Act, 2002 (NSW) Schedule 2 (Freight)	NA	NA	S (home depot only)	NA	NA	NA	S	S
CAO 48.x (Australia)	S	NA	S	NA	NA	S	S	NA
Commercial Vehicle Drivers Hours of Service, 1994 (Canada)	NA	NA	NS	S (berths only)	NA	NS	NS	NA
Work/Rest Rules Rail (Canada) (TC O 0-33)	NA[a]	NA[a]	NS	NA[a]	NA[a]	NA[a]	NS	NA[a]
Canadian Aviation Regulations (700.xx & 624.xx)	NA	NA	NS	S	NA	S	NS	NS
Canadian Crewing Regulations, 2001	NA	NA	NS	NA	NA	NA	NA	NA
Transport Act, 1968 (UK)	NA	NA	S	NA	NA	NS	S	S
Air Navigation Order, 2000 (UK) and CAP 371	S	S	S	S	S	S	NS (see	NA
49 CFR 395 (USA Road)	NA	NA	S	S (berths only)	NA	S	NS (Work) S (Drive)	NA
49 USC 211 (USA Rail)	NA	NA	NS	S	NA	NA	NA	NA
14 CFR 121.xxx (&135.xxx) (USA Aviation)	NA	NA	S	NA	NA	NS	S	NA
46 USC 8104 (USA Marine)	NA	NA	NA	NA	NA	NA	NS	NA

NA—not addressed.
S—sufficient
NS—not sufficient.
[a] Fatigue Management Programme (FMP) to address.
[b] C 147 specifically only addresses sleep quality.

C.B. Jones et al. / Safety Science 43 (2005) 225–252

Figure 4. 4: Legislation regarding Fatigue in Transportation [44]

4.3. FATIGUE IN MARITIME TRANSPORT

In the previous chapters the connection between fatigue and various fields of transport was thoroughly examined. Recent studies have shown that fatigue is present in the maritime industry as well.

Hetherington, Flin and Mearns (2005) [31] state that contemporary research has shown that there are potentially disastrous outcomes from fatigue in terms of health and performance. The maritime industry has not yet forgotten the grounding of Exxon Valdez in 1989, one of the most terrible environmental disasters in the history of transportation. The incident report shows that in the 24 hours prior to the grounding, three watchkeepers had only had 5 or 6 hours of sleep (National Transportation Safety Board [NTSB] 1990), suggesting that fatigue may have been a contributing factor to this unfortunate catastrophe. But even prior to the Exxon Valdez grounding, fatigue was also present at sea.

In the wake of the twenty first century, the seafarers work has become more demanding than ever due to a combination of minimal manning, sequences of rapid turnarounds and short sea passages, adverse weather and traffic conditions, long working hours with insufficient opportunities for recuperative rest [90].

Despite the introduction of work rest mandates by the IMO (2001) and the STCW (1995) many seafarers have to work for more than 12 hours a day with a maximum of 5-6 hours break. A very representative example of an officer's lack for rest time is the fact that during the discharging of a VLCC the chief officer must be present at all times. A VLCC with a 300,000 tonnage takes approximately 44-46 hours to discharge, so this means that the chief officer is required to be awake and present for almost two days time [31].

Furthermore, in a report by the National Transportation Safety Board (1999) seafarers were identified out of the occupational groups included to be second in highest number of continuous working time, close behind rail workers.

Moreover, the seafarers themselves recognized that the impact of fatigue has been significantly greater in the past 10 years than it used to be. Out of 1000 participating officers, 84% felt that stress was also more prevalent,(Cole-Davies 2001). Further studies conducted my NUMAST (National Union of Marine Aviation and Shipping Transport Officers), MCA (Maritime Coastguard Agency), AMCA and MAIB respectively have presented the following foundings:

- 70% of seafarers report poor to very poor sleep
- fatigue related accidents were most prevalent at the beginning of the tour (first week), in the first four hours of a shift, between the hours of 09:00 and 16:00, and in calm conditions [93]
- 66% felt that extra manning was necessary
- 50% of which indicated that they worked more than 85 hours in a week.

Dr. Rothblum [80] of the US Coast Guard indicates that the NTSB has identified fatigue to be an important cross-modal issue, being just as pertinent and in need of improvement in the maritime industry as it is in the aviation, rail, and automotive industries. In addition, several studies have cited fatigue as the primary concern of mariners. A US Coast Guard survey has also shown that fatigue contributed to 16% of the vessel casualties and 33% of the injuries.

4.3.1 MARITIME FATIGUE RISK FACTORS

In the 2001 submission to the IMO (MSC 74/15, 2001), Guidelines on Fatigue provided practical information to assist the marine industry in understanding and mitigating fatigue.

In these guidelines, the potential causes of fatigue were categorized as follows:

- Crew-specific

- Physical Environment
- Ship-specific
- Management

The clear categorization of fatigue risk factors has proven very useful in investigating fatigue in various types of vessels and crews. McCafferty and Baker (2002) [58] indicate that through the work of many different segments of the maritime industry, the variety of factors which impact crewmember fatigue and its effects on human performance, are becoming better recognized [58].

4.3.1.1. CREW SPECIFIC FATIGUE FACTORS

The crew specific fatigue factors have a major impact on human performance and reliability. Human error is one of the most recognized factors that lead to maritime accidents.

According to the IMO (2001) [36] crew specific factors include:

- Sleep and Rest
- Quality, Quantity and Duration of Sleep
- Sleep Disorders/Disturbances
- Rest Breaks
- Biological Clock/Circadian Rhythms
- Psychological and Emotional Factors, including stress
- Fear
- Monotony and Boredom
- Health
- Diet
- Illness
- Stress
- Skill, knowledge and training as it relates to the job
- Personal problems
- Interpersonal relationships

McCafferty and Baker (2002) [58] pinpoint three conditions that play an integral part in the increase of fatigue levels, which are mentioned below:

A) Conditions of Sleep.

• Ability to mass sleep for a period of at least eight hours
• Sleep comfort
• Amount of daily sleep.

B) Biological Clocks/Circadian Rhythms.

Circadian disruptions are very common at sea since crew members normally change shifts (night/day) throughout a trip thus disturbing the normal function of their biological clock.

C) Workload and Work Duration.

• Cognitive and physical energy expended during task performance and over time
• Provision of brief rest periods during the work day
• Length of the workday

Other crew specific factors that affect alertness and performance according to the IMO [34] are:

- Age
- Health
- Diet
- Substance use
- Marital Status

Several studies have indicated that sleeping quality is by far the most important crew specific factor for the prevalence of fatigue. The following figure shows the result of a survey in which the participants were Australian pilot in the Great reef area. It is more than obvious that *sleeping at sea* is significantly harder than in land.

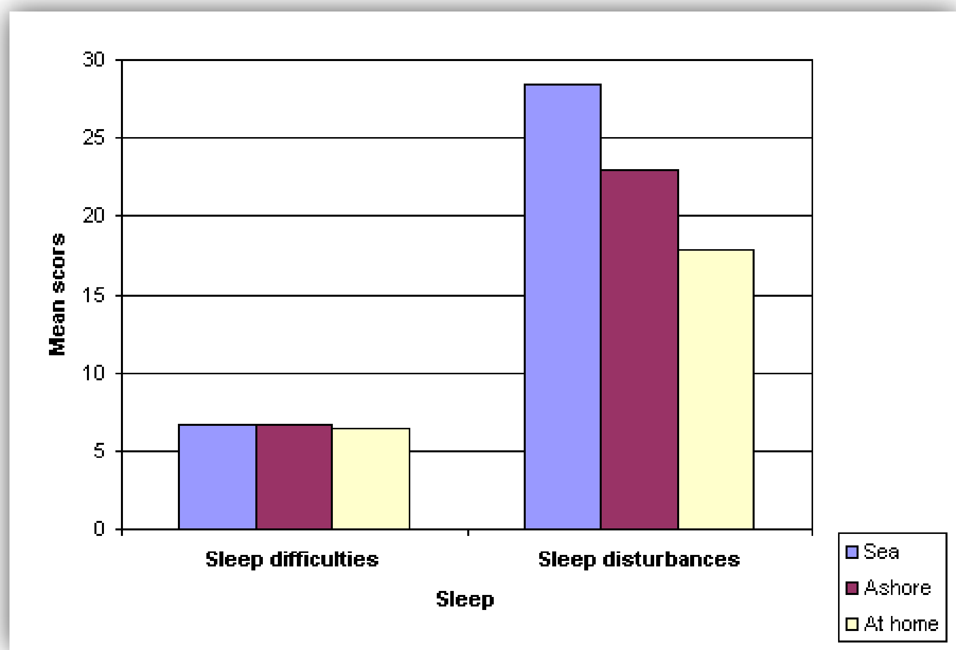


Figure 4. 5: Sleep difficulties at sea and disturbances, ashore and at home.

4.3.1.2 SHIP SPECIFIC FATIGUE FACTORS

According to IMO (2001) [34] ship specific factors include:

- Ship design
- Level of automation
- Level of redundancy
- Equipment reliability
- Inspection and maintenance
- Age of vessel
- Physical comfort in work spaces
- Location of quarters
- Ship motion
- Physical comfort of accommodation spaces.

Another group of factors which have an impact on the mariner’s performance and fatigue is the overall design of the vessel itself. McCafferty and Baker (2002) [58] divide these design factors in two subcategories.

1) Human-machine interaction aspects
2) Accommodation and overall work environment

The quality of a vessel’s overall design is perhaps the more profound way for a naval architect to improve the on-board work environment, thus indirectly mitigating fatigue. ABS studies has shown by providing working and living spaces where human factors/ergonomics principles are applied, fatigue can be controlled or even eliminated while providing a healthy, safe and performance enhancing environment for the seafarers. The IMO guidelines [34] propose that ship specific factors can be assessed by emphasizing in habitability and in other general ergonomic principles.

The primary objective of ergonomics is applying knowledge and technology in creating safe systems and healthy environments, reducing people’s limitations and enhancing their mental and physical capabilities. Moreover, this objective can be attained by establishing regulations and guidelines that promote high compatibility between ship design and mariner’s performance. The ergonomic design of ships, marine structures, and equipment is addressed in numerous handbooks, textbooks, guides, and standards. In the past two decades some of the documents that addressed the maritime industry in terms of design and ergonomics are:

• IMO's Guidelines on Ergonomic Criteria for Bridge Equipment and Layout (MSC 73/Circ 982)

• IMO's Navigational Bridge Visibility and Functions (IMO Res.A.708-(17)

• Ship’s Bridge Layout and Associated Equipment – Requirements and Guidelines (BS EN ISO 8468)

• IMO's Role of the Human Element in Maritime Casualties - Engine Room Design and Arrangements. (IMO DE 38/20/1)

• IMO's Guidelines for Engine Room Layout, Design and Arrangement (MSC 68/Circ 834)

• IMO's Role of the Human Element in Maritime Casualties - Guidelines for the On Board Application of Computers (IMO DE 38/20/2)

• ABS Guide for Crew Habitability on Ships (2001)

• ASTM's Standard Practice for Human Engineering Program Requirements for Ships and Maritime Systems, Equipment, and Facilities (F-1337) (1991)

• ASTM's Standard Practice for Human Engineering Requirements for Ships and Maritime Systems, Equipment, and Facilities. (F-1166)(2000) [58].

The American Bureau of Shipping has been very active in the field of ship design ergonomics by providing papers and guidelines regarding the issue. One of the most interesting and innovative publications was ABS’s *Guidance Notes on the Application of Ergonomics to Marine Systems (*1998). By pinpointing the interplay between ship design, human error and fatigue ABS managed to show the shipping industry the importance of improving working and living conditions at sea.

Calhoun [14] in collaboration with the University of Michigan’s School of Naval Architecture and Marine Engineering, emphasized in six specific factors that have a direct impact on on-board performance:

- Light
- Noise
- Vibrations
- Ventilation
- Temperature
- Ship motions

Figure 4.6 provides a brief representation of factors that can lead to efficient vigilance while highlighting those that Naval Architecture has a great chance to improve. As it can be easily seen the role of the Naval Architect can be beneficial to several parts of the overall procedure. Designing factors influence three different parts of the entire environment including sleeping, working and watch station.

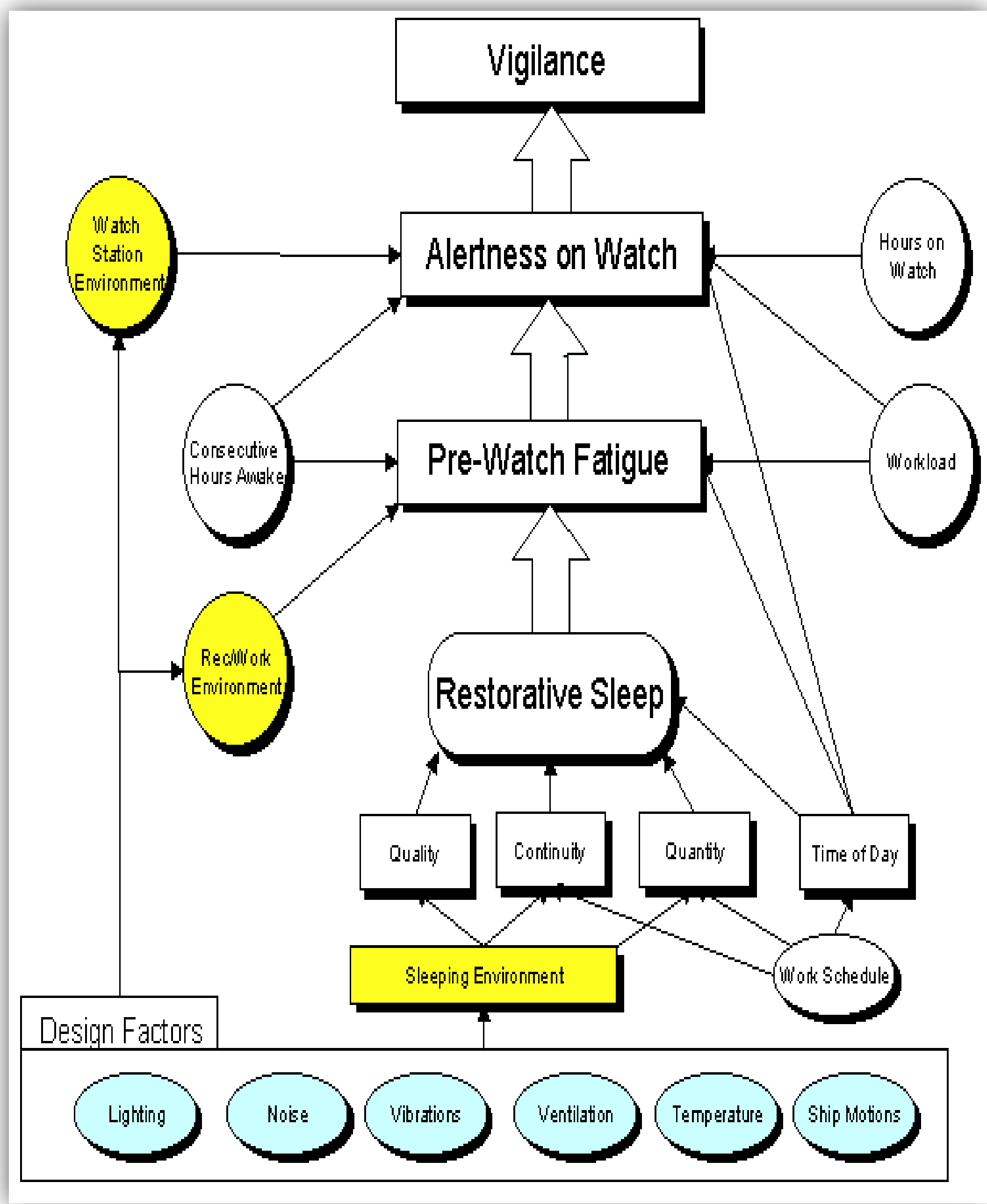


Figure 4. 6: Vigilance though improved ship design [14]

By focusing on these factors the Naval Architect can improve the ship design providing an upgraded working and living environment. While most of these factors can be assessed by various areas of engineering, vibrations and ship motions are exclusive to naval architects as they rest upon ship design elements (hydrostatics, hydrodynamics and hull structure).

4.3.1.2.1 LIGHT

Light is an integral part of an ergonomic environment. While the importance of lighting is rather obvious as far as visibility is concerned, its primary purpose is to maintain the regular pace of the circadian rhythms. Solar light is essential in calibrating our biological clock, making the exposure to natural daylight a great need.

Since most mariners have to work night shifts, this need is not satisfied in a regular basis resulting in casual circadian rhythms disruption. The most important aspect of this disruption is the increase of *drowsiness time* of an individual and consequently the probability of an error. Even in the morning hours, several crew members spend the majority of their day within the confines of the vessel and below decks, where electric light is all that is available. This can create an irregular and shifting sleep cycle that leads to fatigue. Surveys conducted on mariners have shown that the lighting systems installed aboard ships fail to be stimulating and maintain high alertness levels on crew members.

Figure 4. 7: The lack of sunlight in a vessel's Engine Room

Even though there are several maritime lighting guidelines, most of them neglect the importance of proper lighting in the biological clock circle. Moreover, they focus on general aspects of functionality but fail to prevent the drop of alertness and the prevalence of fatigue.

Artificial light may never be a full substitute of natural sunlight but high intensity lighting has proven to be an effective means to stimulate fatigued operators and help improve human performance by increasing alertness. Scientists insist that by providing 1000 lux or more, the effects of fatigue may decrease.

The guidelines currently used by class societies are specifically task oriented, as shown in figure 4.8. The illumination levels required to shift circadian rhythms and to have a stimulating effect on fatigued operators (~1000 lux) are greater than most of the values recommended by ABS [14].

Table 3 is an excerpt from the American Bureau of Shipping (ABS) "Guidance Notes on the Application of Ergonomics to Marine Systems."

Area or specific task	Recommended lux (ft-c)	Minimum lux (ft-c)
Control consoles (panels, switch boards, gauge boards)		
Front	540 (50)	325 (30)
Back	325 (30)	110 (10)
Control rooms (engine rooms, boiler rooms, generator, steering gear room, switchboard room)	540 (50)	220 (20)
Motor rooms (fan rooms, pump rooms, shaft alley)		110 (10)
Machine shops		
General	540 (50)	325 (30)
Bench work	1075 (100)	540 (50)
Corridors, passageway, stairways		
General	210 (20)	110 (10)
Shaft alley escape		32 (3)
Galley	755 (70)	540 (50)
Laundry		540 (50)
Medical spaces		
General	755 (70)	540 (50)
Examination area	1075 (100)	810 (75)
Offices		
Fine tasks (typing, book keeping)	755 (70)	540 (50)
Ordinary tasks (desk work, reading)	540 (50)	430 (40)
General office area	540 (50)	220 (20)
Storage	110 (10)	55 (5)

Figure 4. 8: ABS Lighting Guidelines [14]

4.3.1.2.2 NOISE

The common definition of noise is the presence of undesirable sound. On-board, noise can be the result of various procedures and activities. Its presence can be found in almost every compartment of the vessel making it difficult to entirely eliminate it. Some of the most regular noise-related areas of the ship are engines, pumps and other mechanical equipment.

Noise can affect both physical and mental human condition by inducing fatigue on the workplace and decreasing human effectiveness. Apart from the working environment, noise has been recorded as one of the most integral factors that affect sleep quality. According to Calhoun [14] guidelines and regulations about noise tend to neglect its impact on fatigue inducing since they focus on the prevention of potential hearing loss. Temporary loss of hearing can be the result of even short-term exposure to noise and can also lead to permanent hearing loss. Moreover, guidelines about noise fail to address important physiological outcomes that may appear years after working in a noisy workplace.

Medical experts indicate that the human body perceives all noise as a potential threat or warning, so it responses in a defensive way. Even if noises coming from a piece of equipment are not always a sign of warning, the human body responds as if they actually were. Surveys on mariners have shown that people who work in a noise-full environment are expected to have mood swings, short temper and inability to deal with minor frustrations.

Calhoun [14] describes four effective Noise Control Methods as shown below:

- Isolation via absorbing material
- Noise Barriers that block transmission
- Damping eliminating vibration impact
- Absorption of noise and converting it to heat

ABS through its guidelines regarding noise levels makes recommendations about maximum and preferred levels of dBs (decibels). Interviews and inspections have shown that these levels are often surpassed (figure 4.9).

4.3.1.2.3 SHIP MOTION INDUCED FATIGUE

Motion-induced fatigue as part of naval biodynamic problems is a significant contributor to the performance of ship crews (Coldwell 1989). Coldwell also suggested that this was an important matter for the naval community and which implied a higher incidence of mistakes, some of which may not be easily noticed by a supervisor [23].

Space	Maximum dB(A)	Preferred dB(A)
Work Spaces		
Machinery space (continuously manned)	90	85
Machinery space (not continuously manned)	110	95
Machinery control rooms	75	55
Workshops	85	70
Non-specified spaces	90	85
Navigation Spaces		
Navigation Bridge and chartroom	65	55
Listening post, including bridge wings and windows	70	60
Radio rooms	60	45
Radar rooms	65	55
Accommodation Spaces		
Cabins and hospitals	60	45
Mess rooms	65	55
Recreation rooms	65	50
Open recreation areas	75	65
Offices	65	55
Service Areas		
Galleys	75	65
Serveries and pantries	75	65
Normally unoccupied spaces		
Spaces not specified	90	85
* Table adapted from IMO Assembly Resolution A.486(XII)		

Figure 4. 9:ABS Guidelines regarding Noise levels aboard ships [14]

Working in a constantly moving environment can often induce muscle fatigue since the vessel's motions would probably raise the average energy expenditure of the crew members. This can be easily explained by the need of a crew member to maintain his position/stance while performing a specific task at the same time.

Dobie [23] suggests that whole-body vibration may have impact on general comfort and performance, while in worst cases in health and safety. Moreover, Dobie continues by indicating that whole body vibration can be transmitted to the body in three types of ways:

- The whole body surface
- The buttocks
- By several individual parts of the body

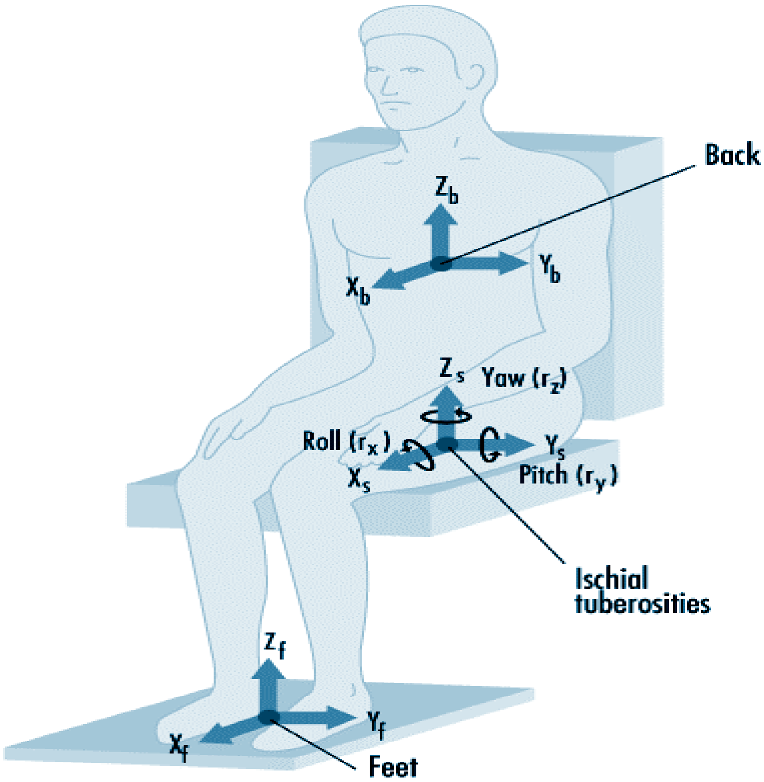


Figure 4. 10: Transmission of vibration throughout the human body

Apart from the human body, vibrations can have a critical effect on the visual target of a crew member (e.g. a control panel), thus resulting in decision making and interpretation errors.

Most common sources of these vibrations, apart from the vessel motions, are these caused by large pieces of equipment such as the propeller and the main engine. Dobie pinpoints that higher frequency vibrations can also originate from hull responses caused by severe slamming in heavy seas.

Calhoun [14] indicates that maritime vibration guidelines, in the same manner to those about noise that were discussed earlier, mainly focus on preventing bodily injury but neglect the impact of vibrations on fatigue and sleep quality. Some effects of whole body vibration are listed below:

Physiological:

- Cardiac rhythm increases
- Respiration rhythm increases
- Blood circulation increases
- Vasoconstriction
- Endocrine secretions
- Central nervous system affected

Comfort and Performance:

- Pain
- Nausea
- Vision problems
- Posture
- Movement and coordination decline
- Force
- Perceptions altered

The above effects are sometimes imperceptible to the operator. They also occur at lower vibration levels than those currently established by vibration guidelines [14].

A lot of research has been conducted regarding the mitigation of vibration on-board. Most of them propose practical countermeasures similar to those proposed for noise. The use of isolators, absorption techniques and materials that can minimize the frequency and intensity of vibrations is highly recommended.

Vibration noise transmitted into the structure of a vessel is best prevented through the isolation of the machinery from the hull. Rubber padding and spring or rubber mounts are some of the measures used for preventing this. The primary goal is to isolate vibrations and noise to the engine room and stopping them from reaching the hull structure.

In their quest of diminishing the unwanted effects of noise and vibrations, naval architects should be aware of some drawbacks that come along. The added weight and cost of suppression materials are a significant issue that impedes the designer from integrating these measures in the vessels design. While IMO has been more than active in the past 10 years in the area of Human Factors, the classification societies have not addressed the issue adequately. It is rather clear that there is a great need for more research on vibration induced fatigue and the human element in general.

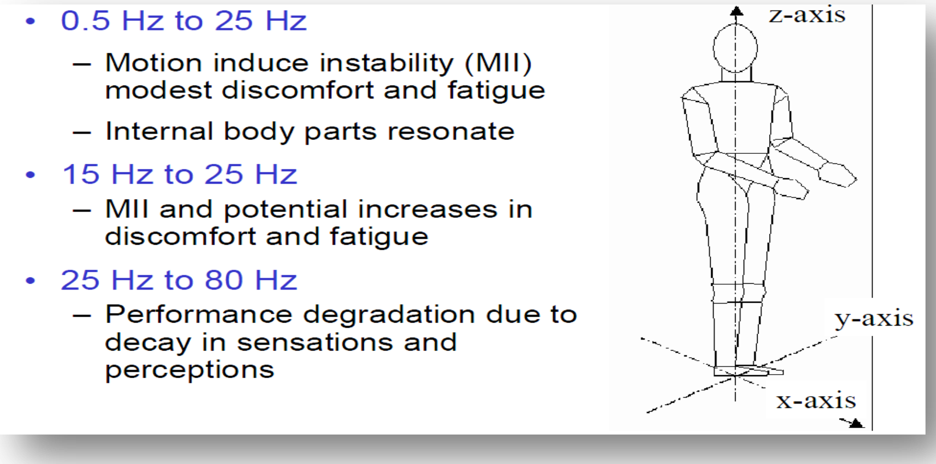
4.3.1.3 PHYSICAL ENVIRONMENT FATIGUE FACTORS

According to IMO (2001) [34], physical environment factors can be summarized in the following text:

"Exposure to excess levels of environmental factors, e.g. temperature, humidity, excessive noise levels, can cause or affect fatigue. Long-term exposure may even cause harm to a person's health. Furthermore, considering that environmental factors may produce physical discomfort, they can also cause or contribute to the disruption of sleep."

Ship motion, noise and vibrations which were discussed in the previous paragraph are the main contributing environmental factors. Within the ABS *Guide to Crew Habitability on Ships*, habitability criteria and measurement methodologies are presented for optimizing conditions of the ambient working and living environment. Relevant information for vibration, noise, indoor climate, and lighting are given in order to control fatigue related factors of the physical environment [58].

A typical example of the ABS *Guide to Crew Habitability on Ships* [61] regarding vibrations can be seen in figure 4.4.



<u>Figure 4. 11:</u> Vibrations effects to human body and movement [61]

4.3.1.4 MANAGEMENT FATIGUE FACTORS

The last category of factors resulting in fatigue is that related to management issues. According to the IMO (2001) [34] these factors include:

1. Organizational Factors

• Staffing policies and Retention
• Role of riders and shore personnel
• Paperwork requirements
• Economics
• Schedules-shift, Overtime, Breaks
• Company culture and Management style
• Rules and Regulations
• Resources
• Upkeep of vessel
• Training and Selection of crew

2. Voyage and Scheduling Factors

• Frequency of port calls
• Time between ports
• Routing
• Weather and Sea condition on route
• Traffic density on route
• Nature of duties/workload while in port

These factors are recognized to influence on-board fatigue and are mostly related to management policy and practice. Examples of these factors include top-level organizational goals, shipping companies regarding decisions relating to vessel operations, schedules, and voyages and compliance to regulations.

In paragraph 4.5 where legislation regarding fatigue in the maritime industry is discussed, these factors will be presented more thoroughly in accordance to the STCW, IMO and various relevant regulations.

4.3.2 THE IMPACT OF STRESS ON MARINER’S FATIGUE

Stress is a contributory factor to the productivity and health costs of an organization as well as to personnel health and welfare (Cooper, Dewe, & O'Driscoll). A survey by Parker et al. (1997) for AMSA (Australian Maritime Safety Authority) presented some very interesting results regarding seafarer’s stress. By the use of a self report questionnaire, respondents were asked to rate how frequently they felt stressed and at what level. Moreover, they were asked how frequently and to what extent did they engage in health related behaviors such as exercising and drinking.

The number of participants was 1,806 seafarers including crew, masters, mates, pilots, and engineers. In addition, the questionnaire was given to a normative group of people in order to compare the results to those of the mariners. Seafarers reported significantly higher levels of stress from sources of work pressure than did the normative group, especially when asked about relationships with others and the home/work interface.

The general results indicated that:

- 80% seafarers reported occasional to frequent stress at sea over
- 65% of engineers, 60% of crew, and over 60% of masters reported moderate to high stress levels.

In the same study the interaction between stress and decreased levels of alertness was highlighted indicating that chronic psychological stress – the type of stress induced by interpersonal relationships, task design, and management style – creates a constant drain on crewmember energy levels [31].

The Crew Endurance Management (CEM) [103] guide by the US Coast Guard list the most common cause for stress as:

Interpersonal relationships:

- Lack of support from coworkers and supervisors

Task design:

- Heavy workload
- Infrequent rest breaks
- Long work hours
- Shiftwork
- Hectic routine tasks
- Little sense of control

Management style:

- Authoritative management style
- Lack of participation by workers in decision making
- Poor communication between management and employees
- Ambiguity or conflicting requirements
- Lack of family-friendly policies

4.4 RESEARCH REGARDING FATIGUE IN MARITIME TRANSPORATION

The past two decades a lot of parties have been active in investigating, measuring and battling fatigue in the maritime domain. These parties include government organizations, classification societies, private researchers and scholars. Some of these studies and surveys are listed below:

4.4.1 ITF SEAFARER FATIGUE: Wake up to the dangers (1997)

The participants of the ITF report [V] were 2,500 seafarers of 60 nationalities, serving under 63 different flags. The results of the survey indicate that fatigue at sea is most of the times the long hours that crew members have to work during their time on-board. Some of the results showed:

- 65 % of the participants stated that their average working hours were more than 60 hours per week
- 25% of them reported working more than 80 hours a week (42% of masters)
- 36% of the sample was unable to regularly obtain 10 hours rest per day
- 18% regularly unable to obtain a minimum of 6 hours uninterrupted rest.

- 55% considered that their working hours presented a danger to their personal health and safety. Indeed, nearly half the sample felt that their working hours presented a danger to safe operations on their vessel.
- 60% reported that their hours had increased in the past 5 to 10 years.
- Fatigue was more evident during the first hours of their duty.
- Long tours of duty were also common (30% reporting usual tour lengths of 26 weeks or above).

4.4.2 THE NEW ZEALAND MARITIME SAFETY

This report summarizes some of the most important risk factors that contribute to fatigue by accumulating data from seafarers in New Zealand. Some of the most important findings of this report include:

- 60% of seafarers admitted falling asleep on duty at least once
- Most of the participants indicate that the reduction of manning levels and other economic/management factors resulted in fatigued operators
- The survey of masters and mates on the Cook Straight ferries found that the key cause of fatigue was shorter more disrupted sleep
- Ship motions, noise and vibration were also recognized as fatigue related factors
- Workers had to work in most of the scheduled rest
- The average age of the crew was significantly high (above 50 years).

4.4.3 THE CARDIFF PROGRAMM

In 2006 Smith, Allen and Wadsworth, introduced the *The Cardiff Seafarers' Fatigue research programme* [90]. Their main areas of focus were:

- Prediction of the worst possible fatigue scenario for health and safety
- Practical recommendations for mitigating fatigue in accordance to the vessel type and trade
- Advice packages in order to battle fatigue by recognizing hidden hazards in working environments, work shifts and others aspects of life at sea.

The realization of this project was successful by using the following elements:

• Reviews of the literature
• A questionnaire survey of working and rest hours, physical and mental health
• Physiological assays assessing fatigue
• Instrument recordings of sleep quality, ship motion and noise
• Self-report diaries recording sleep quality and work patterns
• Objective assessments and subjective ratings of mental functioning

• Analysis of accident and injury data [90]

4.4.4 MAIB BRIDGE WATCHKEEPING SAFETY STUDY (2004)

The Marine Accident Investigation Branch, in their bridge watchkeeping safety study [54] also recognized fatigue in their investigation of collisions and groundings of several vessels due to errors occurring on the bridge. The study shows that twelve vessels grounded with sole watchkeepers. All were dry cargo/container vessels, 84% were less than 3,000 GT (Gross Tonnage), 92% carried only two deck officers, and all had three or fewer deck ratings. All of these groundings occurred in clear or good visibility, and 75% occurred during darkness. Only one grounding occurred in a port or harbor area, the remainder occurred during coastal passage.

This data highlights the link between small dry cargo ships operating in the short sea and fatigue induced by insufficient manning. The same study indicates that alertness and performance tend to be at their lowest during the early hours of the morning, a fact well discussed earlier in this thesis.

MAIB have concluded that that the records of hours of rest on board many vessels, which almost invariably show compliance with the regulations, are not completely accurate. The number of recent groundings in which fatigue has been a contributory factor, indicates that the hours of rest regulations are not having significant effect with regards to the bridge watchkeeping arrangements on many vessels. There is also pressure on masters and chief officers to do some of their ancillary work while on watch, with the inevitable consequence of degraded attention to their watchkeeping duties [54].

4.4.5 THE TNO REPORT (2005)

In their 2005 report on fatigue in the shipping industry, Houtman et al (2005) [33] made a thorough presentation of the issue by recognizing all the parties involved (e.g. shipping companies). TNO research on other sectors of transport was critical in recognizing dangers that were till then overlooked.

Focus was given on twelve areas for fatigue management:

• Lengthening of the resting period
• Optimizing the organization of work
• Reducing administrative tasks
• Less visitors / inspectors in the harbor / better co-ordination of inspections
• Reducing overtime
• Proper Human Resource Management
• Education and training
• Development of a management tool for fatigue

• Proper implementation of the ISM-code
• Healthy design of the ship
• Health promotion at work
• Expanding monitoring of fatigue causes, behaviors or consequences, including near misses.

Emphasis was clearly given in the proper compliance to the regulations while it suggested four points of the above point to be the most important for reducing fatigue:

• proper implementation of the ISM-Code
• optimizing the organization of work on board vessels
• lengthening of the rest period
• reducing administrative tasks on board vessels.

4.4.6 NTUA'S IDENTIFYING AND ASSESSING NON-TECHNICAL SKILLS ON GREEK MARITIME OFFICERS (2010)

In this survey the NTUA's School of Naval Architecture and Marine Engineering[2] presented the findings from an attitude questionnaire[110], conducted in captains A&B and 1st & 2nd engineering officers of Greek owning ship, that cover various aspects of the relation between human element and maritime safety. In this research project, Crew Resource Management (CRM) skills analysis was introduced in maritime industry. This term stands for the critical cognitive, social, and interpersonal resource skills that complement technical abilities so as to contribute a safe and efficient task performance. In this outline the basic categories of non-technical skills in safety critical industries include situation awareness, decision-making, communication, teamwork, leadership, managing stress, coping with fatigue.

The questionnaire included questions about fatigue perception and hours of sleep which provided interesting findings regarding fatigue issues in the maritime domain. The most important findings included:

- Officers of the deck stated to sleep less uninterrupted hours, but more in total number than their shipmates engineering officers

- The lack of sleep on officers of the deck of Ro-Ro ships where the scheduled departures – arrivals, transits through restrained waters, require all officers of the deck on task, which consequently allow even less available hours for sleep.

- STCW 95 followed, even though marginally, about total hours of sleep in every 24 hour

[2] Laboratory of Maritime Transport

- STCW 95 is not followed by the hours of rest in a non-routine day where transit through restrained waters, loading – unloading or emergency situations took place.

The statistical data collected by this survey served as our main source for assigning the prior probabilities distribution in our Bayesian Network.

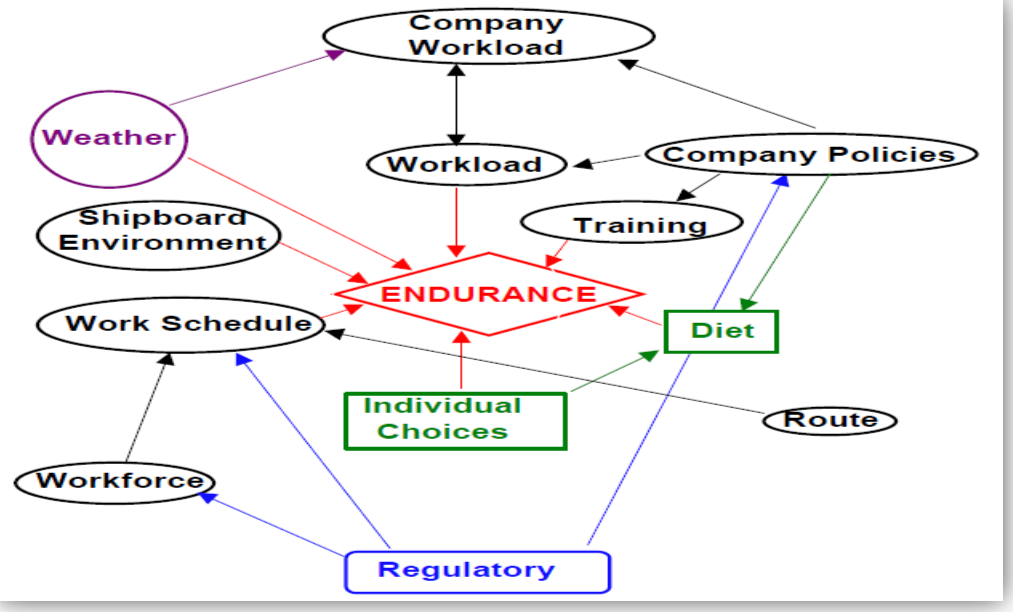
4.4.7 CREW ENDURANCE MANAGEMENT SYSTEM

The Crew Endurance Management System [103] was assembled by the US Coast Guard in order to help maritime companies ensure the highest possible levels of performance and safety. The guide focused in two parts:

- The identification of specific factors affecting crew endurance in their particular operations
- The management of these factors toward optimizing crewmember endurance

CEMS also addressed the problem of Circadian Rhythm disruption (The Red Zone) pinpointing that during these drowsy periods the decrease of alertness levels may cause human errors. Furthermore, the program proposed three steps for the proper implementation of CEMS in maritime operations, as listed below:

- Phase I: Program development which consists of 4 parts:
    1. Receive Training in CEM Principles and Practices
    2. Identify System Areas of Risk
    3. Identify Specific Risk Factors
    4. Propose Modifications
- Phase II: Program Deployment
- Phase III: Program Assessment



<u>Figure 4. 12:</u> Factors that affect the Marine's endurance (CEM) [103]

At this point it is essential to highlight the individual choices node proposed by CEM system. Fatigue may be the result of a variety of different factors but the most underrated in literature is the personal judgment and decisions of each individual that lead to its prevalence. In conclusion, it is essential for an individual to have proper knowledge about fatigue in order not to underestimate the consequences of his actions and choices.

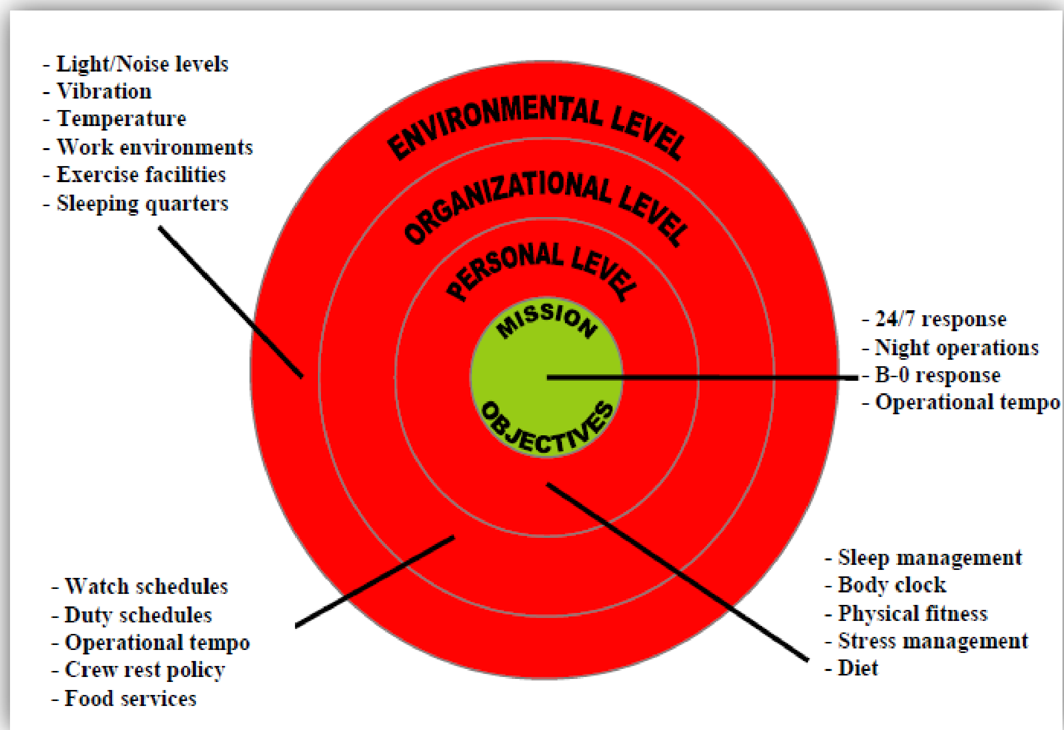


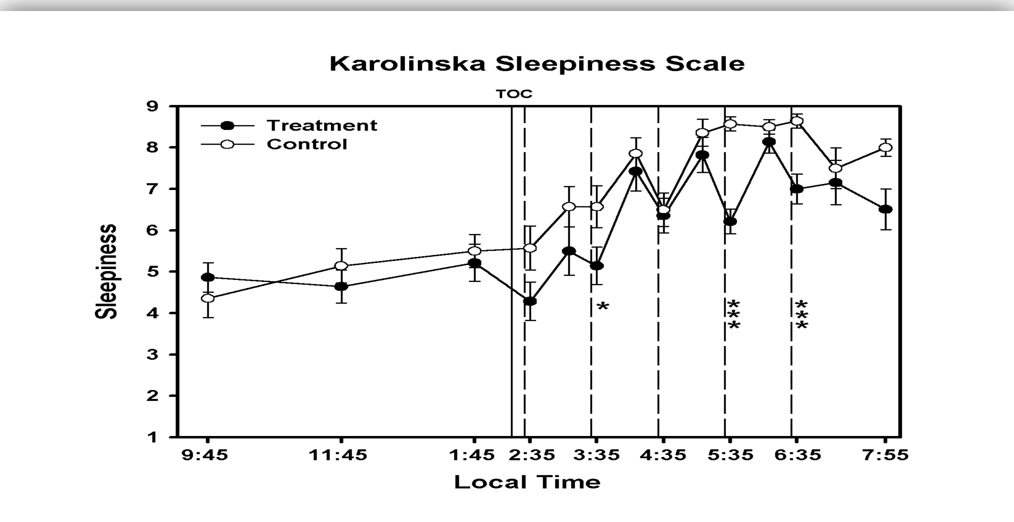
Figure 4. 13: Factors that affect Fatigue according to Crew Endurance Management [103]

4.4.8 FATIGUE AT SEA - A FIELD STUDY IN SWEDISH SHIPPING

This study [52], performed by VTI, collected data about the fatigue level of bridge watch keepers in order to revise earlier sleep models, and devise innovative solutions for the shipping industry.

Data collection included interviews with shipping companies and a field study onboard 13 cargo vessels. 32 participants took part in representing two watch systems; 2-watch and 3-watch. Subjective sleepiness and stress estimations were performed once every hour. EOG was used to record eye movement behavior. Reaction time test was made to examine performance. 3-watch participants are more satisfied with their working hours and working situation. Tendencies indicate that 2-watch participants are a bit more tired, whereas the stress is the same. All are less sleepy and less stressed at home. Time on shift had effect on sleepiness. The highest KSS (Karolinska *Sleepiness Scale)* scores were recorded in the late night and early morning. After night shift the reaction times have higher variance and more long reaction times are present. The mean value after night shift was significantly higher than after day shift.

Fatigue measurement methods included the KSS, questionnaires, interviews and reaction time tests provided the following results:



<u>Figure 4. 14:</u> The Karolinska Sleepiness Scale [52]

- Most Swedish companies do not regard fatigue as an important concern
- The majority of participants stated that 8 hour sleep is the minimum for avoiding fatigue issues
- Fatigue monitor equipment would be welcomed by the majority of personnel
- Fatigue is affected by the shift/watch system (shift rotation)
- The average amount of sleep in 24 hours is between 6-7 hours, regardless the shift system
- Sleep quality is low (disturbed)

4.5 LEGISLATION ON FATIGUE IN THE MARITIME SECTOR

4.5.1 IMO & THE ISM CODE

The IMO recognized that there is a direct connection between health and safety of a ship's crew and the way that the vessel is managed. In an attempt to make sure that shipping companies and operators take a closer look on the potential impact of their management strategies, the IMO established the International Safety Management Code.

International Maritime Organization's International Code, *International Management for Safe Operation of Ships and for Pollution Prevention* (the "ISM Code") was adopted in November 1993. During Phase I the ISM Code required the establishment of a certified safety management system July 1, 1998. The main goals of the Code were to promote safety at sea, prevent injuries and loss of life and finally setting rules to diminish potential damage to the environment and to property. In addition, it also required from shipping firms to establish *specific* safety objectives, based on their sphere of operations, and this includes objectives related to crew fitness-for-duty (which incorporated fatigue factors) and control of human error.

Phase II of the ISM Code became mandatory on the first of July, 2002 and is to be applicable to all vessels above 500 gross tonnage which were not covered under Phase I. Phase II introduces a new safety management system, a system that prescribes the management procedures for safety and pollution prevention for ships or offshore structures. It has also set forth policy and practice relating to factors that directly or indirectly affect crewmembers, their roles and responsibilities, work hours, reporting schemes, paperwork requirements, etc. The responsible parties were required to provide the resources and support needed to implement and maintain the safety management system. The Code also requires certification of compliance with the requirements of the ISM Code and the safety management system [58].

4.5.2 IMO AND STCW

A different aspect that relates to ship management concerns manning issues. In 1995, the IMO made new amendments to the international Standards for Training, Certification, and Watchkeeping (STCW) Convention. These proposed regulations have played an important part in improving the mariners' readiness and capabilities. Some of the more important provisions of the 1995 amendment include:

• Requires certification of masters, officers, and ratings only when they meet the requirements for service, age, medical fitness, training, qualification, and passing examinations

• Requires special training for certain types of ships (tankers, Ro-Ro, and passenger ships)

• Requires Flag States establish and enforce rest periods for watchkeeping personnel. Watchstanding personnel must be provided a minimum of ten hours of rest for every 24-hour period (the ten hours may be divided into two periods, but one must be of at least six uninterrupted hours)

• Requires that watch systems be arranged so that watchkeeping personnel is not impaired by fatigue

• Requires instructors and assessors be qualified for the types of training or assessment of competence of seafarers. Those involved in training and/or assessment must be qualified in the task for which the training/assessment is being conducted [58].

STCW is the most important instrument of the marine industry that can affect the life on board. Through STCW fatigue can be managed by established limits on work hours and minimum rest periods for seafarers. Major revisions to the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (the STCW Convention) and its associated Code have been adopted at a Diplomatic Conference in Manila, thereby ensuring that the necessary global standards will be prepared to train and certify seafarers to operate technologically advanced ships for some time to come. The Conference was held in Manila from 21 to 25 June under the auspices of the International Maritime Organization (IMO). Amendments adopted in 2010 will be implemented on 1 Jan 2012. These amendments addressed fatigue as a major issue in the maritime industry and proposed revised requirements on work hours and rest and new requirements for the prevention of drug and alcohol abuse, as well as updated standards relating to medical fitness standards for seafarers.

4.5.3 ILO 180

The International Labor Organization has also participated in the attempts to reduce fatigue at sea. The ILO 180, *Convention concerning seafarers' hours of work and the manning of ships, (1996*), set limits relating to non-watch-keepers work hours. The main purpose of these regulations was to mitigate fatigue in marine workplaces (e.g. engine rooms).

The most important achievement of ILO 180 was setting specific work hours limitations for seafarers that are listed below:

Maximum hours of work shall not exceed:

(i) 14 hours in any 24-hour period and

(ii) 72 hours in any seven-day period or

Minimum hours of rest shall not be less than:

(i) ten hours in any 24-hour period and

(ii) 77 hours in any seven-day period.

CHAPTER 5

INTRODUCTION TO BAYESIAN NETWORKS

5 INTRODUCTION TO BAYESIAN NETWORKS

This chapter is a brief introduction to probabilistic graphic modeling and Bayesian Networks. It must be stated that belief networks are far more complex and demanding than presented in this thesis. The lack of space and the need for a rather synoptic presentation has left important elements of Bayesian Networks unaddressed. For deeper understanding of the capabilities and potential of BN the author suggests the publications of J.Pearl (1988) and F.Jensen (1996 & 2007), which are listed in the references [73] [40] [41], regarding intelligent systems and BN. Most part of this chapter was based to the thorough contents of these books.

5.1 AN INTRODUCTION TO UNCERTAINTY AND GRAPHICAL MODELS

5.1.1 UNCERTAINTY

D. Hubbard has described uncertainty as the lack of certainty, a state of having limited knowledge in which it is impossible to describe precisely existing state or future outcome. Decision making is widely recognized by engineers as an integral part of the whole engineering design process. Because of the fact that uncertainty has a significant impact on decision making, the engineering community has tried to manage uncertainty via innovative methods and intelligent systems. The presence of uncertainty in the scientific and professional world has led scholars to develop tools in order to address issues such as imprecision and event dependence. The most reliable tool for modeling uncertainty has been the use of probabilities theory.

Jensen (1996) [40] proposes a way to incorporate uncertainty in a rule based system by extending the production rules to the following format.

If condition with certainty x **then** fact with certainty f(x), where f is a function

The inference system must be extended with new inference rules, which shall ensure a coherent reasoning under uncertainty. For example, if x is the certainty of inferring C from A and y the certainty via inferring C from B, we can conclude that the certainty of C is the inference of the function g(x , y).

The answer to uncertainty was given by decision theory experts through modeling classical probability theory into a more precise mathematical context. Through these methods, researchers managed to quantify reasoning under uncertainty by taking advantage of the capabilities of modern computer systems. One of the most effective tools to manage and represent uncertainty has been the use of probabilistic graphical models, a modeling method that will be discussed in the following paragraph.

Other methods to deal with uncertainty include:

• Three-valued logic: True / False / Maybe

• Fuzzy logic (truth values between 0 and 1)
• Non-monotonic reasoning (especially focused on Penguin informatics)
• Dempster-Shafer theory (and an extension known as quasi-Bayesian theory)
• Possibabilistic Logic [63].

5.1.2 PROBABILISTIC GRAPHICAL MODELS

A graphical model is a probabilistic model for which a graph denotes the conditional independence structure between random variables. Probability theory, statistics and machine learning are some of the fields that have benefitted from the use of these models. Many scientists describe them as a marriage between probability and graph theory. The three fundamental cornerstones of graphical models are representation, inference, and learning.

Michael Jordan (1998) describes the primary purpose and function of graphical models:

'An integral part in the idea a graphical model is the notion of modularity -- a complex system is built by combining simpler parts. Probability theory provides the glue whereby the parts are combined, ensuring that the system as a whole is consistent, and providing ways to interface models to data. The graph theoretic side of graphical models provides both an intuitively appealing interface by which humans can model highly-interacting sets of variables as well as a data structure that lends itself naturally to the design of efficient general-purpose algorithms. Many of the classical multivariate probabilistic systems studied in fields such as statistics, systems engineering, information theory, pattern recognition and statistical mechanics are special cases of the general graphical model formalism – examples include mixture models, factor analysis, hidden Markov models, Kalman filters and Ising models. The graphical model framework provides a way to view all of these systems as instances of a common underlying formalism. This view has many advantages -- in particular, specialized techniques that have been developed in one field can be transferred between research communities and exploited more widely. Moreover, the graphical model formalism provides a natural framework for the design of new systems'.[3]

5.2 BAYESIAN NETWORKS AND BAYESIAN INFERENCE

5.2.1 WHAT IS A BAYES NET?

One of the most prevalent and effective graphical models to manage uncertainty is the Bayesian Network which was popularized in 1988 by Judea Pearl in *Probabilistic Reasoning in Intelligent Systems.* A Bayesian network, belief network or directed acyclic graphical model, is a probabilistic graphical model that correlates the conditional dependencies of a number of random variables with the use of a Directed

[3] M. I. Jordan . "Learning in Graphical Models". MIT Press. 1998

Acyclic Graph. A directed acyclic graph is a directed graph with no directed cycles. The formation of a DAG includes vertices and directed edges, each edge connecting one vertex to another so that a cyclic route is impossible to appear. In the following figure we can see the fundamental difference of an acyclic and a non-acyclic graph.

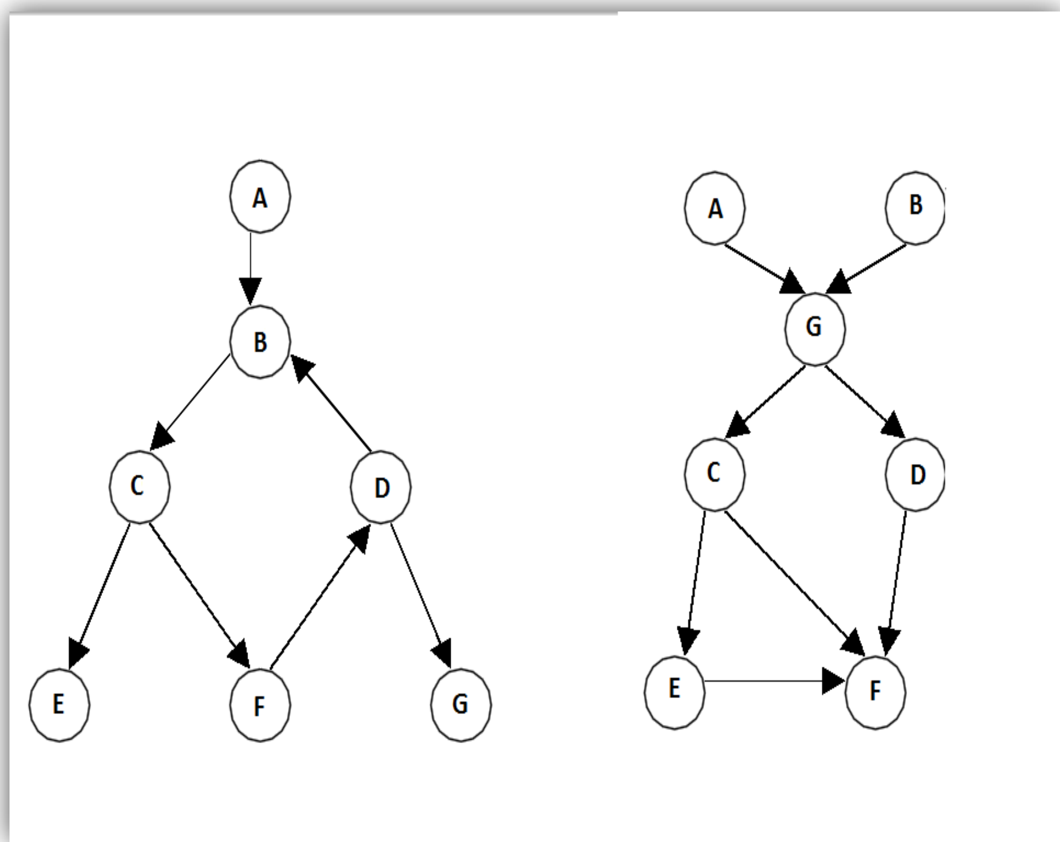
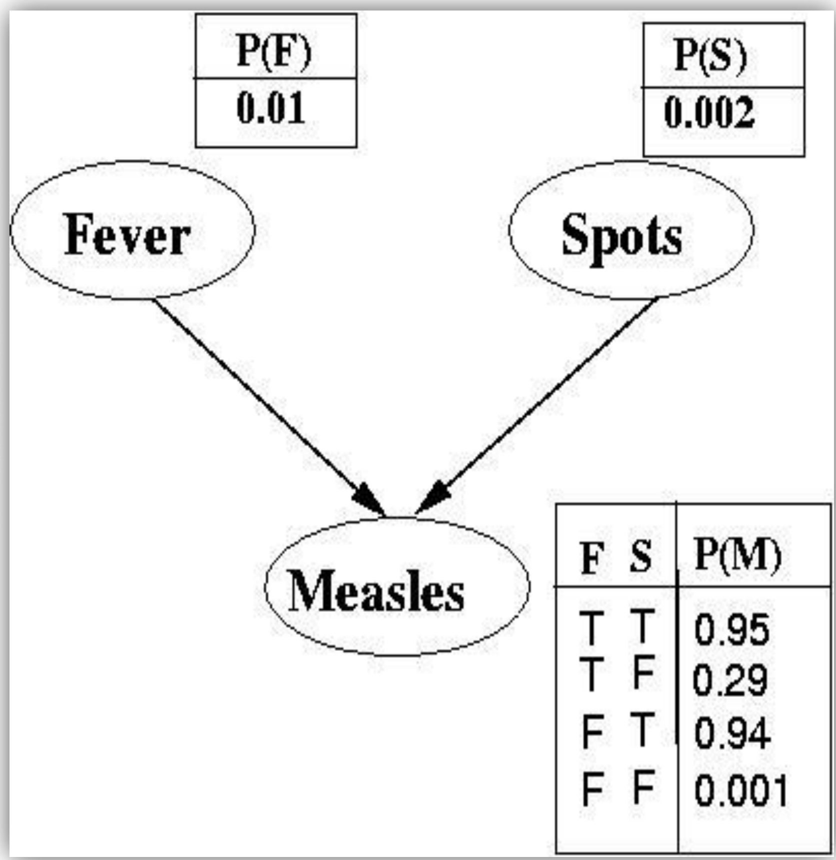


Figure 5. 1: The difference between non-acyclic (left) and acyclic (right) graphs [40]

A common example of a Bayesian network is the representation of the probabilistic relationships between diseases and symptoms. Given symptoms, the network can be used to compute the probabilities of the presence of various diseases.

The nodes in Bayesian Networks represent random variables in the Bayesian sense: they may be observable quantities, latent variables, unknown parameters or hypotheses. Edges represent conditional dependencies between parent and child nodes. Each node is associated with a probability function that takes as input a particular set of values for the node's parent variables and gives the probability of the variable represented by the node. These probabilities of the child nodes are sorted in Conditional Probabilities Tables or CPT's as it can been seen in the following figure. Fever and spots are the parent nodes that affect in terms of conditional probabilities the child node Measles. The CPT shows for example what is the probability of Measles P(M) when Fever state is T and Spots state is T (figure 5.2).



<u>Figure 5. 2:</u> A casual network and its Conditional Probabilities Table

5.2.2 CONDITIONAL PROBABILITIES AND INDEPENDENCE IN BAYESIAN NETWORKS

5.2.2.1 CONDITIONAL PROBABILITIES AND BAYES THEOREMS

In the previous paragraph we mentioned the term conditional probability. The basic concept in the Bayesian treatment of certainties in causal networks is ***conditional probability***. Whenever a statement of the probability, P (A), of an event *A* is given, then it is given conditioned by other known factors. A statement like "the probability of the die turning up 6 is 1/6" usually has the unsaid prerequisite that it is a fair die or rather, as long as I know nothing of it, I assume it to be a fair die. That **means** that the statement should be "Given that it is a fair die, the probability ...." In this way, any statement on probabilities is a statement conditioned on what **else** is known.

A Conditional probability statement is of the following kind:

"Given the event B, the probability of the event A is x."

The notation for the statement above is

- $P(A|B) = x$.

It should be stressed that $P(A|B) = x$ does not mean that whenever B is true then the probability for A is x. It means that if B is true, and *everything else known is irrelevant for A,* then $P(A)=x$.

The fundamental rule for probability calculus is the following:

- $P(A/B)\,P(B) = P(A, B)$ (5.1)

Where P(A/B) is the probability of the joint event A ^ B. Remembering that probabilities should always be conditioned by a context **C,** the formula should read

- $P(A/B,C)P(B/C) = P(A,B/C)$ (5.2)

From (5.1) it follows that $P(A/B)P(B) = P(B/A)P(A)$ and this yields the well known *Bayes rule:*

- $P(B/A) = P(A/B)P(B)/P(A)$ (5.3)

Bayes' rule conditioned on C reads

- $P(B/A,C) = \frac{P(A/B,C)P(B,C)}{P(A/C)}$ (5.4)

[40]

Joint probability is the probability of two events in conjunction. That is the probability of both events together. The joint probability of *A* and *B* is written P(A^B), P(AB) or P(A,B).

Marginal probability is then the unconditional probability P(A) of the event *A*; that is, the probability of *A*, regardless of whether event *B* did or did not occur. If *B* can be thought of as the event of a random variable *X* having a given outcome, the marginal probability of *A* can be obtained by summing (or integrating, more generally) the joint probabilities over all outcomes for *X*. For example, if there are two possible outcomes for *X* with corresponding events *B* and *B'*, this means that. $P(A) = P(A \cap B) + P(A \cap B')$. This is called marginalization.

5.2.2.2 D- SEPERATION AND CONDITIONAL INDEPENDENCE

Types of connections in Bayesian Networks

Bayesian Networks are casual networks that propagate certainty/evidence through 3 different ways as discussed below:

A) Serial connection

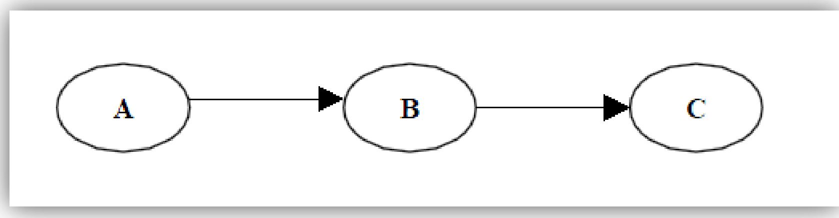


Figure 5. 3: Serial Connection [40]

A has influence on B which in turn has influence on C. When there is evidence given about B, the communication between A and C is blocked.

B) Diverging connections

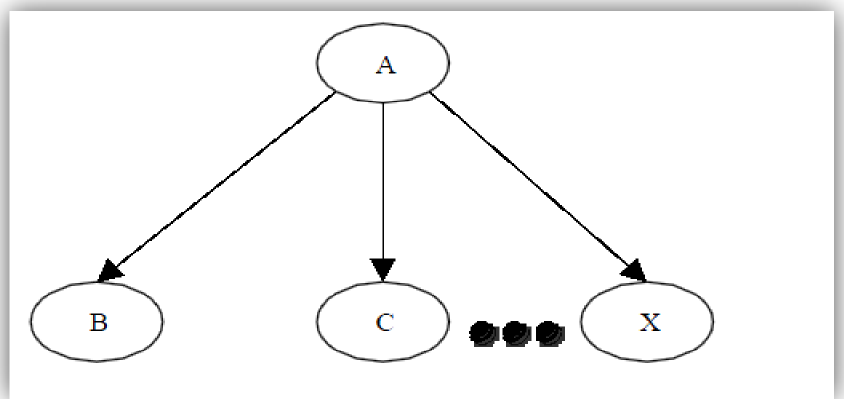


Figure 5. 4: Diverging Connection [40]

In this connection A is the parent node while B, C and X are the child nodes. If evidence is given about A, communication between child nodes is blocked.

C) Converging connections

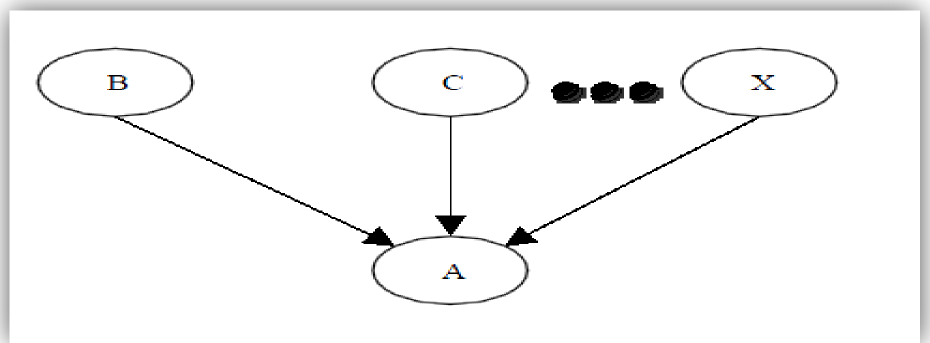


Figure 5. 5: Converging Connection [40]

In this connection A is the child node while B,C and X are the parents. If evidence is given about A, communication is opened between its parents.

D-separation

These three types of connections cover all the ways in which certainty can be transmitted through a variable, and following the rules it is possible to decide for any pair of variables in a causal network whether they are dependent, given the evidence entered into the network. The rules are formulated in the following, (Jensen 1996):

Definition (d-separation)

"Two variables A and B in a causal network are *d-separated* if for all paths between A and B there is an intermediate variable V such that either

- The connection is serial or diverging and the state of V is known

Or

- The connection is converging and neither V nor any of Vs descendants have received evidence.

If A and B are not d-separated we call them *d-connected.*"

Conditional independence

D-separation, the blocking of the transmission of certainty through a casual network is, in the Bayesian calculus, reflected in the concept of *conditional independence. The* variables A and C are *independent given the variable B* if:

- $P(A/B) = P(A/B,C)$ (5.6)

In plain words, it means that whether there is evidence about B, no knowledge regarding A will change the probability of C [40] .

5.2.2.3 BAYESIAN NETWORK

According to Jensen (1996), a Bayesian Network consists of the following:

- A set of *variables* and a set of *directed edges* between variables.
- Each variable has a finite set of mutually exclusive states.
- The variables together with the directed edges form a *directed acyclic* ***graph*** (DAG)

- To each variable A with parents $B(1)\ \ldots,\ B(n)$ there is attached a conditional probability table P(A | $B(1), \ldots B(n)$.

A Bayesian Network can best be described by the functioning of the ***chain rule***:

Let **X** be a Bayesian network over **U** == {A₁,**….A$_m$}.** Then the joint probability distribution **P(U)** is the product of all conditional probabilities specified in X**:**

$$P(U) = \prod P(Ai \mid pa(Ai))$$

Where pa(A$_i$) is the parent of **A$_i$**

5.2.3 BAYESIAN INFERENCE

The most common problem we wish to solve using Bayesian networks is probabilistic inference. Bayesian inference is a method of statistical inference in which some kind of evidence or observations are used to calculate the probability that a hypothesis may be true, or else to update its previously-calculated probability. The easier way to understand the meaning of the Bayesian Inference is through the Bayes Theorem.

- $$P(B/A) = \frac{P(A/B)P(B)}{P(A)}$$

- B represents a specific hypothesis, which may or may not be some null hypothesis.
- A represents the evidence that has been observed.
- P(B) is the *prior probability* of H that was inferred before new evidence became available.
- P(B/A) is the *conditional probability* of seeing the evidence E if the hypothesis H happens to be true. It is also called a *likelihood function* when it is considered as a function of B for fixed A.
- *P*(A) is the *marginal probability* of A: the *a priori* probability of witnessing the new evidence A under all possible hypotheses. It can be calculated as the sum of the product of all probabilities of any complete set of mutually exclusive hypotheses and corresponding conditional probabilities.
- P(B/A) is the *posterior probability* of B given A and is the new estimate of the probability that the hypothesis B is true, taking the evidence A into account.

The factor P(A/B) / P(A) represents the impact that the evidence has on the belief in the hypothesis. If it is likely that the evidence A would be observed when the hypothesis under consideration is true, but when no hypothesis is assumed, it is inherently unlikely that A would have been the outcome of the observation, then this factor will be large. Multiplying the prior probability of the hypothesis by this factor would result in a larger posterior probability of the hypothesis given the evidence. Conversely, if it is unlikely that the evidence A would be observed if the hypothesis under consideration is true, but *a priori* likely that A would be observed, and then the factor would reduce the posterior probability for B. Under Bayesian inference, Bayes theorem therefore measures how much new evidence should alter a belief in a hypothesis.

Later in this chapter, we will discuss a specific example in order to show the use of Bayesian Networks and the importance of the Bayesian Inference in practice.

5.3 PRESENTATION OF A BAYESIAN NETWORK

5.3.1 TYPICAL PRESANTATION OF A PROBLEM OF UNCERTAINTY

Mr. Holmes lives in Los Angeles. One morning when Holmes leaves his house, finds that the grass in his yard is wet. The grass could be wet because of rain (R), or because he has forgotten to switch off the automatic watering system (S). His faith of these two potential events increases.

Holmes also finds that the neighbor's lawn, Dr. Watson, is also wet. Now Holmes is almost sure that it has been raining. A representation of the situation is shown in Figure 5.6, where the rain (R) and the automatic watering system (S) are causes for the wet grass of Holmes. Only the rain can cause Watson grass to be wet.

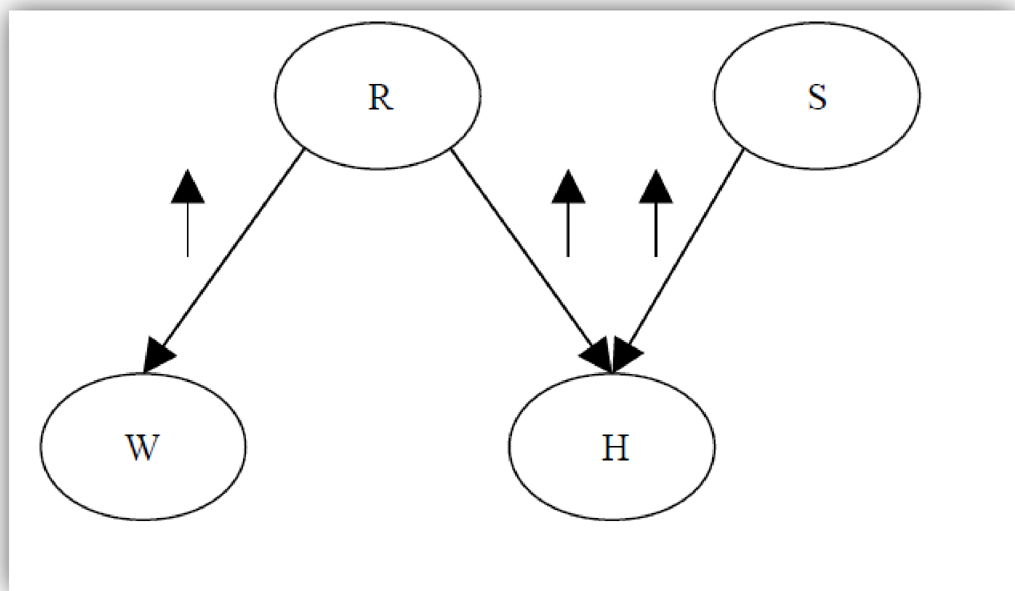


Figure 5. 6: Graphical presentation of the 'wet grass' example [40]

When Holmes realizes that his grass is wet, apply reasoning in the opposite direction from that of explanatory arrows. Since both incidence functions that result in H increase, certainty for the R and S also increases. The increased certainty of R in turn creates a greater certainty of W.

Consequently, when Holmes inspects the lawn of Watson and discovers that it is also wet, he rapidly increases the certainty of R. The next step in the reasoning is difficult for machines, but natural for people and in-depth explanation is required: the wet grass of Holmes explained, and so there is now no reason to think that the automatic watering system was open. Therefore, the certainty of S is reduced to the initial value.

The in-depth explanation is yet another example of dependence changing on the available information. In its original condition, when nothing is known, the R and S are independent. However, when we have information related to the lawn of Holmes, then the R and S become dependent.

5.3.2 USE OF BAYESIAN NETWORKS IN A TYPICAL EXAMPLE

In this paragraph we will transform the problem of 5.3.1 into a Bayesian Network, while explaining the practical use of the graphical model and apposing all the calculations that take place.

Assume that the prior probabilities for the R and S nodes are P(R) = (0.2,0.8), and P(S) =(0.1,0.9). The remaining probabilities are shown in Table 5.1. Initially, we calculate the root chances for W and H by the formula 5.1. That is, first calculate the P (W, R) and then marginalize R. The result is P (W) = (0.36, 0.64).

Table 5. 1: P (W/R) and P (H/R, S)

	R=y	*R=n*
S=y	1	0.2
S=n	0	0.8

P(W\R)

	R=y	*R=n*
S=y	(1,0)	(0.9,0.1)
S=n	(1,0)	(0,1)

P(H\R,S)

The calculation of P (H, R, S) follows the same procedure, except that the product in this case is:

$$P(H, R, S) = P(H / R, S)\, P(R, S)$$

Since the R and S are independent we have:

$$P(H, R, S) = P(H / R, S)\, P(R)\, P(S)$$

The result is given in Table 5.2 Marginalizing R, S out of P(H,R,S) gives P (H) = (0.272 , 0.728). Now we have constructed joint probability tables for two of the clusters, (W, R) and (H, R, S), with variable R common.

Table 5. 2: Prior probability table for P (H,R,S)

	R=y	*R=n*
S=y	(0.02,0)	(0.072,0.008)
S=n	(0.18,0)	(0,0.72)

The certainty H=y is used for updating P(H,R,S) by deleting all entries with H=n and dividing by P(H=y). The result will be a probability table with all entries summing to one, therefore we do not need to calculate P(H). After all the entries with H=n have been erased (Table 5.3.), we simply normalize the table by dividing the sum of the remaining entries (see Table 5.4.).

Table 5. 3: P (H,R,S) with entries H= n eliminated

	R=y	*R=n*
S=y	(0.02,0)	(0.072,0)
S=n	(0.18,0)	(0,0)

Table 5. 4: Calculation of P*(H,R,S) = P(H,R,S/ H=y)

	R=y	*R=n*			*R=y*	*R=n*
S=y	$\frac{1}{0.272}(0.02,0$	$\frac{1}{0.272}(0.072,0)$	$\approx$	*S=y*	(0.074,0)	(0.264,0)
S=n	$\frac{1}{0.272}(0.18,0$	$\frac{1}{0.272}(0,0)$		*S=n*	(0.662,0)	(0,0)

We then get:

P*(R=y) = 0.736 and P*(S=y)= 0.339 .

Use the P*(R) for updating P(W,R) (see Table 5.5)

P(W,R)= R(W/R)*P*(R) =P(W,R) P*(R)/ P(R)*

Table 5. 5: Calculation of P*(W,R)= P(W/R)* P*(R) = P(W,R) P*(R) / P(R)

	R=y	R=n			R=y	R=n
W=y	$0.2 \cdot \frac{0.736}{0.2}$	$0.16 \cdot \frac{0.264}{0.8}$	=	W=y	0.736	0.0528
W=n	0	$0.64 \cdot \frac{0.264}{0.8}$		W=n	0	0.2112

Now we use the fact that W=y for updating the distribution for (W, R) (see Table 5.6). We take P**(R=y) = 0.93.

We still have to calculate the P**(S) = P(S/W=y, H=y). The result must reflect the impact of the in – depth explanation; since the wetted grass is explained by the rain, the probability for S=y should be reduced to its initial value.

The calculation shall follow the same pattern. A message on to P**(R) sent by (W,R) to (H,R,S) (see Figure graph)

*P** (H,R,S) = P*(H,R,S) P**(R) /P*(R)*

Using marginalization we get P**(S=y)= 0.161 .

Table 5. 6: P**(W,R) =P(W,R /W=y, H=y)

	R=y	R=n
W=y	$\frac{0.736}{0.7888}$	$\frac{0.0528}{0.7888}$
W=n	0	0

Table 5. 7: P**(R,S) =P(R,S /H=y,W=y)

	R=y	R=n
S=y	0.094	0.067
S=n	0.839	0

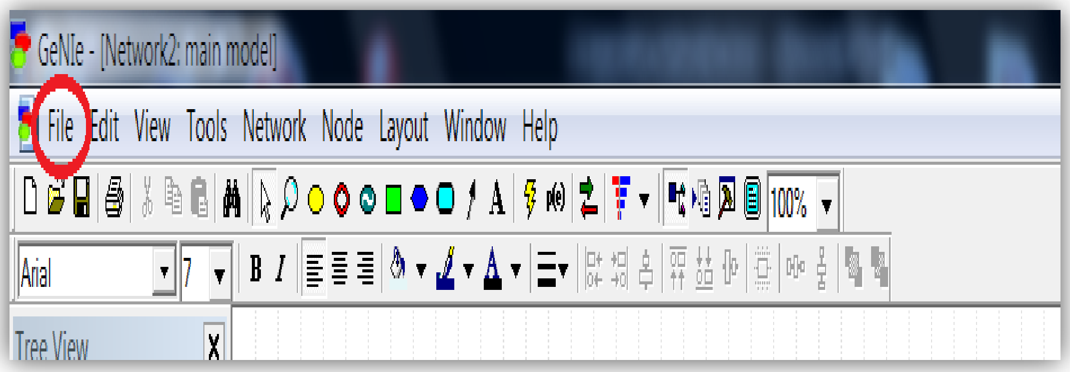
The reason for the probability of S not dropping to its initial value of 0.1 is that Watson may have forgotten the system open as well. This is reflected in the probability P (W=y/R=n) =0.2.

5.3.3 USING GENIE

GeNie was developed by the University of Pittsburgh as an instrument to manage Graphical Models in decision making. It is characterized by a user friendly interface and a plethora of different functions within the Bayesian Networks domain. In this paragraph we will present a simple demonstration of using Genie for the example of 5.3.1 and 5.3.2.

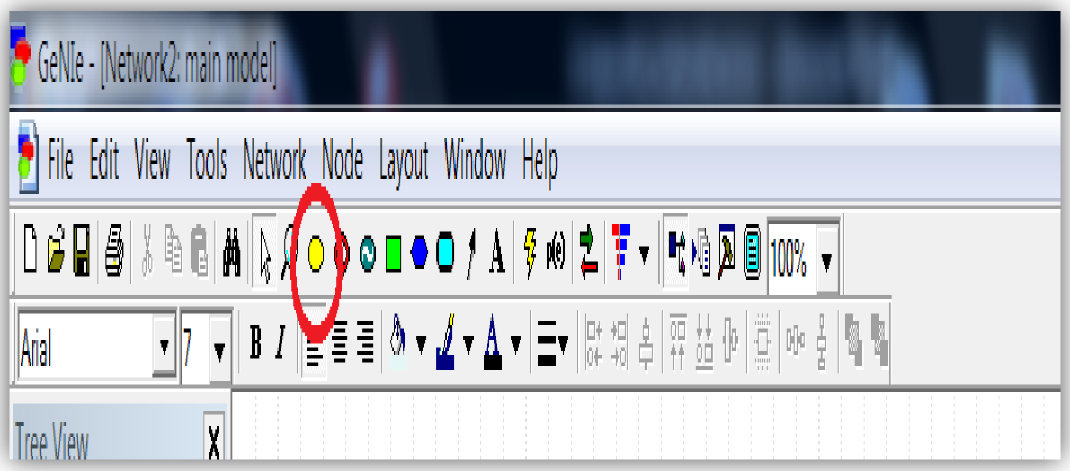
Step 1

Create a new network by clicking on the FILE → NEW NETWORK

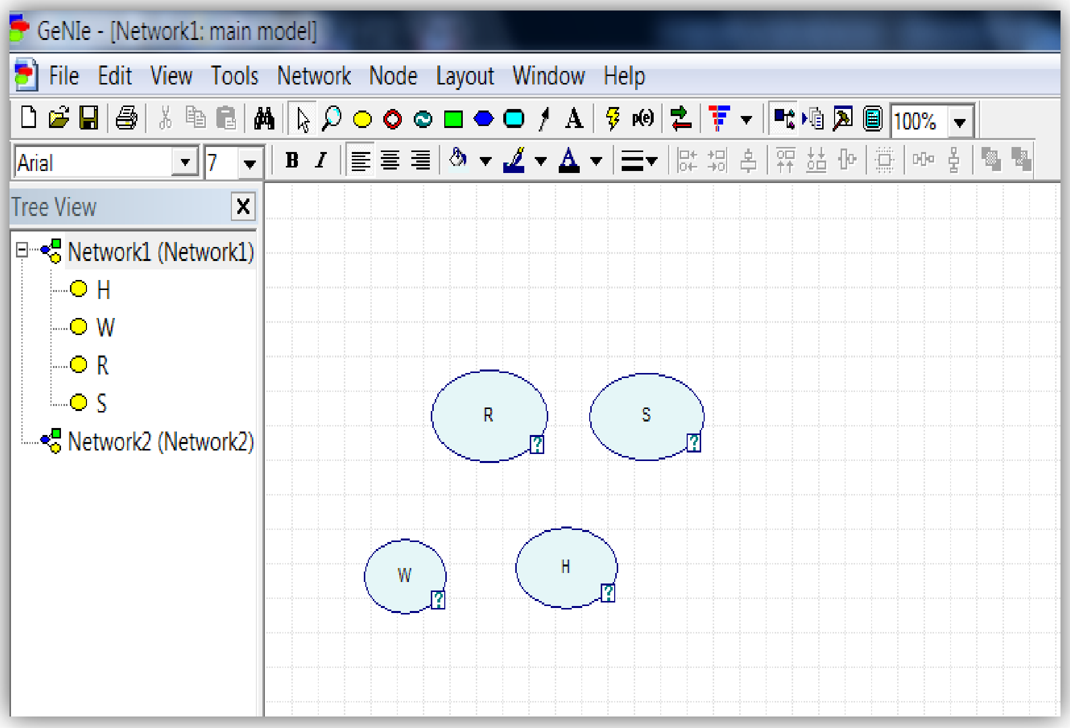


Step 2

Create the nods for this network by clicking on the node icon in the toolbar. For this particular network the nodes are H(HOLMES), W(WATSON), R(RAIN), SYSTEM(S).

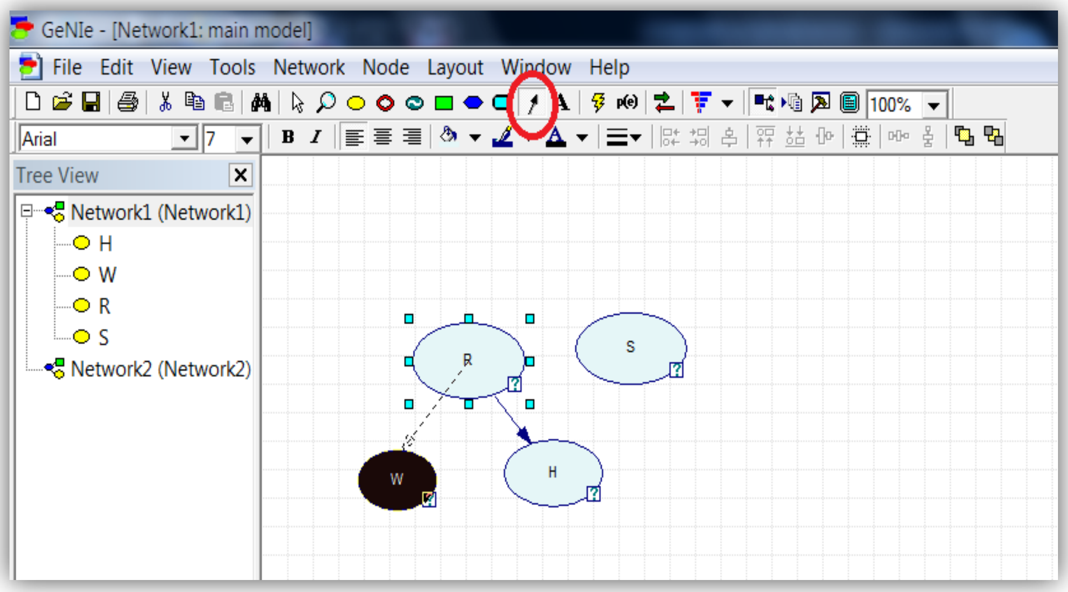


If you set the nodes right you have completed the first part of your BN.



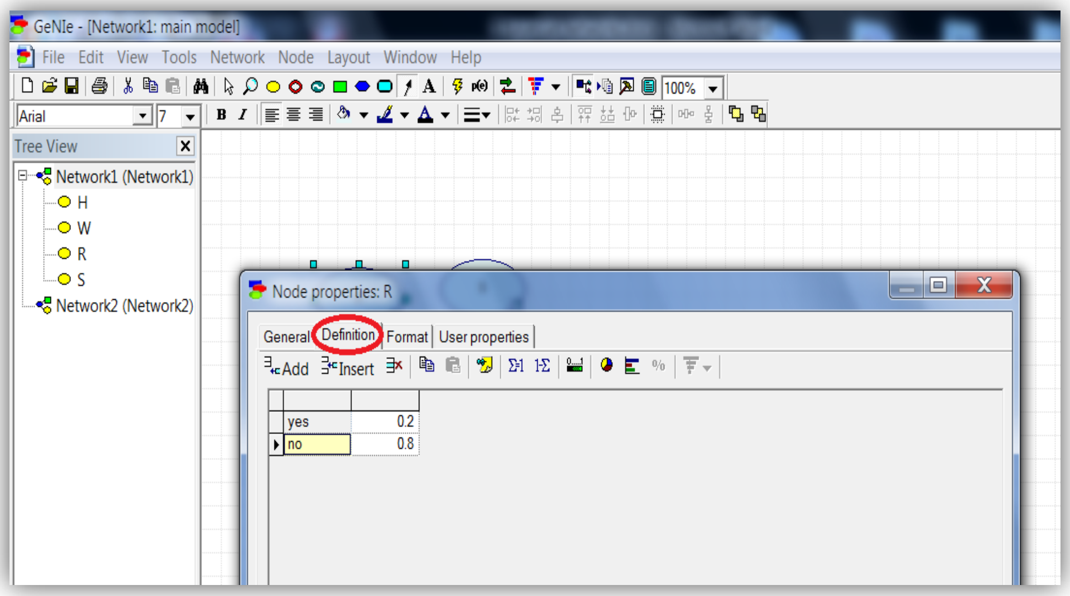
Step 4

Define the dependencies between the nodes. For example R has impact on W and H. Select the arc icon and drag the arrow from the parent node to the child node.



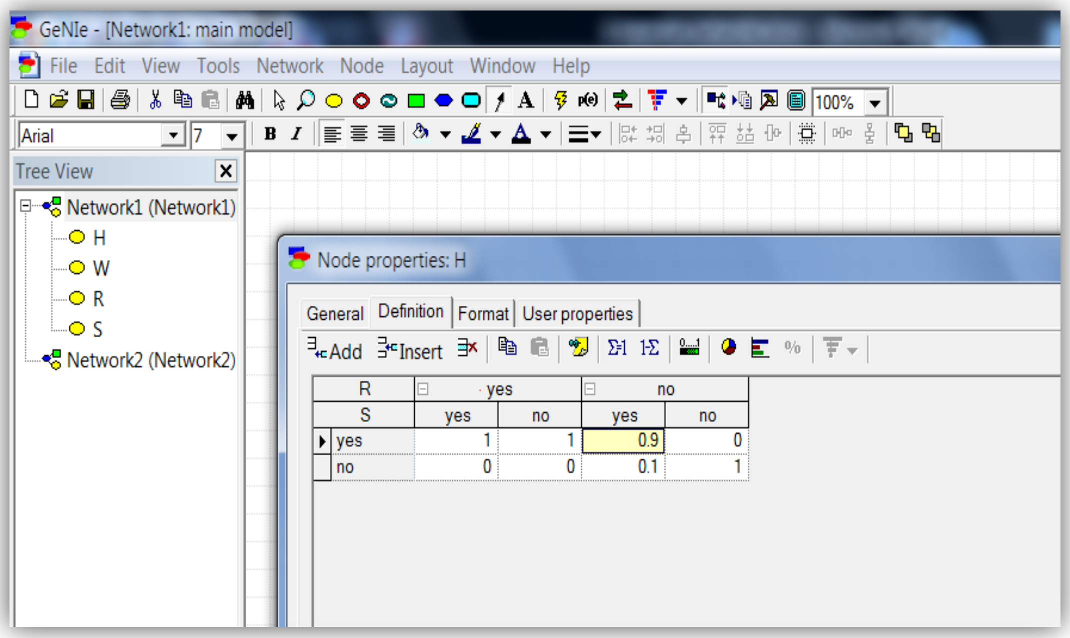
Step 5

Set the states for each node. In this part, double click on the target node and then on DEFINITION. There you can name each state and set the prior probabilities for the parent nodes. For example on the R node the states are yes and no and the probabilities 0.2 and 0.8 respectively.



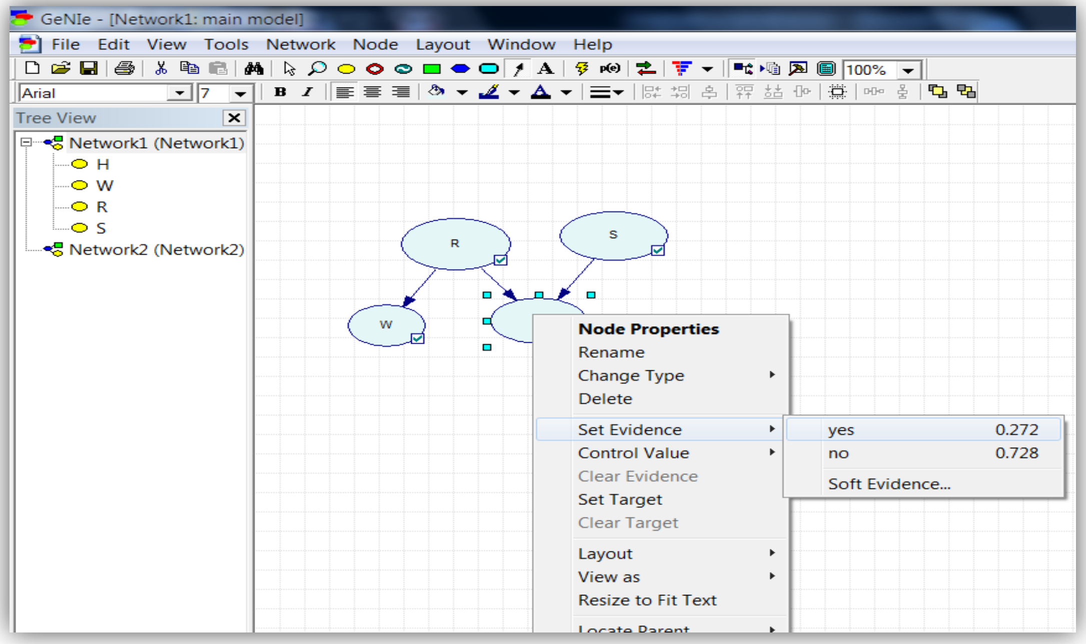
Step 6

Set the conditional probabilities tables for the child nodes. The following table is a 2x4 matrix which includes all the possible scenarios and their outcomes in probabilistic terms. Note that when there is more than one parent nodes conditional independence must be present.



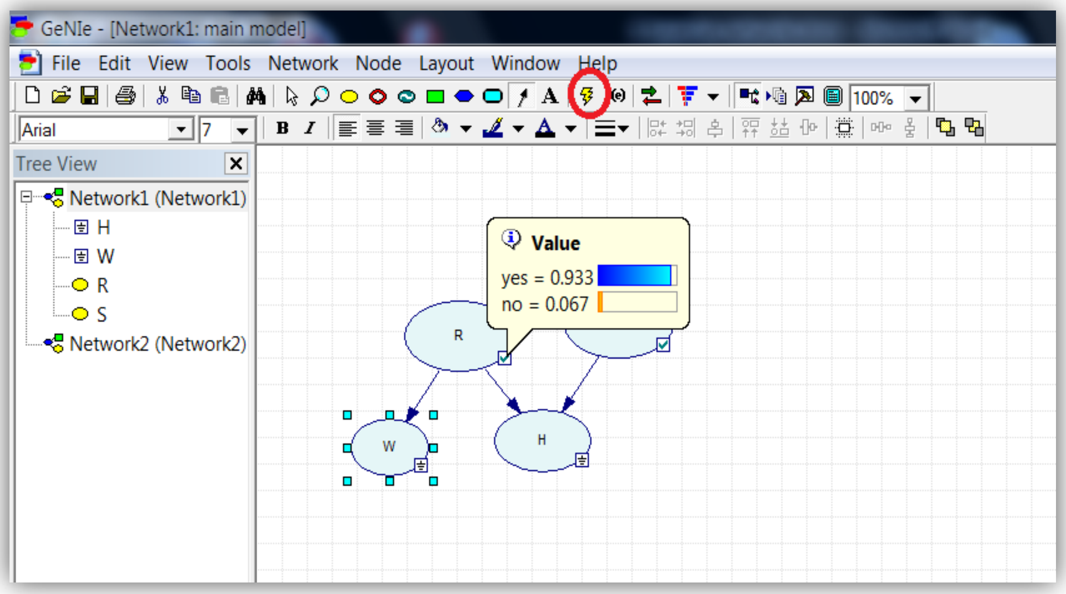
Step 7

Setting evidence: Since we are certain that H=y we left click on the node and chose SET EVIDENCE and set it to yes. We then follow the same procedure for W=yes.



Step 8

Updating the network and getting the Bayesian Inference. In order that information is propagated throughout the network we click on the update icon (lightning). Then when all nodes and tables are updates we can see the posterior probabilities of its node by dragging the mouse on the tick icon in the bottom right side of the node.



We notice that R= y is 0.933 which is the exact same value we get after marginalizing Table 5.7 in the previous paragraph.

5.3.4 NOISY OR GATES

The most integral part of a Bayesian network is the setting of the CPT's. While prior probabilities are generally easy to acquire, the dependence of the parents-child nodes is a complex procedure especially when the number of parents is high. In the example cited in 5.3.1 the parent nodes to H were S and R creating a 2x4 CPT. If for example the parent nodes were 8 and the states of H were 4 we would have a 4x8 CPT making the conditional probabilities assignment extremely difficult.

The noisy-or principle is a modeling trick that help us overcome these difficulties. Noisy-OR gates are usually used to describe the interaction between n causes X1, X2….Xn and their common effect Y. The causes Xi are each assumed to be sufficient to cause Y in absence of other causes and their ability to cause Y is assumed independent of the presence of other causes [42].

The Noisy OR gate applies when there are several possible causes X1, X2, . . . , Xn of an effect variable Y, where (1) each of the causes I has a probability P(i) of being sufficient to produce the effect in the absence of all other causes, and (2) the ability of each cause being sufficient is independent of the presence of other causes. The above two assumptions allow us to specify the entire conditional probability distribution with only n parameters P(1, 2, . . . , n). P(i) represents the probability that the effect Y will be true if the cause X is present and all other causes Xj, j/=i, are absent [69].

Jensen 1996 describes the Noisy or gate in the following excerpt, [40] (pg 48-51):

Let A1……,An,, be binary variables listing all the causes of the binary variable B. Each event Ai· = y causes B = y unless an inhibitor prevents it, and the probability for that is qi (see Figure 5.7).

That is, P (B = n | A = y) = qi. We assume that all inhibitors are independent. Then P(B = n/A1,A2 …,An) = $\Pi_{j \in Y} q_j$ *where Y is the set of indices for variables in the state y. For example:*

$$P(B = y / A1 = y,\ A2 = y,\ A_3 = \ldots\ldots = An = n)$$
$$= 1 - P(B = n/A1 = y, A2 = y, A_3 = y \ldots = An = n)$$
$$= 1 - q1 \cdot q2$$

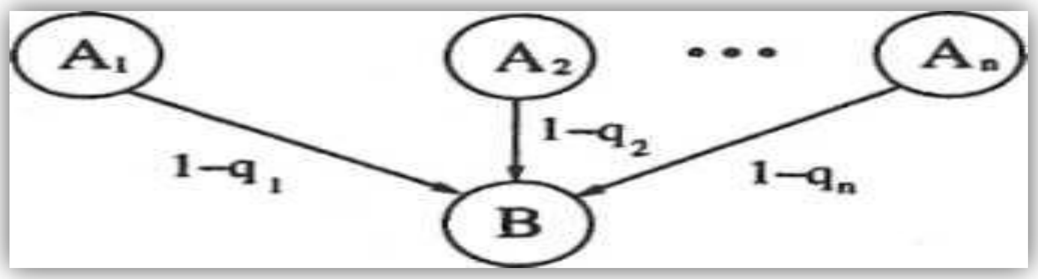


Figure 5. 7: Noisy OR Gates example

- *We require $P(B = y/ A1 = \ldots\ldots = An = n)$ to be zero. This may seem to restrict the applicability of the approach. However, as in the example above, if $P(B = y) > 0$ when none of the causing events in the model are on, then introduce a background event which is always on.*
- *The complementary construction to noisy or is called noisy and. A set of causes shall all be on in order to have an effect. However, the causes have random inhibitors which are mutually independent.*

- *The noisy or-gate can be modeled directly without performing the calculations. This highlights the assumptions behind the noisy or-gate. If a cause is on, then its effect may be prevented by an inhibitor, and the probabilities for the inhibitors to be present are independent.*

5.4 COMMON BAYESIAN NETWORK APPLICATIONS

Some of the fields that have benefited from the use of Bayesian networks are:

- Medicine
- Biology
- Law
- Engineering
- Computer science
- Artificial Intelligence

5.4.1 GENERAL

In this paragraph we are going to present some common example of Bayesian Networks applications in various scientific domains [108].

A) ENVIRONMENT

- Assessing the viability of fish populations (Lee and Reiman 1997)
- Management of the food chain of lakes (Varis et al. 1990)
- Eco-risk assessment (Pollino and Hart 2005)
- Farming systems modeling (Varis anf Kuikka 1997)

B) BIOLOGY

- Brain function studies, (Rajapakse et al, 2007)
- Protein structure, (Bradford,Needham et al., 2006)
- Genes networks analysis, (Mittal et al., 2005)
- Non-Parametric regression in genetics, (Imoto et al., 2002)

B) MEDICINE

- Risk Analysis and Management Methodology (CRAMM), (Maglogiannis, Zafiropoulos et al., 2005)
- Prognosis Bayesian networks, (Verduijin et al., 2007)
- Cancer diagnosis (Nicandro Cruz-Ramirez et al, 2007)

C) INDUSTRY

- Jet engines failure (Ferat et al., 2007)
- Supply chain management (Han-Ying Kao et al., 2005)
- Oil products impact (Cattanach et al., 1995)

D) ECONOMICS AND OPERATIONS RESEARCH

- Corporate alliances analysis, (Letterie et al., 2006)
- Informations recovery via conversation (Kyoung-Min Kim et al., 2006)
- Robotics, (Lazkano et al., 2006)

F) EDUCATION

- Internet based learning (Garcia et al., 2005)
- Digital image libraries (Kahn Jr. 2001)

G) RISK MANAGEMENT AND ASSESMENT

- Corporations risk and decision making (Bonafede and Giudici, 2007)
- Risk distribution databases, (Druzdzel et al., 1995)

5.4.2 MARITIME

There are several studies within the Maritime domain that used Bayesian Network in order to treat uncertainty.

Trucco, Cagno et al (2007) [102] attempted to include Human and Organizational Factors (HOF) in their analysis of risk. Their approach was developed to address the sector of maritime industry, but it can be used in other sectors, as well. A Bayesian Network was created in order to model the Maritime Transport System (MTS), taking into consideration the various factors that are involved as well as their reciprocal interdependence. The particular model was used to quantify the importance of HOF in the risk analysis during the fundamental stages of designing a High Speed Craft (HSC). The study focused on the open sea collision applied via an innovative method of unification of the Fault Trees Analysis (FTA) and Bayesian Belief Network regarding the influences of organizational operations and regulations, as they are addressed by the IMO and the FSA. This approach allowed the recognition of cross-correlation of probabilities between the basic events in the case of a collision as well as the network of faith that includes the operational and organizational factors.

In their study Norrington et al. (2007) presented a methodology of reliability modeling regarding research and operations of rescue of coast guard coordinative centers. Various sources are found by governmental reports, interviews or supervision personnel. The incorporation of information was achieved with the use of belief networks [108].

Bayesian Networks were recently used by the Norwegian FSA for estimating the safety of passenger ships (2005). This particular study focused in finding effective Risk Control Options (RCOs) in the sector of marine navigation. In order to reduce the frequency of collisions and groundings, the study indicates that following RCOs provide considerably improved safety of marine navigation with a limited cost:

- Electronic Chart Display and Information Systems (ECDIS)
- The track control system (track control)
- The Automatic Identification System (AIS) combined with the operational radar
- The improved planning of bridges
- The improved learning of navigator [108].

5.4.3 FATIGUE

Bayesian networks are considered by many scholars as a state of the art instrument to deal with uncertainty. Fatigue, which is the main subject of this thesis, is an issue that has to manage uncertainty in order to predict its prevalence and potential outcomes. Belief networks give researchers this particular versatility.

In their study Peilin, Qiang and Looney [42] [43] introduce a probabilistic model based on Bayesian Networks that gives the probability of human fatigue by acquiring information from various visual cues and certain relevant contextual information. A brief review regarding the physiological and psychological aspects of fatigue is made in order to pinpoint the risk factors that create it. The influence of these factors, that were acquired via quantification of data from various relevant fatigue studies, were the information variable in their model. Specific emphasis was given to visual characteristics such as eye-lid movement, gaze, head movement, and facial expression. These signs were recorded as the main signal for inferring fatigue. The most difficult part of this endeavor was the parameterization of the model (CPT's) which was made possible by the extraction of data from related studies and subjective knowledge as well. The use of the noisy or gates played a significant part in eliminating complexity problems of joint distributions. The inference results produced by running the fatigue model using Microsoft BNs engine MSBNX ,a program very similar to GeNie.

While their model managed to produce a static representation of fatigue, it failed to capture the dynamic dependency between fatigue and time. In order to overcome this limitation the static model was reproduced into a Dynamic Bayesian Network which can record the impact of time. By connecting various visual fatigue evidences with time, this dynamic fatigue model leaded to a more robust and accurate estimation of fatigue.

This particular model and many statistical data that came with it served as the basis of our own static model for fatigue probability inference aboard ships. Peilin, Qiang and Looney used [43] a computer vision system in order to record visual signs in different time periods, a practice which allowed them to give their model a dynamic perspective. Unfortunately, monitoring fatigue on board is a more complex task that cannot be recorded by any available computer system. Most of our sources and evidences came from relevant research regarding the issue as well as seafarer's diaries and interviews.

5.5 WHY BAYESIAN NETWORKS ARE SO HELPFUL TO THESIS THESIS. ADVANTAGES DISADVANTAGES

In this paragraph, we discuss the advantages of using Bayesian networks and why they are the most effective means to predict fatigue in a maritime environment. The parameterization of a fatigue model may be a very complex and demanding task, nevertheless, the proper use of statistical data and the capabilities of Bayes theories can become a very accurate and practical way to reduce fatigue at any workplace.

Bayesian networks provide a powerful instrument to capture the uncertainties, dependencies and dynamics exhibited by fatigue. Through BN it becomes easier to incorporate information and observations, model uncertainty and aspects of fatigue that are difficult to quantify and above all, setting a graphical model with a huge number of different sources of data. All these benefits along with the contemporary research regarding probabilistic models (especially BN software) make Bayesian Networks the ideal instrument for fatigue inference and a genuine 'weapon' to overcome any potential limitations.

Moreover, BN can be used, even in the case of missing data in order to learn the causal relationships and gain an understanding of the various problem domains and to predict future events [63].

Furthermore, large conditional probabilities tables may require the need of a tool for extensive calculation and analysis. The popularization of BN has led many programmers to develop user friendly software as GeNie so these limitations could be easily put aside.

Petri Myllymäki summarizes some of the BN's distinctive advantages over alternative modeling approaches [FF]:

Decision theory:

Using BN in decision theory for risk analysis can provide the optimal procedure in decision making.

Consistent, theoretically solid mechanism for processing uncertain information:

BN reduces the probability of an inference to be ambiguous by using consistent calculus for uncertainty.

Smoothness properties:

Bayesian networks can be easily modified according to the contemporary changes without having to re-model 'from scrap' through the use of updating.

Flexible applicability:

The same Bayesian network model can be used for solving both discriminative tasks (classification) and regression problems (configuration problems and prediction).

A theoretical framework for handling expert knowledge:

Expert knowledge can be interpreted into prior probabilities which are independent to any potential sampling data which allows the interaction of expertise with statistical data. While using BN expert can finally compare their prior estimation to that of the data.

A clear semantic interpretation of the model parameters:

They can be used directly without the need of prior learning making them superior to other forms of networks such as neural networks.

Different variable types:

While most probabilistic models work with a specific type of variables and distributions, BN overcome that limitations and allow various type of different variable to coexist in the same domain with no need of transformation.

A theoretical framework for handling missing data:

Marginalization in BN helps us put aside any limitation that comes from missing. While the main argument against BN is that the parameterization can be very complex and time consuming, the theoretical context of BN indicates the possibility of creating a BN with a small number of parameters. This fact has led high tech corporations like Microsoft and organizations like NASA to develop applications based on Bayesian Networks for exploiting their numerous capabilities.

CHAPTER 6

A BAYESIAN NETWORK FOR PREDICTING FATIGUE IN MARITIME TRANSPORT

6 A BAYESIAN NETWORK FOR PREDICTING FATIGUE IN MARITIME TRANSPORT

In this chapter we present the nodes of our Bayesian Network regarding fatigue aboard ships. The categorization was made according to IMO's guidelines for fatigue mitigation. Finally, we set forth our sources, the states of each parent node, the prior probabilities and the Conditional Probabilities Tables (CPT) that represent the dependence between the parent and the child nodes. At this point it should be mentioned that the Noisy OR principle, which was discussed in the previous chapter, was used in order to calculate the probabilities for the CPT's where the parent nodes were great in number.

6.1 MODEL PRESENTATION

6.1.1 TARGET NODE

1. Fatigue

Fatigue is the target node of this Bayesian Network while the primary goal of its function is the calculation of the posterior probability. For this node we have tried to use the same parent-node structure that Ji, Qiang and Looney (2003) [42] introduced in their paper regarding drivers' fatigue. In order to guarantee the overall precision of our model, we have used certain CPTs of this survey while making specific changes according to our own subjective judgment and knowledge.

Furthermore, in order to enhance the model's reliability the following assumptions were taken into consideration.

- Fatigue is inevitable even if all factors favor its mitigation.
- The parent nodes for fatigue are universal for almost every transport domain.

States of fatigue:

- Yes
- No

The following image is the first of the CPTs that we will provide in order to demonstrate the connection between the parent nodes and the child one. Those nodes who are solely parent nodes were given a prior probability distribution that is presented in similar manner with the CPT's

Note: Since we found no better way to present the CPT's and prior probability tables, we provide snapshots from the actual software used. We ask the reader to excuse us for the quality of these images.

30.Work Environment	Poor							
2.Overall Sleep Quality	Poor							
4.Physical State	Poor				Helthy			
3.Biological Clock	Drowsy		Awake		Drowsy		Awake	
5.Work condition	Poor	Fair	Poor	Fair	Poor	Fair	Poor	Fair
Yes	0.98	0.95	0.96	0.89	0.97	0.91	0.94	0.83
No	0.02	0.05	0.04	0.11	0.03	0.09	0.06	0.17

30.Work Environment	Poor							
2.Overall Sleep Quality	Fair							
4.Physical State	Poor				Helthy			
3.Biological Clock	Drowsy		Awake		Drowsy		Awake	
5.Work condition	Poor	Fair	Poor	Fair	Poor	Fair	Poor	Fair
Yes	0.96	0.87	0.91	0.74	0.93	0.79	0.85	0.57
No	0.04	0.13	0.09	0.26	0.07	0.21	0.15	0.43

30.Work Environment	Fair							
2.Overall Sleep Quality	Poor							
4.Physical State	Poor				Helthy			
3.Biological Clock	Drowsy		Awake		Drowsy		Awake	
5.Work condition	Poor	Fair	Poor	Fair	Poor	Fair	Poor	Fair
Yes	0.96	0.88	0.92	0.77	0.93	0.81	0.87	0.62
No	0.04	0.12	0.08	0.23	0.07	0.19	0.13	0.38

30.Work Environment	Fair							
2.Overall Sleep Quality	Fair							
4.Physical State	Poor				Helthy			
3.Biological Clock	Drowsy		Awake		Drowsy		Awake	
5.Work condition	Poor	Fair	Poor	Fair	Poor	Fair	Poor	Fair
Yes	0.9	0.71	0.8	0.43	0.83	0.53	0.67	0.05
No	0.1	0.29	0.2	0.57	0.17	0.47	0.33	0.95

Source: [42] [43]

6.1.2 PARENT NODES

6.1.2.1 CREW SPECIFIC FACTORS

2. Overall Sleep quality

This node represents the overall sleep quality in terms or quantity, environment condition and the opportunity for occasional naps. In our research regarding fatigue we have concluded that sleeping quality is by far the most important contributor in inducing fatigue, a fact that can be easily proved by the results provided by our network (see Chapter 7).

States of sleep quality:

- Poor
- Fair

Source: [42] [90]

6.Sleep Quantity	Deprived							
37.Sleep Environment	Poor				Fair			
8.Sleep Condtion	Bad		Fair		Bad		Fair	
7.Napping	No	Min30	No	Min30	No	Min30	No	Min30
Poor	0.99	0.98	0.89	0.86	0.97	0.95	0.85	0.86
Fair	0.01	0.02	0.11	0.14	0.03	0.05	0.15	0.14

6.Sleep Quantity	Sufficient							
37.Sleep Environment	Poor				Fair			
8.Sleep Condtion	Bad		Fair		Bad		Fair	
7.Napping	No	Min30	No	Min30	No	Min30	No	Min30
Poor	0.75	0.73	0.33	0.31	0.64	0.62	0.1	0.05
Fair	0.25	0.27	0.67	0.69	0.36	0.38	0.9	0.95

Source: [42] [90]

3. Biological clock

The human biological clock, widely known amongst scholars and researchers as Circadian Rhythms, is a useful *instrument* for pinpointing the time periods when the body is awake and the red zone when each individual is vulnerable to the effects of fatigue and lack of alertness.

States of Biological Clock:

- Drowsy
- Awake

44.Light	Poor				Sufficient			
9.Circadian intemediate.	Drowsy		Awake		Drowsy		Awake	
25. Recent Change of Shift	Yes	No	Yes	No	Yes	No	Yes	No
Drowsy	0.98813	0.94065	0.88130	0.40652	0.9808	0.904	0.808	0.04
Awake	0.01186	0.05934	0.11869	0.59347	0.0192	0.096	0.192	0.96

Source: [42] [14] [103]

4. Physical state

Most surveys and research projects have indicated that fatigue can be the result of lack of exercise, nutrition issues and aspects of general fitness and well being. For example, an operator who has no physical exercise routine is significantly more exposed to fatigue and human error than a person who has taken good care of his body and general health.

States of Physical state:

- Poor

- Healthy

10.Sleep Di...	Regular				Rare			
12.Age	Plus_fourtyfive		Minus_fourtyfive		Plus_fourtyfive		Minus_fourtyfive	
13.Fitness	Poor	Fair	Poor	Fair	Poor	Fair	Poor	Fair
Poor	0.9069	0.734	0.867	0.62	0.76725	0.335	0.6675	0.05
Healthy	0.0931	0.266	0.133	0.38	0.23275	0.665	0.3325	0.95

Source: [40]

5. Work Condition

The work condition node describes the overall nature of the task at hand. Since the parent nodes are the type of work in terms of tedium and the heaviness of the workload, it is made clear what this node actually represents; a very common example of a poor work condition at sea can result in the helmsman error when a watchkeeper falls asleep on duty both because of fatigue issues and the monotonous nature of his task.

States of Work Condition:

- Poor
- Fair

24.Workload	Heavy		Normal	
20.Type of task	Tedious	Normal	Tedious	Normal
Poor	0.85	0.62	0.6	0.05
Fair	0.15	0.38	0.4	0.95

Sources: [42]

6. Sleep Quantity

Sleep quantity can be described in two different ways:

- Hours that an individual has spent sleeping (in order for all sleeping parts[4] to take place)
- Hours that an individual has remained awake.

Heavy workload, low manning levels and emergency situations are some of the factors that can influence sleep quantity. Sleep deprivation is perhaps the most crucial part of the overall sleeping quality while staying awake for more than 20 hours can lead to numerous human errors and general underperformance.

[4] Sleep architecture (Chapter 3)

States of Sleep Quantity:

- Deprived
- Sufficient

11. Hours Awake	Twelve	Fourteen	Sixteen	Eighteen	Twenty	Twentyfour	Morethanaday
Deprived	0	0.05	0.2	0.65	0.85	0.98	1
Sufficient	1	0.95	0.8	0.35	0.15	0.02	0

Sources: [42] [110] [4] [5]

7. Napping

In chapter 3 we indicated that napping for more than 30 minutes can be beneficial for seafarers as research has shown that this time is sufficient for being restorative to the human body and mental performance as well. In accordance to sleep quantity, the opportunities for naps are connected to the nature of the workload aboard the ship.

States of Napping:

- No
- Minimum30 min

24.Workload	Heavy	Normal
No	0.97	0.7
Min30	0.03	0.3

Sources: [42]

8. Sleep Condition

Sleep condition can best be described as the ability of each individual to sleep by putting aside distractions, anxiety and other factors. A very common problem for seafarers, when they have sufficient time for rest, is their difficulty to attain sleep. The most common distractions for sleeping are stress and anxiety.

States of Sleep Condition:

- Bad
- Fair

14.Anxiety	High	Normal
Bad	0.6	0.05
Fair	0.4	0.95

Sources: [110] [90]

9. Circadian intermediate

This intermediate node is used in order to take advantage of [42] CPT regarding jet lag and time state. Our own research has indicated that both shift rotation and lighting have huge impact on the Circadian Rhythms so we felt that it was important to include them in our model as well.

States of Circadian intermediate:

- Drowsy
- Awake

27.Jet Lag	Yes		No	
15. Circadian time state	Drowsy	Awake	Drowsy	Awake
Drowsy	0.9	0.3	0.6	0.05
Awake	0.1	0.7	0.4	0.95

Sources: [42]

10. Sleep Disorders

A sleep disorder is a medical disorder of an individual's sleeping patterns. Some sleep disorders are serious enough to interfere with normal physical, mental and emotional functioning. Several surveys have indicated that a great number of mariners suffer from sleep disorders thus affecting their physical condition, sleep quality and performance.

Sleep Disorders:

- Regular
- Rare

14.Anxiety	High	Normal
Regular	0.3	0.05
Rare	0.7	0.95

Sources: [42] [90] [5]

11. Hours awake

This node is introduced in order to give our model a more dynamic perspective. The node states are based on the need for hours of sleep for an average adult (8) and several graphs that (mostly by Sirois, 1998) that pictures the impact of sleep deprivation and fatigue on alertness. Most probabilities for the CPTs were based on NTUA's survey regarding the average hours of sleep of officers.

States of Hours awake:

- 12
- 14
- 16
- 18
- 20
- 24
- More than a day

24.Workload	Heavy	Normal
Twelve	0.01	0.04
Fourteen	0.01	0.04
Sixteen	0.13	0.4
Eighteen	0.6	0.5
Twenty	0.15	0.01
Twentyfour	0.08	0.01
Morethanaday	0.02	0

Sources: [110]

12. Age

While a specific survey [90] has proved that a more experienced is seafarer shows lower stress levels and greater self confidence than a young inexperienced mariner, medical research has shown that the overall physical efficiency decreases with age. Literature has found the age of 45 as the hub of this age-physical condition relationship.

States of age:

- 45 <
- 45 >

Plus_fourtyfive	0.2
Minus_fourtyfive	0.8

Sources: [110]

13. Fitness

General fitness is an essential part for good physical condition and the mitigation of fatigue. Physical fitness is generally achieved through exercise, proper nutrition and adequate rest. An overweight operator will get tired more easily than a fit person while the consumption of drugs or alcohol can also cause fitness and physical condition problems.

States of Fitness:

- Poor
- Fair

16.Nutricion	Poor							
17.Illness	Yes				No			
18.Drug/Alcohol use	Yes		No		Yes		No	
19. Physical Exercise	No	Regular	No	Regular	No	Regular	No	Regular
Poor	0.9772	0.943	0.924	0.81	0.9088	0.772	0.696	0.24
Fair	0.0228	0.057	0.076	0.19	0.0912	0.228	0.304	0.76
16.Nutricion	Fair							
17.Illness	Yes				No			
18.Drug/Alcohol use	Yes		No		Yes		No	
19. Physical Exercise	No	Regular	No	Regular	No	Regular	No	Regular
Poor	0.9715	0.92875	0.905	0.7625	0.886	0.715	0.62	0.05
Fair	0.0285	0.07125	0.095	0.2375	0.114	0.285	0.38	0.95

Sources: [110] [34]

14. Anxiety

Anxiety is a feeling of nervousness, apprehension, fear, or worry. Some fears and worries are justified, such as worry about a loved one or in anticipation of taking a quiz, test, or other examination. Problem anxiety interferes with the sufferer's ability to sleep or otherwise function. Stress is also connected with anxiety while most mariners identify anxiety as a main contributor for sleep deprivation, bad decision making, communication problems and underperformance. While it is impossible for a human to eliminate anxiety completely, we have divided anxiety into normal and high level. Despite the general scientific approach for anxiety, we have made separate nodes for stress and anxiety. While many scholars describe the terms as almost synonymous, in our network high stress levels lead to anxiety, which serves as an intermediate state. The correlation between stress and anxiety allows our model to propagate the effect of stressors to fatigue through a more complex but precise procedure

States of Anxiety:

- High
- Normal

21.Stress	High	Normal
High	0.65	0.05
Normal	0.35	0.95

Sources: [110]

15. Circadian Time State

CEM [103] has proposed several ways to manage the red zone of the circadian rhythms, which is described as the daily period of lowest energy and alertness, normally occurring between bedtime and sunrise. Contemporary research has shown that these periods are often between 3:00 – 5:00 a.m. and p.m. periods during which the majority of transportation accidents have taken place.

Drowsy	0.125
Awake	0.875

States of Circadian time state:

- Drowsy
- Awake

Sources: [14] [4]

16. Nutrition

Nutrition is the provision, to cells and organisms, of the materials necessary (in the form of food) to support life. Many common health problems can be prevented or alleviated with a healthy diet. In plain words, nutrition can be described as the *fuel* that is spent in order to cover an individual's bodily needs. Therefore, by adopting a healthy diet, a seafarer reduces the possibility of poor physical condition and growing fatigue. A very common result of a poor diet is anemia, an affection that can cause various symptoms that impede the individuals overall physical capabilities.

States of nutrition:

- Poor
- Fair

Poor	0.1
Fair	0.9

Sources: [34]

17. Illness

According to medical dictionaries illness is a state of poor health. When the symptoms and effects of an illness have considerable impact on one's organism, illness is considered a synonym for disease. In our network, we try to demonstrate the connection between illness and poor diet. Medical research has shown that poor diet lowers the human organism's defenses, making it vulnerable to illnesses. Finally, illness may come as a result of extreme weather phenomena (such as rain) and unsuitable clothing for the occasion. The impact of illness on a mariner's performance is severe and it has been recorded that physical capabilities can drop to less than 10% of the optimum level.

States of Illness:

- Yes
- No

16.Nutricion	Poor	Fair
Yes	0.15	0.03
No	0.85	0.97

Sources: various interviews

18. Drug/Alcohol use

For this node we try to represent the impact of drugs (per scripted or non per scripted) or alcohol use on mariners' performance. While there are strict regulations against such practices, this phenomenon is present on board. These incidents lead in human errors that are often underreported. The use of alcohol for example can result in errors in the most simple tasks and procedures. Finally, medications suchas strong antibiotics can make an individual unable to perform any task given.

States of Drugs/Alcohol use:

- Yes
- No

Yes	0.05
No	0.95

Sources: various interviews

19. Physical exercise

Scholars have described physical exercise as any bodily activity that enhances or maintains physical fitness and overall health or wellness. During the past few years IMO has proposed the establishment of gymnasiums and other exercise facilities on board. It is crucial for mariners to maintain a good exercise routine in order to be ready for the demanding everyday needs while at sea.

States of Physical Exercise:

- No
- Regular

No	0.6
Regular	0.4

Sources: [34]

20. Type of task

The Type of Task node describes the nature of the task at hand. During a trip of a merchant vessel, each member of the crew performs a specific task. At this point, we divide the tasks in two categories: tedious and normal. Related fatigue surveys have shown that a monotonous job is more vulnerable to alertness decrease and fatigue. Such jobs can be the helmsman and watchkeepers in general. The experiencing of microsleeps during a night shift on the bridge can be found in literature as the ‘helmsman error’, a result of a tedious procedure and the prevalence of fatigue as well. The prior probability for this node was also partly based on the questionnaire responses regarding the nature of their duty and whether they are satisfied with it.

States of type of task:

- Tedious
- Normal

Tedious	0.2
Normal	0.8

Sources: [42] [54] [110]

21. Stress

Almost all research projects mentioned in paragraph 4.4 have indicated that stress is an important “party” in mariner’s performance. The variety of stressors that have been recorded in all these surveys make the quantification of stress an extremely difficult task to perform. In our model, we list the most important of these factors such as management pressure and psychological condition.

States of Stress:

- High
- Normal

22.Training	Poor							
23. Psycological condition	Unstable				Stable			
35.Recreational Facilities	Poor		Fair		Poor		Fair	
29.Management Demands	Demandi...	Normal	Demandi...	Normal	Demandi...	Normal	Demandi...	Normal
High	0.97872	0.9468	0.9696	0.924	0.8936	0.734	0.848	0.62
Normal	0.02128	0.0532	0.0304	0.076	0.1064	0.266	0.152	0.38

22.Training	Adequate							
23. Psycological condition	Unstable				Stable			
35.Recreational Facilities	Poor		Fair		Poor		Fair	
29.Management Demands	Demandi...	Normal	Demandi...	Normal	Demandi...	Normal	Demandi...	Normal
High	0.9468	0.867	0.924	0.81	0.734	0.335	0.62	0.05
Normal	0.0532	0.133	0.076	0.19	0.266	0.665	0.38	0.95

Sources: [110] [90]

22. Training

In our network we introduce the training node in order to represent its impact on stress. Smith [20] has proposed that inadequate training can increase stress levels significantly, especially in emergency situations. Furthermore, stress can inflict both sleeping disorders and general physical condition issues.

States of Training:

- Poor
- Adequate

Poor	0.1
Adequate	0.9

Sources: [110] [90]

23. Psychological condition

In this node, the effect of an individual's general psychological condition on stress is represented in the CPT. Many interviewees have described that while they experience an extreme psychological conflict, stress come more easily and their overall performance is impaired. Many organizations, especially military, perform psychological test in order to prevent such incidents before the beginning of every trip.

States of Psychological condition:

- Unstable
- Stable

Unstable	0.01
Stable	0.99

Sources: various

6.1.2.2 MANAGEMENT FACTORS

24. Workload

In this node, the workload represents the amount of tasks that an individual has to process in a given amount of time. The definition of workload is correlated to the time of rest of a seafarer as well as the opportunities for napping and sufficient sleep. A quite representative example of heavy workload is the discharging of a VLCC. During this procedure the bridge officer has to stay awake for almost 40 hours in order to supervise the discharging. An average time that an adult must stay awake in order to mitigate fatigue should not exceed 16 hours. Finally, workload also consists the excessive amount of paperwork that a mariner has to handle while on board.

29.Management Demands	Demanding				Normal			
28.Manning Levels	Low		Normal		Low		Normal	
26. High Alert State	Yes	No	Yes	No	Yes	No	Yes	No
Heavy	0.988975	0.88975	0.9559	0.559	0.9755	0.755	0.902	0.02
Normal	0.011025	0.11025	0.0441	0.441	0.0245	0.245	0.098	0.98

States of Workload:

- Heavy
- Normal

Sources: [90] [54]

25. Recent change of shift

In order to abate fatigue of regular night shift operators, shift rotation was introduced onboard merchant vessels. While this procedure was established for mitigating fatigue, an abrupt change of day to night shift can seriously disrupt the human biological clock. In our model, we introduce the *Recent change of shift* node in order to show the correlation between this procedure and the effect of the drowsy time period of the Circadian Rhythms.

States of Recent change of shift:

- Yes
- No

Yes	0.15
No	0.85

Sources: [110] [4]

26. High Alert State

The high alert state represents the condition on board when all crew members must remain stand-by. A typical example could be a fire emergency or when approaching port. It is clear by the definition of this node that whenever there is such a state the workload tends to be a heavier than usual and the amount of rest time available decreases significantly.

States of High Alert State:

- Yes
- No

Yes	0.05
No	0.95

Sources: [110]

27. Jet Lag

In the jet lag node we try to show the effect of moving through various time zones in a short period on the human biological clock. Maritime transport is not as exposed to jet lag as other transport fields such as aviation, nevertheless we cannot neglect its effect completely since many mariners have reported related issues. The presence of jet lag increases the duration of the drowsy time of the circadian clock.

States of Jet Lag:

- Yes
- No

Yes	0.05
No	0.95

Sources: [42]

28. Manning Levels

In the past two decades, the prevalence of automation has had a severe impact on manning levels. While no machine could ever replace a human on-board completely, ship complements decreased radically. Shipping companies may have benefited from this new trend but on the other hand workload aboard ships became heavier and sometimes unbearable. The most common complaint of a seafarer is the fact that manning levels have a growing tendency to minimize even further. IMO and STCW have tried to put limitations to this ever-growing trend in order to battle fatigue related accidents but the fact remains that almost 80% of in-service merchant vessels are undermanned. In our node we show the connection between manning levels, workload and management demands.

States of Manning levels:

- Low
- Normal

29.Management Demands	Demanding	Normal
Low	0.8	0.4
Normal	0.2	0.6

Source: [90] [110] [33]

29. Managements Demands

In this node, we summarize the rest of the management and organizational factors such as company support and pressing schedules. A typical example of a management related accident could be a pressing deadline which could lead in turn to the violation of several regulations. A survey [110] has shown that the support of the shipping company is an efficient measure to battle stress and anxiety.

States of Management Demands:

- Demanding
- Normal

Demanding	0.6
Normal	0.4

Sources: [110]

6.1.2.3 SHIP SPECIFIC AND ENVIRONMENTAL FACTORS

30. Work Environment Total

This node represents the overall quality of the work environment on-board. While we kept the intermediate node from [42] model, we introduced the connection of the work environment and ship specific elements as the vessel's motions and vibrations which are almost exclusive to the maritime domain. Finally, we make the assumption that poor quality overall facilities (such as recreational, laundry, galley etc) increase the probability of fatigue prevalence onboard.

States of Work Environment:

- Poor
- Fair

40.Vessel Motions	Extreme							
39.Vibrations	Normal							
31.Work Environment intertemediate.	Poor							
32.Overall Facilities	Poor				Fair			
44.Light	Poor		Sufficient		Poor		Sufficient	
45.Humidity	High	Normal	High	Normal	High	Normal	High	Normal
Poor	0.88674	0.87123	0.87466.	0.85538	0.87631.	0.85757	0.86176.	0.83793
Fair	0.11325	0.12876.	0.12533	0.14461...	0.12368	0.14242	0.13823.	0.16206

40.Vessel Motions	Extreme							
39.Vibrations	Normal							
31.Work Environment intertemediate.	Fair							
32.Overall Facilities	Poor				Fair			
44.Light	Poor		Sufficient		Poor		Sufficient	
45.Humidity	High	Normal	High	Normal	High	Normal	High	Normal
Poor	0.86571	0.84333	0.8483871	0.81923	0.85079	0.82264	0.82909.	0.79111
Fair	0.13428	0.15666	0.1516129	0.18076.	0.14920	0.17735	0.17090	0.20888

40.Vessel Motions	Extreme							
39.Vibrations	Normal							
31.Work Environment intertemediate.	Poor							
32.Overall Facilities	Poor				Fair			
44.Light	Poor		Sufficient		Poor		Sufficient	
45.Humidity	High	Normal	High	Normal	High	Normal	High	Normal
Poor	0.87123	0.85079	0.85538	0.82909	0.85757	0.83214	0.83793	0.80416
Fair	0.12876	0.14920	0.14461	0.17090	0.14242.	0.16785.	0.16206	0.19583

40.Vessel Motions	Extreme							
39.Vibrations	Normal							
31.Work Environment intertemediate.	Fair							
32.Overall Facilities	Poor				Fair			
44.Light	Poor		Sufficient		Poor		Sufficient	
45.Humidity	High	Normal	High	Normal	High	Normal	High	Normal
Poor	0.84333	0.812	0.81923	0.77619.	0.82264	0.78139	0.79111	0.73142
Fair	0.15666	0.188	0.18076	0.22380...	0.17735	0.21860	0.20888	0.26857

40.Vessel Motions	Normal							
39.Vibrations	Extreme							
31.Work Environment intertemediate.	Poor							
32.Overall Facilities	Poor				Fair			
44.Light	Poor		Sufficient		Poor		Sufficient	
45.Humidity	High	Normal	High	Normal	High	Normal	High	Normal
Poor	0.83793.	0.80416	0.812	0.765	0.81568	0.77073.	0.78139	0.71515.
Fair	0.16206.	0.19583.	0.188	0.235	0.18431	0.22926.	0.21860	0.28484

40.Vessel Motions	Normal							
39.Vibrations	Extreme							
31.Work Environment intertemediate.	Fair							
32.Overall Facilities	Poor				Fair			
44.Light	Poor		Sufficient		Poor		Sufficient	
45.Humidity	High	Normal	High	Normal	High	Normal	High	Normal
Poor	0.79111	0.73142	0.74594	0.65185	0.75263	0.66428	0.68666.	0.53
Fair	0.20888	0.26857 .	0.25405	0.34814	0.24736	0.33571	0.31333.	0.47

40.Vessel Motions	Normal							
39.Vibrations	Normal							
31.Work Environment intertemediate.	Poor							
32.Overall Facilities	Poor				Fair			
44.Light	Poor		Sufficient		Poor		Sufficient	
45.Humidity	High	Normal	High	Normal	High	Normal	High	Normal
Poor	0.80416.	0.75263	0.765	0.68666	0.77073	0.69677	0.71515.	0.59130
Fair	0.19583	0.24736	0.235	0.31333	0.22926.	0.30322	0.28484	0.40869

40.Vessel Motions	Normal							
39.Vibrations	Normal							
31.Work Environment intertemediate.	Fair							
32.Overall Facilities	Poor				Fair			
44.Light	Poor		Sufficient		Poor		Sufficient	
45.Humidity	High	Normal	High	Normal	High	Normal	High	Normal
Poor	0.73142.	0.624	0.65185	0.44705.	0.66428	0.47777	0.53	0.06
Fair	0.26857	0.376	0.34814	0.55294	0.33571.	0.52222.	0.47	0.94

Sources: [42] [90] [110]

31. Work Environment Intermediate

The usability of this node is the same as node 8. In order to use the universal transport node from [42] model we have kept it intact. The parent nodes for this one are light, noise and temperature capturing the overall nature of a regular work environment.

States of Work Environment Intermediate:

- Poor
- Fair

42.Temperature	Extreme		Normal	
41.Noise	Extreme	Normal	Extreme	Normal
Poor	0.9	0.84	0.78	0.04
Fair	0.1	0.16	0.22	0.96

Sources: [42]

32. Overall Facilities

In this node we try to capture the overall quality of the vessel's facilities. Modern and ergonomic facilities can provide a pleasant work environment making the mariner's life easier and more pleasant. Factors that may contribute to the overall facilities quality are the level of automation and the frequency of ship's maintenance. It can be observed in the CPT that we are rather skeptic about the impact of the overall facilities on the quality of the total work environment.

States of Overall Facilities:

- Poor
- Fair

35.Recreational Facilities	Poor							
36.Maintenance	Rare				Frequent			
33.Level of Automation	Poor		Fair		Poor		Fair	
34.Age of Veseel	Milleniu...	Milleniu...	Milleniu...	Milleniu...	Milleniu...	Milleniu...	Milleniu...	Milleniu...
Poor	0.58	0.55	0.55	0.5	0.55	0.5	0.5	0.4
Fair	0.42	0.45	0.45	0.5	0.45	0.5	0.5	0.6
35.Recreational Facilities	Fair							
36.Maintenance	Rare				Frequent			
33.Level of Automation	Poor		Fair		Poor		Fair	
34.Age of Veseel	Milleniu...	Milleniu...	Milleniu...	Milleniu...	Milleniu...	Milleniu...	Milleniu...	Milleniu...
Poor	0.55	0.5	0.5	0.4	0.5	0.4	0.4	0.1
Fair	0.45	0.5	0.5	0.6	0.5	0.6	0.6	0.9

Sources: [61]

33. Level of Automation

For this node the following assumption is made:

The higher the level of automation is, the more efficient the overall facilities are. However, we did not neglect the fact that the more modern and technologically advance a piece of equipment is, the more complex and difficult is for the average seafarer to understand its functions, thus the child CPT was filled with cautiousness.

States of Level of Automation:

- Poor
- Fair

Poor	0.15
Fair	0.85

Sources: [14]

34. Age of Vessel

In this node we show that the age of the vessel is a significant factor for the overall quality of the facilities on-board. The newer the vessel is, the higher the probability for more ergonomic facilities is. While most vessels that were constructed over 15 years ago are constantly been renovated, several legislations have made mandatory for new ships facilities such as elevators and better recreational facilities. However, these installations are rarely part of the renovation of an in-service vessel due to extravagant costs.

States of Age of Vessel:

- 2000 minus
- 2000 plus

Millenium_minus	0.4
Millenium_plus	0.6

Sources: [110]

35. Recreational Facilities

Internet availability, television and several other leisure activities are regarded as the recreational facilities of a vessel. The importance of these facilities is great since the maritime work environment is very unique and complex compared to other domains. Some mariners have to stay months away from home. Therefore, the recreational facilities help the mariner reduce stress levels and have pleasant time and space to rest after a tiresome workday. States of Recreational Facilities:

- Poor
- Normal

31.Work Environment intertemedi...	Poor							
39.Vibrations	Extreme				Normal			
40.Vessel Motions	Extreme		Normal		Extreme		Normal	
44.Light	Poor	Sufficient	Poor	Sufficient	Poor	Sufficient	Poor	Sufficient
Poor	0.85606.	0.83035.	0.79787	0.74324	0.83035	0.79347	0.74324.	0.64814
Fair	0.14393.	0.16964	0.20212	0.25675	0.16964	0.20652.	0.25675	0.35185

31.Work Environment intertemedi...	Fair							
39.Vibrations	Extreme				Normal			
40.Vessel Motions	Extreme		Normal		Extreme		Normal	
44.Light	Poor	Sufficient	Poor	Sufficient	Poor	Sufficient	Poor	Sufficient
Poor	0.80612.	0.75641	0.68333	0.525	0.75641	0.67241	0.525	0.05
Fair	0.19387.	0.24358.	0.31666.	0.475	0.24358.	0.32758.	0.475	0.95

Sources: [103]

36. Maintenance

In this node we show the importance of frequent maintenance on the overall quality of facilities. The lack of maintenance can result in an unhealthy and hazardous working /living environment aboard ships.

States of Maintenance:

- Rare
- Frequent

Rare	0.1
Frequent	0.9

Sources: various

Note: The following nodes are presented synoptically as they are discussed thoroughly in paragraphs 4.3.1.1. and 4.3.1.2 in order to give emphasis to the responsibilities of the Naval Architect in fatigue related issues.

37. Sleep Environment

This node describes the overall quality of the vessel's environment including maritime exclusive aspects such as ship's motions and vibrations.

States of Sleep Environment:

- Poor
- Fair

38.Sleep Environment intermediate	Poor				Fair			
39.Vibrations	Extreme		Normal		Extreme		Normal	
40.Vessel Motions	Extreme	Normal	Extreme	Normal	Extreme	Normal	Extreme	Normal
Poor	0.83636	0.72727...	0.8	0.60869	0.78571.	0.55	0.71875	0.1
Fair	0.16363.	0.27272...	0.2	0.39130.	0.21428	0.45	0.28125	0.9

Sources: [23] [14]

38. Sleep Environment intermediate

Taking advantage of the CPT from [42] model, this node functions in a similar way as node 8 and 30. Contrary to node 37, this one captures the universal nature of sleep environment neglecting specific aspects discussed above (e.g. vibrations).

States of Sleep environment intermediate:

- Poor
- Fair

47.Random Light	Yes							
46.Random Noise	Yes				No			
42.Temperature	Extreme		Normal		Extreme		Normal	
45.Humidity	High	Normal	High	Normal	High	Normal	High	Normal
Poor	0.87	0.78	0.79	0.65	0.76	0.61	0.61	0.36
Fair	0.13	0.22	0.21	0.35	0.24	0.39	0.39	0.64

47.Random Light	No							
46.Random Noise	Yes				No			
42.Temperature	Extreme		Normal		Extreme		Normal	
45.Humidity	High	Normal	High	Normal	High	Normal	High	Normal
Poor	0.8	0.68	0.68	0.47	0.65	0.42	0.43	0.05
Fair	0.2	0.32	0.32	0.53	0.35	0.58	0.57	0.95

Sources: [42]

39. Vibrations

Vibrations are a common issue onboard. Extreme vibrations levels can result in hazardous working and sleeping environments and the prevalence of fatigue.

States of vibrations:

- Extreme
- Normal

Extreme	0.05
Normal	0.95

Sources: [14] [103]

40. Vessel Motions

Another vessel exclusive fatigue risk factor is the vessel motions. Extreme motions can make the performing of a specific task extremely difficult and the sleeping environment unbearable. The main factors that influence the vessel motions are extreme weather phenomena including waves and tides.

States of Vessel Motions:

- Extreme

- Normal

43.Weather	eleven_plus_heavystorm	ten_eleven_storm	eight_nine_high_waves	six_seven_considerable_waves
Extreme	1	0.98	0.73	0.55
Normal	0	0.02	0.27	0.45

43.Weather	four_five_moderate_waves	three_calm_waves	calm_no_wave
Extreme	0.25	0.13	0.03
Normal	0.75	0.87	0.97

Sources: [14] [23]

41. Noise

This node represents the maximum allowed noise levels that a human can endure in order to avoid several threatening dangers for his general welfare. A noisy environment can result to fatigue or even more serious issues such as permanent deafening as well.

States of Noise:

- Extreme
- Normal

Extreme	0.15
Normal	0.85

Sources: [14] [96]

42. Temperature

Extreme temperature levels can affect the seafarer's performance significantly. There are specific parts of a ship, such as the engine room, where the high temperatures that are produced making the environment unhealthy and hazardous for everyone performing any task under these circumstances.

States of Temperature:

- Extreme
- Normal

Extreme	0.05
Normal	0.95

Sources: various

43. Weather

In the weather node we take into consideration every climatic phenomenon that can affect the living environment onboard. A common example could be the presence of extreme heaves that influence several hydrostatic and structural aspects of the vessel thus affecting the ship's motions in turn. Our selected states are a correlation of the Beaufort wind scale and several known sea states.

States of Weather:

- Eleven_plus_heavystorm
- Ten_eleven_strom
- Eight_nine_high_waves
- Six_seven_considerable_waves
- Four_five_moderate_waves
- Three_calm_waves
- Calm_no_wave_

eleven_plus_heavystorm	0.001
ten_eleven_storm	0.009
eight_nine_high_waves	0.05
six_seven_considerable_waves	0.1
four_five_moderate_waves	0.2
three_calm_waves	0.39
calm_no_wave	0.25

Sources: [108]

44. Light

Sufficient lighting is an integral part for a healthy and ergonomic environment. While sunlight cannot be replaced by any form of artificial lighting, proper illumination on the workplace can enhance the individual's performance and maintain the proper function of the Circadian rhythms.

States of Light:

- Poor
- Sufficient

Poor	0.2
Sufficient	0.8

Sources: [14]

45. Humidity

This node captures the importance of humidity in a specific workplace or sleep environment. Many seafarers have reported this issue as a fatigue risk factor, while [103] survey states that it is perhaps one of the most important factors regarding an onboard sleeping environment.

States of Humidity:

- High
- Normal

High	0.1
Normal	0.9

Sources: [14] [103]

46. Random Noise

Random noises are those that may serve as a distraction for an individual's sleeping patterns. Announcements made via microphones which address all on-duty crew members can be an unwanted distraction for those who are sleeping.

States of Random Noise:

- Yes
- No

Yes	0.2
No	0.8

Sources: [14] [110]

47. Random Light

Any kind of unwanted light that can distract an individual’s sleeping continuity. A typical example is the presence of sunlight during the sleeping time of a night shift operator at daytime.

States of Random Light

- Yes
- No

Yes	0.2
No	0.8

Sources: [14] [110]

CHAPTER 7

BAYESIAN NETWORK APPLICATION FOR FATIGUE IN MARITIME SCENARIOS AND ACCIDENTS

7 BAYESIAN NETWORK APPLICATION FOR FATIGUE IN MARITIME SCENARIOS AND ACCIDENTS

The scale listed below will serve as an index of our acceptance levels for fatigue prevalence amongst mariners. Our fundamental assumption is that the seafarers will eventually suffer the effects of fatigue even if all factors, such as sleeping quality and work environment, are at a favorable state. Apart from indicating the posterior probability of our Bayesian Network, the scale introduces the Red Zone (P(fatigue =yes > 0.85) where the consequences of fatigue are able to impair the human performance leading to dangerous outcomes, such as micro-sleeps and serious decision making errors.

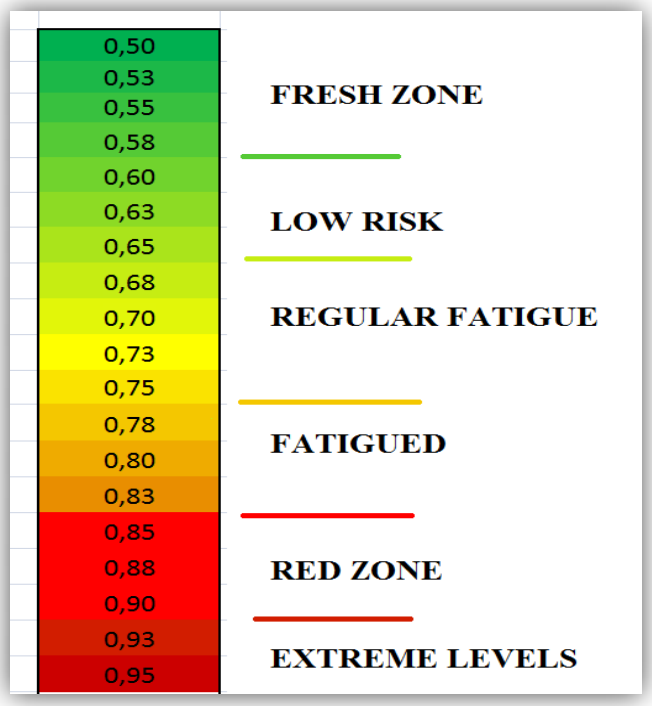


Figure 7. 1: Fatigue Acceptance Scale

In order of provide a more explanative statement of the fatigue scale, we include a representative examples for each of the scale's zones as shown above:

- Fresh Zone: Describes the period when an individual feels fresh an active and his performance is free of the effects of fatigue, (e.g. at the first hours(but not at the very beginning) of the task at hand in a healthy and ergonomic environment)
- Low Risk: When fatigue is present but rarely affects actions or overall performance, (e.g. an operator working for a couple of hours with a healthy background → sufficient sleep and physical condition)

- Regular Fatigue: The lengthier zone of the whole scale that describes the period when the individual feels that fatigue starts to be present and slightly irritating but is regarded as a logical consequence of a day at work (e.g. right after the 15:00 to 16:00 drowsy period for a clerk working his 9:00 to 17:00 schedule)
- Fatigued: At the end of a long day at work when fatigue signs (e.g. yawn or slow reactions) are obvious and there is a considerable need for rest, (e.g. at the end of a day at work where there was no available rest break)
- Red Zone: Fatigue has become dominant, reaction times are considerablyslow and the probability of error is high even for the most simple tasks, (e.g. a sleep deprived driver making his way home after 20 hours of working in a hazardous environment while on heavy workload)
- Extreme Levels: Describes the period when fatigue has full control over an individual, making the need for rest a top priority. In this zone the probability of errors of any kind is almost definite, (e.g. a watchkeeper who falls asleep while on duty as a result of sleep deprivation, hazardous environment and exhaustive workload).

7.1 THE IMPACT OF DYNAMIC FACTORS ON FATIGUE PREVALENCE

7.1.1 SUFFICIENT SLEEP AND SLEEP DEPRIVATION

In this paragraph we are going to demonstrate the impact of sleep deprivation on fatigue related issues. Throughout the entire body of our research, we realized that the overall sleeping quality of an individual is the most important contributing factor to the emergence of fatigue. Furthermore, scholars have indicated that the critical point among sufficient sleep and deprivation, for an average adult, is the period between six to eight hours of uninterrupted sleep. While this observation might not apply to every single adult, since other factors such as age and physical condition take part, it has been accepted as a fundamental assumption when studying fatigue.

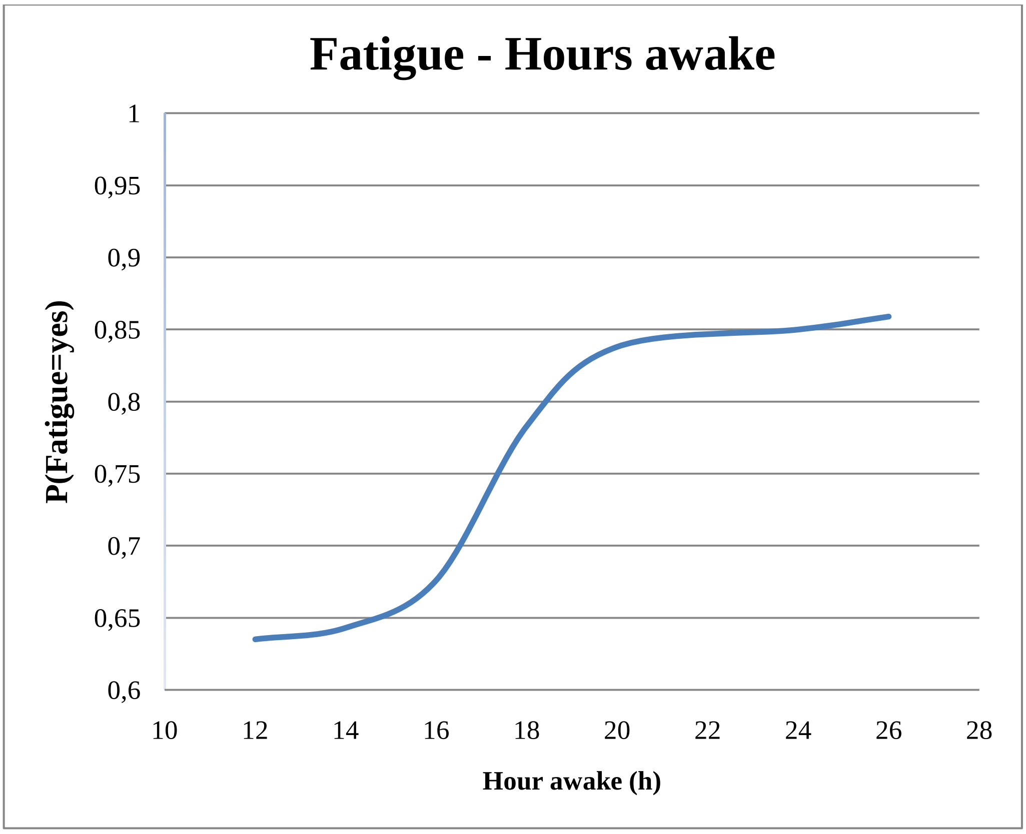
In order to show this particular interaction between fatigue and adequate sleep, we modeled our Bayesian Network in such manner that allows us to import various sleeping quantity inputs. While most nodes contain only two states, the *hours awake* node provides seven states, with their conditional probabilitie,s for the user to import as evidence. It is important to mention at this point that prior and conditional probability tables indicate that most mariners sleep between six to seven hours in a normal workday, while these hours are significantly reduced in a heavy workload day with the average values accumulated around six hours.

The following table and figure contains the results of the posterior probability for the *fatigue* node for each of the *Hours Awake* states that are imported as evidence. Each time we import evidence, we update the network in order to set the evidence node state as 1 and then propagate the information for the calculus of the rest of the posterior probabilities. Note: From now on, evidence will be presented as (e).

<u>Table 7. 1:</u> Fatigue - Hours Awake

11.Hour Awake State (e)	1.Fatigue Posterior Probability P(Fatigue = yes)	% Change
Twelve (12)	0,635	0,00
Fourteen (14)	0,643	1,26
Sixteen (16)	0,676	5,13
Eighteen (18)	0,783	15,83
Twenty (20)	0,838	7,02
Twenty-four (24)	0,850	1,43
More than a day (24+)	0,858	0,94

Note: When *More than a day* is imported, the sleep quantity node intakes immediately the *deprived* state almost in a similar manner as we import evidence. In plain words, this means that whenever an individual has not slept for more than twenty four hours it is definite that he/she will be sleep deprived.



<u>Figure 7. 2:</u> Fatigue - Hours Awake

The figure above indicates that the critical limit of prevalence, which is set as P (Fatigue= yes) = 0.85, is surpassed when *Hours Awake* exceed 20. The abrupt turn from 16 to 20 pinpoints the fact that the thin line between enough sleep and sleep deprivation rests between 6-8 hours of uninterrupted sleep. When the workload aboard is heavy, there is rarely the chance for more than 6 hours of sleep. Furthermore, accidents and investigations reports do not seem to identify the significance of napping, which scientists describe as crucial in workplaces where sleeping patterns are easily disturbed. If a mariner manages to sleep more than eight hours a day, even for a small number of consecutive days, then fatigue probability decreases significantly. The same occurs for sleep deprivation as well.

7.1.2 WEATHER AND SEA STATE

The maritime environment is a unique workplace in comparison to any other transport domain. In our attempt to provide a representative modeling tool for such an inimitable environment, we created a network that considers weather and sea state as an integral part of the problem.

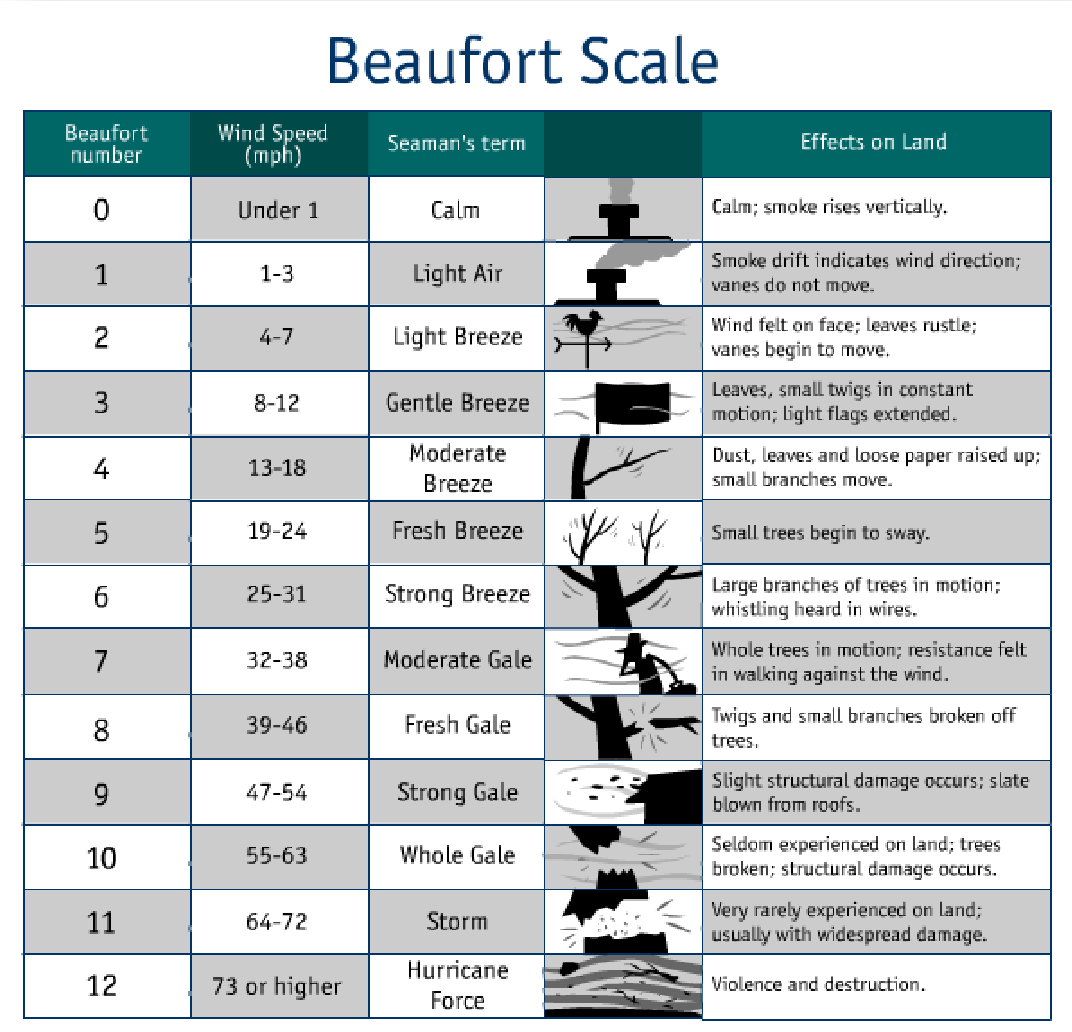
The science of Naval Architecture and Marine Engineering has always focused on the interaction of a vessel's hydrostatics, hydrodynamics, overall structural endurance withthe variety of weather phenomena. Though various sources of literature and interviews with experts and mariners, it was found that the sea state affects directly both the working and sleeping environment, thus making it a common fatigue related factor.

In order to demonstrate this interaction we have introduced the weather node in similar manner to the *Hours Awake* one. Using knowledge from both scientific expertise and statistical data, we applied our experience and judgment into creating a node that connects weather and the vessel's motions. While some probabilities are rough estimations provided by experts, this node succeeds in representing the connection between the ship's dynamic movement and a bad weather scenario.

Making the assumption that the vessel's motions are primarily affected by waves that create specific sea states environments', we used the Beaufort scale in order to correlate these two parties, as listed below.

Note: Both literature and experts agree that States 1) and 2) are rather rare, a fact reflected in their prior probabilities that are significantly low. 12+ values in the Beaufort scale refer to phenomena such as hurricanes and typhoons.

Figure 7.3 is the presentation of the Beaufort scale. On the third row we can see the mariner's term for each stage of the scale while on the fifth indicates a list of effects at land relating to wind speed.



Beaufort Scale

Beaufort number	Wind Speed (mph)	Seaman's term		Effects on Land
0	Under 1	Calm		Calm; smoke rises vertically.
1	1-3	Light Air		Smoke drift indicates wind direction; vanes do not move.
2	4-7	Light Breeze		Wind felt on face; leaves rustle; vanes begin to move.
3	8-12	Gentle Breeze		Leaves, small twigs in constant motion; light flags extended.
4	13-18	Moderate Breeze		Dust, leaves and loose paper raised up; small branches move.
5	19-24	Fresh Breeze		Small trees begin to sway.
6	25-31	Strong Breeze		Large branches of trees in motion; whistling heard in wires.
7	32-38	Moderate Gale		Whole trees in motion; resistance felt in walking against the wind.
8	39-46	Fresh Gale		Twigs and small branches broken off trees.
9	47-54	Strong Gale		Slight structural damage occurs; slate blown from roofs.
10	55-63	Whole Gale		Seldom experienced on land; trees broken; structural damage occurs.
11	64-72	Storm		Very rarely experienced on land; usually with widespread damage.
12	73 or higher	Hurricane Force		Violence and destruction.

<u>Figure 7. 3:</u> The Beaufort scale

Our weather node has seven states as presented below:

1) Eleven Plus – Heavy storm (hurricane)
2) Ten to Eleven – Severe Storm
3) Eight to Nine – High Waves
4) Six to Seven – Considerable Waves
5) Four to Five – Moderate Waves
6) Two to Three – Calm Waves
7) One to Two – Calm Sea

In the following table and figure, we present the results of the posterior probability, P (Fatigue = Yes), for each *Weather* node state that was imported as evidence.

Note: The conditional probability table of the Vessel Motions node was arranged taking into consideration the impact of weather on the movements of a merchant ship of average size such as a Bulk Carrier of 10000-40000 tones DWT (deadweight).

Table 7. 2 : Fatigue -Weather

43.Weather Node states(e)	1.Fatigue Posterior Probability P(Fatigue = yes)	% Ch.[5]
Eleven Plus – Heavy storm	0,84	0,00
Ten to Eleven – Severe stor.	0,837	0,36
Eight to Nine – High Waves	0,824	1,58
Six to Seven – Considerable Waves	0,801	2,87
Four to Five – Moderate Waves	0,78	2,69
Two to Three – Calm Waves	0,773	0,91
One to Two – Calm Sea	0,763	1,31

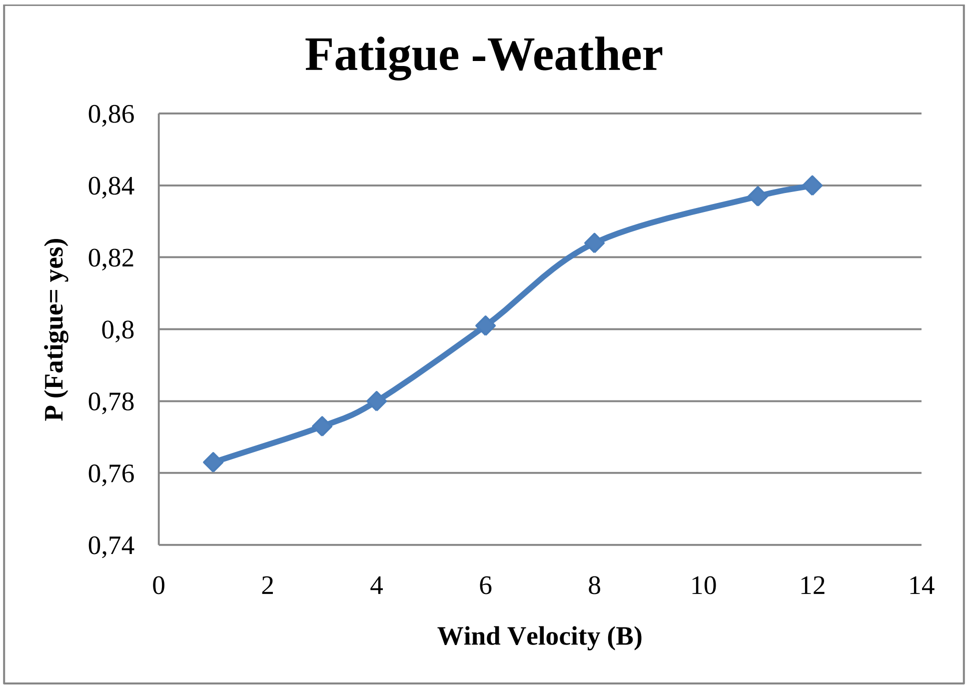


Figure 7. 4: Fatigue - Weather

In the figure above the passage from moderate calm sea to considerable waves (three to seven) is represented by a rapid abrupt increase on the fatigue probability. The posterior probability not reaching the red zone is due to the fact that at this point the weather node serves as the only evidence of our rather 'Good will' network. It is crucial to mention that early in this chapter we realize that sleep is proven to be more influential than any other contributing factor.

[5] % change of P(Fatigue =Yes)

7.2 MARITIME ACCIDENTS

7.2.1 EXXON VALDEZ

The *Exxon Valdez* oil spill occurred in Prince William Sound, Alaska, on March 24, 1989, when the *Exxon Valdez,* an oil tanker bound for Long Beach, California, struck Prince William Sound's Bligh Reef and spilled 260,000 to 750,000 barrels (41,000 to 119,000 m^3) of crude oil. It is considered to be one of the most devastating human-caused environmental disasters ever to occur in history. As significant as the *Valdez* spill was — the largest ever in U.S. waters until the 2010 *Deepwater Horizon* oil spill — it ranks well down on the list of the world's largest oil spills in terms of volume released. However, Prince William Sound's remote location, accessible only by helicopter, plane and boat, made government and industry response efforts difficult and severely taxed existing plans for response.

Figure 7. 5: The Exxon Valdez oil spill

Apart from identified as one of the most disastrous accidents of all time, the Exxon Valdez oil spill is also the most common example of Human Factor related incidents in the maritime domain. Even if the spill took place over twenty years ago, when double-hulls were not yet mandatory for oil tankers, scientists still investigate the incident in order to provide safer vessels and procedures and eventually prevent similar catastrophes in the future [66].

In this paragraph we will try to apply our fatigue-Bayesian Network on the Exxon Valdez incident through the import of evidence that was provided from the accident's report. Furthermore, we will provide an alternate step-by-step scenario of what the fatigue posterior probability would be if all the evidence had the preferred state or the states proposed by the legislation party (e.g. STCW).

Note1: At this point, we will investigate the 3rd mate's (Cousins) actions and background, who was the bridge watchkeeper at the time of the grounding.

Note 2: The vessel motions conditional probability table was slightly altered because of the ship's size. The changes that were made indicate the fact that weather phenomena have lesser impact on a 200000 DWT tanker's motions than it would have on 10000 DWT Bulk Carrier or General Cargo ship.

The following findings are part of the Final Report, submitted by the Alaska Oil Spill Commission, published in February 1990 by the State of Alaska [X]:

7.2.1.1 ACTUAL INCIDENT

1. Manning Levels: Low (e1)

'Cousins was the only officer on the bridge-a situation that violated company policy and perhaps contributed to the accident. A second officer on the bridge might have been more alert to the danger in the ship's position, the failure of its efforts to turn, the autopilot steering status, and the threat of ice in the tanker lane'

The 3rd Mate, Cousins, was left alone on the bridge against company's policies and legislation. It is important to mention that if the 3rd mate had better knowledge regarding fatigue, he would probably identify the risk of staying on the bridge alone.

2. Type of Task: Tedious (e2)

Knowing the nature of the job of a watchkeeper, we assumed the tedious nature of the task at hand.

3. Management Demands: Demanding (e3)

'Minimum vessel manning limits are set by the U.S. Coast Guard, but without any agency wide standard for policy. The Coast Guard has certified Exxon tankers for a minimum of 15 persons (14 if the radio officer is not required). Frank Iarossi, president of Exxon Shipping Company, has stated that his company's policy is to reduce its standard crew complement to 16 on fully automated, diesel-powered vessels by 1990. "While Exxon has defended their actions as an economic decision", the manning report says, "criticism has been leveled against them for manipulating overtime records to better justify reduced manning level".

In addition to the 3rd Mate left alone on the bridge, it seems that Exxon Valdez was undermanned for a vessel of its type and size.

4. Hours Awake: Twenty (e4)

"*By this time Third Mate Cousins had been on duty for six hours and was scheduled to be relieved by Second Mate Lloyd LeCain. But Cousins, knowing LeCain had worked long hours during loading operations during the day, had told the second mate he could take his time in relieving him. Cousins did not call LeCain to awaken him for the midnight-to-4-a.m. watch, instead remaining on duty himself."*

"Cousins' duty hours and rest periods became an issue in subsequent investigations. Exxon Shipping Company has said the third mate slept between I a.m. and 7:20 a.m. the morning of March 23 and again between 1: 30 p.m. and 5 p.m., for a total of nearly 10 hours sleep in the 24 hours preceding the accident. But testimony before the NTSB suggests that Cousins "pounded the deck" that afternoon, that he did paperwork in his cabin, and that he ate dinner starting at 4:30 p.m. before relieving the chief mate at 5 p.m. An NTSB report shows that Cousins' customary in-port watches were scheduled from 5:50 a.m. to 11:50 a.m. and again from 5:50 p.m. to 11:50 p.m. Testimony before the NTSB suggests that Cousins may have been awake and generally at work for up to 18-20 hours preceding the accident."

It is important to mention that if the 3rd mate had had better knowledge regarding fatigue, he would probably have identified the risk of staying awake for that amount of time. Instead he chose to relieve the 2nd mate, who would have probably been affected by fatigue as well, making himself vulnerable to errors and underperformance.

From the report's excerpt listed above we can assume that the 3rd Mate was awake for almost twenty hours prior the incident.

Table 7. 3: Exxon Valdez Actual

Evidence	1.Fatigue Posterior Probability P(Fatigue = yes)
no evidence	0,776
e1	0,81
e2	0,855
e3	0,859
e4	0,883

At this point we feel obliged to mention that the 3rd mate was not supposed to stay alone in the bridge. The captain, who the investigations showed that he was under the influence of alcohol, was sleeping at the time of the incident and even when the situation became out of hand, he returned to the bridge but made a series of mistakes that led to the magnitude of this disaster.

The posterior probability change from (e2) to (e3) is relatively low due to the fact that:

- The prior probability distribution of the Management Demand node is in favor of the *Demanding* state since schedules are often pressing aboard merchant ships.
- The red zone has already been reached by the Type of Task evidence.

We must also mention that the type of task seems to be of great importance even in this early point of our network testing.

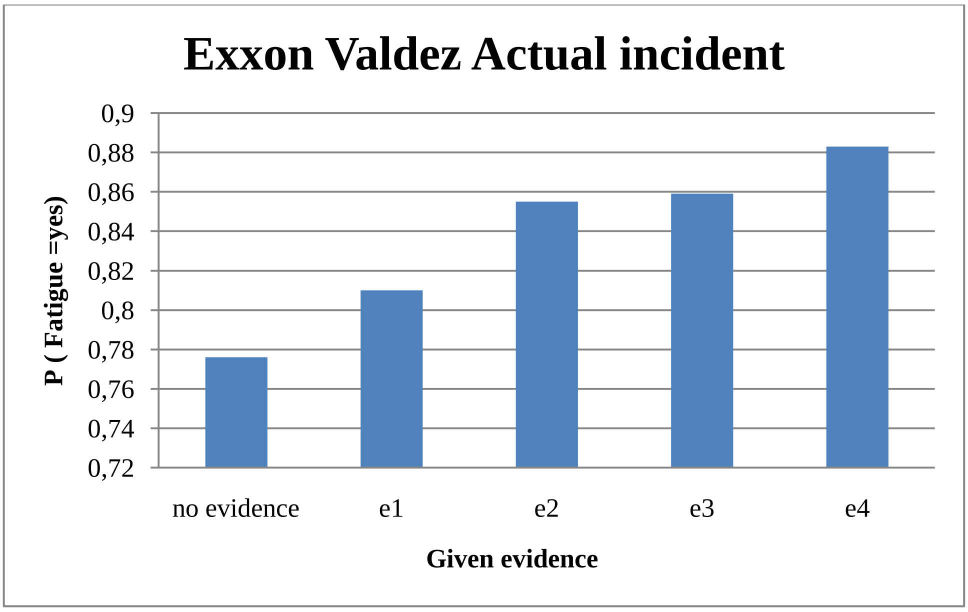


Figure 7. 6: Exxon Valdez Actual Incident

7.2.1.2 OPTIMAL ALTERNATE SCENARIO

1) Manning Levels: Normal (e1)

2) Type of work: Normal (e2)

➢ We decided to change this node's state in order to present the possibilities of the watchkeeper's job to become more interesting and less monotonous.

3) Management Demands: Normal (e3)

4) Hours Awake (e4)

➢ Eight Hours of uninterrupted sleep suggested by the STCW 75 → Sixteen Hours awake within a day.

Table 7. 4: Exxon Valdez Alternate scenario

Evidence	1.Fatigue Posterior Probability P(Fatigue = yes)
no evidence	0,776
e1	0,717
e2	0,695
e3	0,663
e4	0,612

The table above indicates that the best way for the posterior probability to drop is through sufficient sleep (e4) and less monotonous activities.

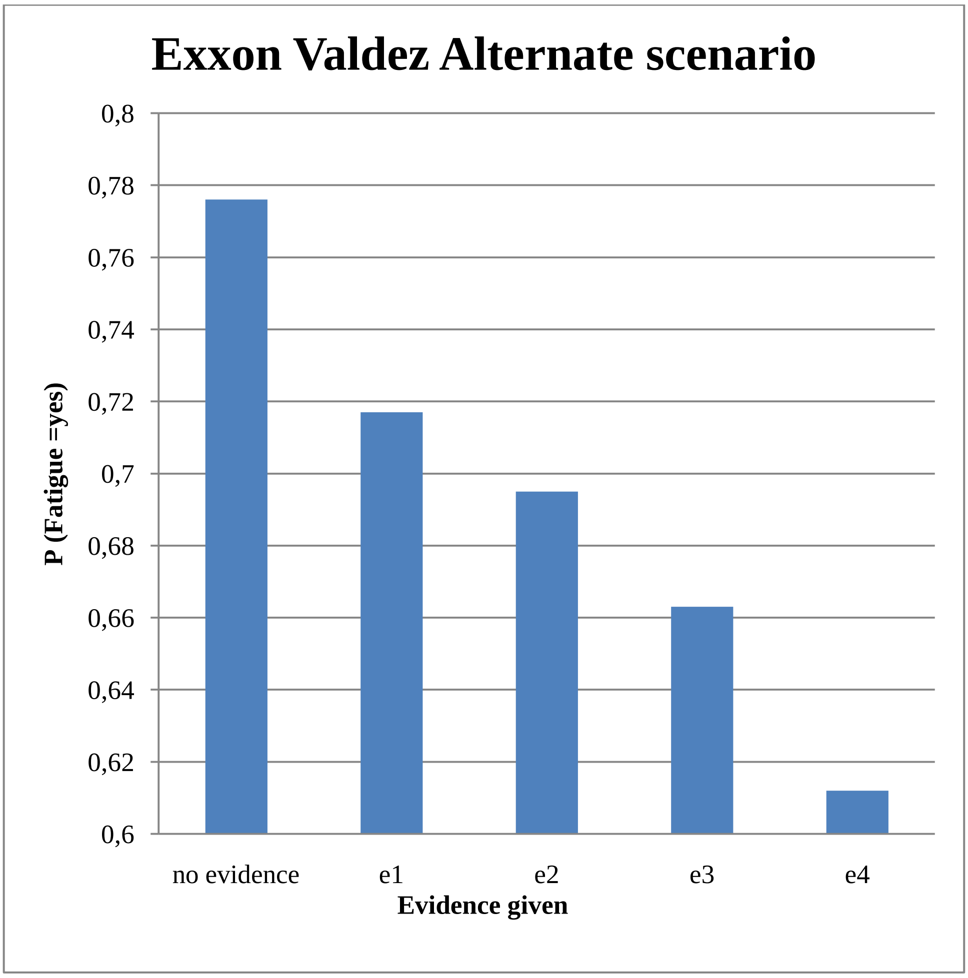


Figure 7. 7: Exxon Valdez Alternate scenario

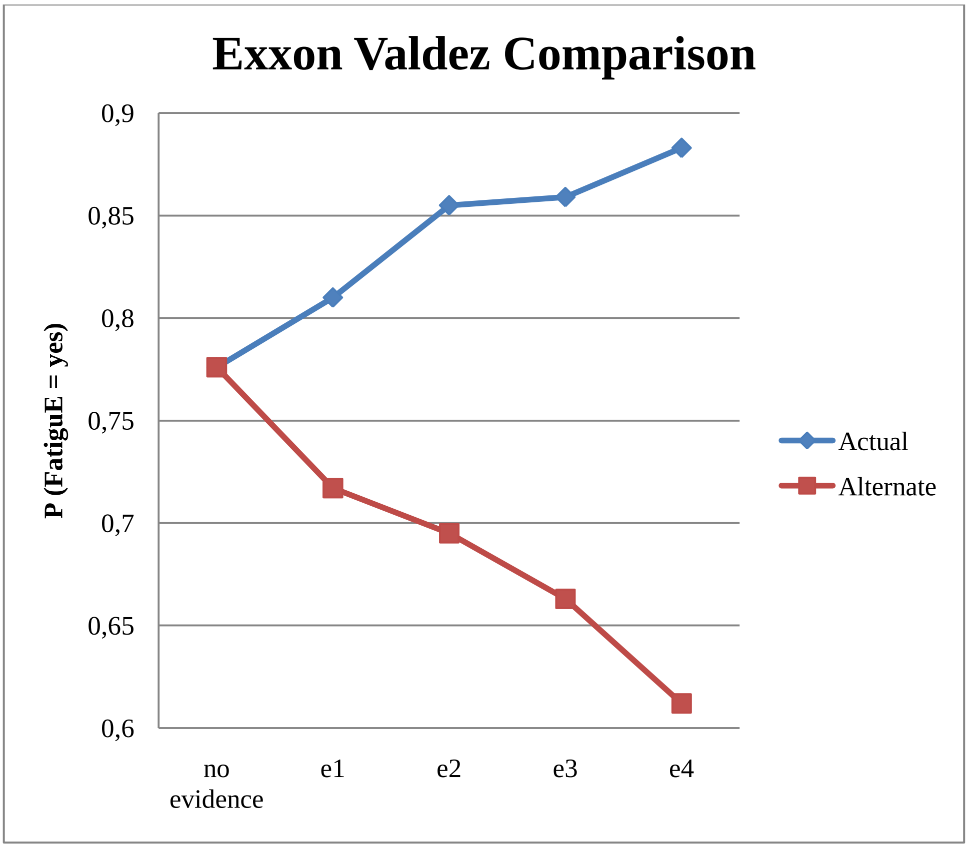


Figure 7. 8: Exxon Valdez scenario Comparison

The figure above indicates the following fact:

- By providing a better and healthy framework, the posterior probability would decrease more than it would increase if the environment was equally hazardous.

7.2.2 MFV BETTY JAMES

In this paragraph we will be investigating the grounding of Fishing Vessel Betty James (130 G.T.) on the evening of 9 July 2000. Our main resource of information was the Report No 34/2000 conducted by MAIB, (MAIB). The following excerpt was taken from the synopsis of this investigation [56].

"Mfv Betty James landed her catch in Mallaig, Scotland, on the evening of 9 July 2000, then sailed at 0015 the following day to return to the fishing grounds. At 0230 she ran aground. The person on watch had fallen asleep and a planned alteration of course to take the vessel between the isles of Rhum and Eigg was missed. A watch alarm was fitted and working, but it failed to wake either the watchkeeper or the crew asleep below in the accommodation."

Figure 7. 9: The grounding of Betty James

At this point, we will investigate the actions and performance of the watchkeeper who fell asleep while on duty on the bridge. After studying thoroughly the report provided by MAIB we were able to identify the follow findings that will serve as evidence for our network. Apart from importing evidence of the actual incident we will also provide an alternate *Good Will* scenario similar to that of paragraph 7.2.1.

7.2.2.1 ACTUAL INCIDENT

1) Drug? Alcohol Use: Yes (e1)

"*The watchkeeper had consumed three bottles of beer while in Mallaig. Three bottles of beer is a moderate quantity of alcohol to consume, which under normal circumstances might have had only a negligible effect on Peter Matheson. However, given that in the previous seven days he had not consumed any alcohol nor had any periods of sleep greater than 4 hours, duration, it is possible that the alcohol consumed by Peter Matheson had a greater soporific effect than he realized*".

Following the investigation findings we can assume that alcohol consumption had an impact on the operator's performance. It is important to highlight the fact that the watchkeeper overestimated his endurance to the effects of alcohol, a typical practice amongst mariners or individuals in general.

2. Type of Task: Tedious (e2)

"Wheelhouse practices and ergonomics allowed him to conduct his watch while seated, and kept him inactive"

Apart from the already monotonous nature of watchkeeping, the operator remained seated and inactive, (reading newspapers).

3. Manning Levels: Low (e3)

'He was alone in the wheelhouse'

4. Work Environment: Poor (e4)

"The presence of a television, video recorder and domestic radio in the wheelhouse encouraged a recreational, rather than working, environment"

While our network takes into consideration different factors in order to define the quality of a workplace, we can make the assumption that a distracting environment is a poor one.

5. Hours Awake: 18 Hours (e5)

'He probably had no more than 6 hours of sleep in the previous 24.'

6. Sleep Disorders: Regular (e6)

'He had experienced a disrupted sleeping pattern since the vessel sailed on 3 July'

Since the grounding occurred on 9 July, we can assume that the watchkeeper had sleep disorder for almost a week prior the incident.

Note 1: We have altered the Vessels motions CPT in similar manner to the Exxon Valdez example because of the ship's size (L = 16.49 m). The changes were minor because even though bad weather may had a more significant impact on a small vessel, ships of that type and size do not sail in open waters where extreme weather phenomena might appear.

Note 2: Although the actual incident took place at 2:30, a period very close to the 3:00 to 5:00 drowsy time of the circadian rhythms, we decided not to import evidence on this node, as the watchkeeper might have been asleep for some time.

Once again, the monotonous nature of watchkeeping is enough to drive the posterior probability to the red zone almost solely by itself. Furthermore, it is obvious that even if music and leisure activities can be an effective way to ameliorate the mariners' morale, in this case it proved to be a distracting factor producing a hazardous work environment instead of a countermeasure for tediousness.

Table 7. 5: Betty James Actual incident

Evidence	1.Fatigue Posterior Probability P(Fatigue = yes)
no evidence	0,779
e1	0,801
e2	0,854
e3	0,87
e4	0,924
e5	0,926
e6	0,936

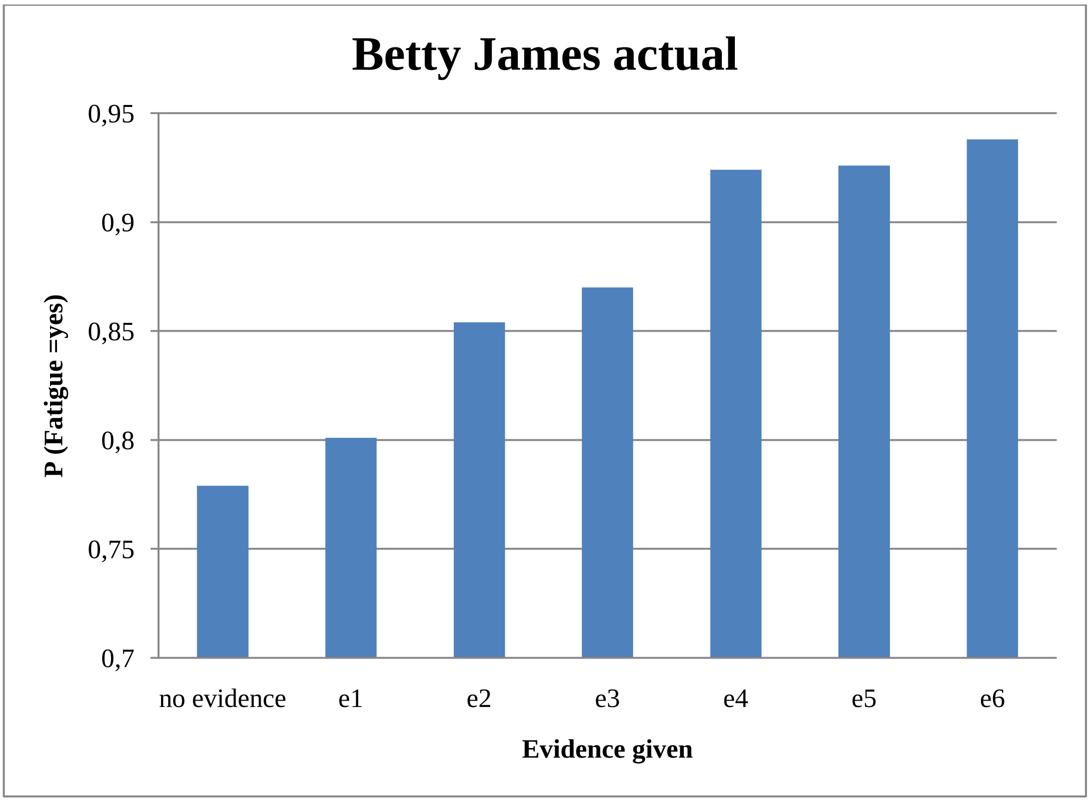


Figure 7. 10: Betty James Actual incident

In this incident, the 0.85 boundary/red zone is surpassed rapidly, early in the evidence importing process. Another interesting finding is that even if the watchkeeper had not had sufficient sleeping time prior to the accident, the impact of sleep deprivation was minimal since extreme fatigue levels had already been reached.

7.2.2.2 OPTIMAL ALTERNATE SCENARIO

1) Drug/Alcohol Use: No (e1)

2. Type of Task: Normal (e2)

- In similar manner to that of Exxon Valdez.

3. Manning Levels: Normal (e3)

4. Work Environment: Fair (e4)

- At this point we propose a non distracting environment importing soft evidence of P (W.E. = Fair) = 0.8.

5. Hours Awake: 16 Hours (e5)

- Proposed by STCW 75.

6. Sleep Disorders: Rare (e6)

Table 7. 6: Betty James Alternate scenario

Evidence	1.Fatigue Posterior Probability P(Fatigue = yes)
no evidence	0,779
e1	0,778
e2	0,763
e3	0,698
e4	0,631
e5	0,55
e6	0,535

The table above proves a basic truth about watchkeeping. If there was an additional watchkeeper on duty (mandatory for almost every flag state these days) the accident may had never happened, a fact easily made out by the transition of (e2) to (e3). Finally, sufficient sleep, as proposed by STCW, drops the probability almost 8% and into the fresh zone. The 30% drop of the posterior probability again proves that it is easier to make the situation better in the similar way it would get worse.

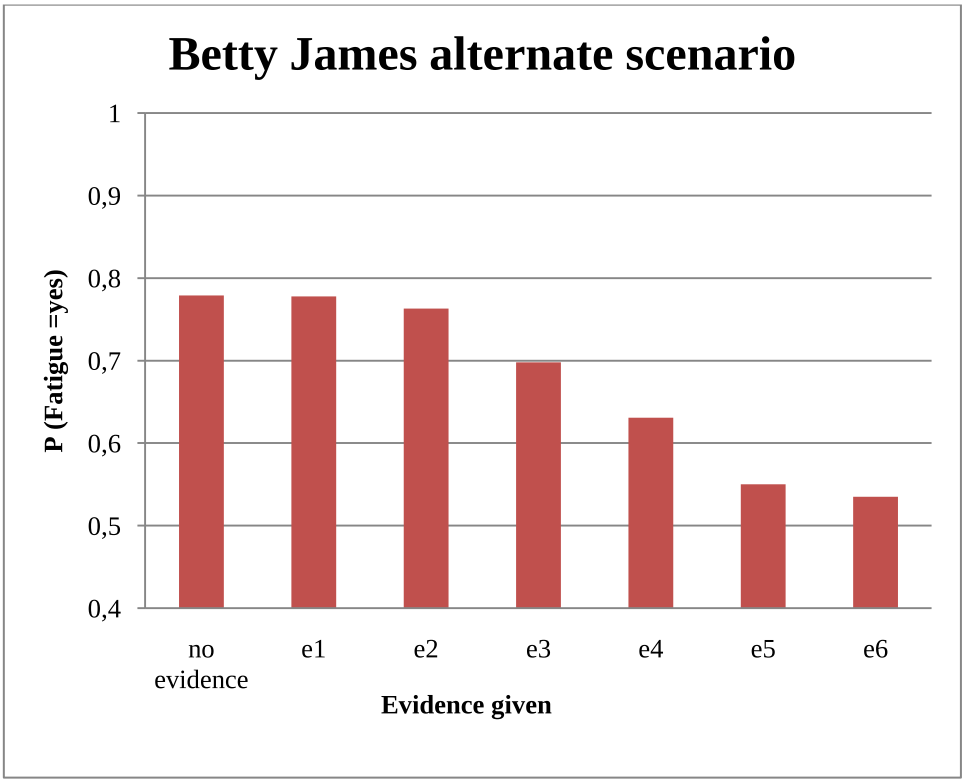


Figure 7. 11: Betty James alternate scenario

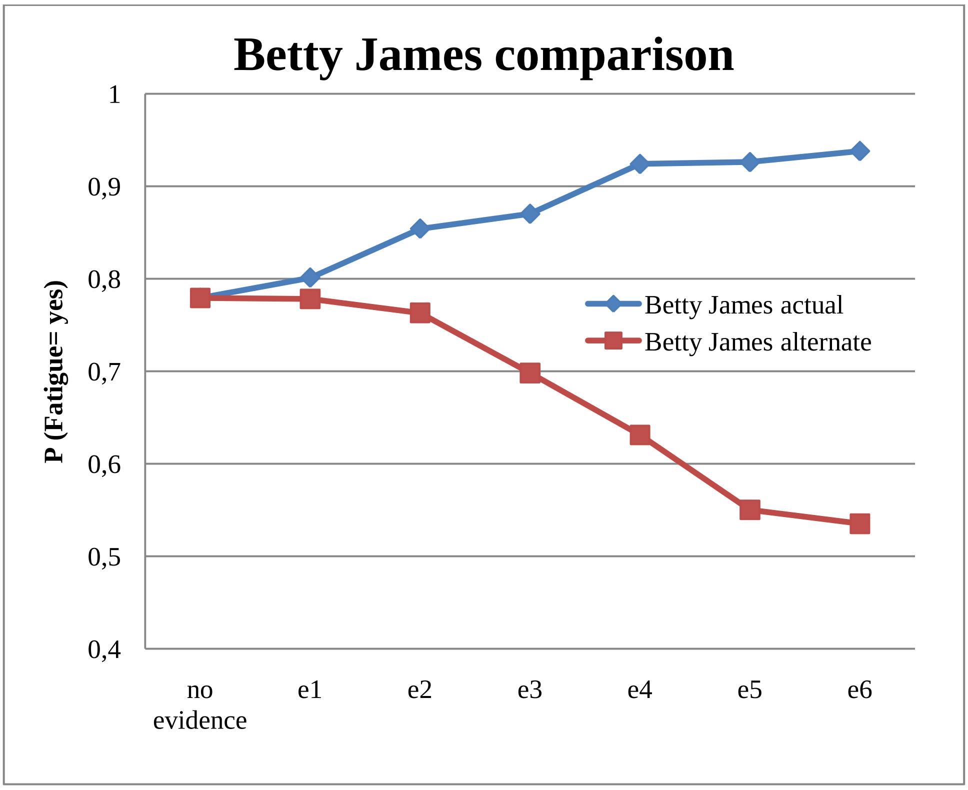


Figure 7. 12: Betty James scenario comparison

7.2.3 ANTARI (GENERAL CARGO 2446 G.T.)

In a similar approach to the preceding paragraph, at this point we are investigating the grounding of General Cargo vessel Antari (2446 G.T.). Once again, our main resource of information was the Report No 7/2009 February 2009 conducted by MAIB. The following excerpt was taken from the synopsis of this investigation [55]:

"At 0321 on 29 June 2008 the general cargo vessel Antari grounded on the coast of Northern Ireland, while on passage from Corpach, Scotland to Ghent, Belgium. The officer of the watch had fallen asleep shortly after taking over the watch at midnight when the vessel was passing the peninsula of Kintyre (Scotland). With no-one awake on the bridge, the vessel continued on for over 3 hours, crossing the North Channel of the Irish Sea before grounding on a gently sloping beach about 7 miles north of Larne".

Figure 7. 13: The Antari Grounding

The analysis of the findings and the import of evidence in our network will be part of the same procedure followed in the preceding examples.

Note 1: The Vessel Motion CPT was altered in similar manner to the preceding example, the 6000 DWT General Cargo has greater endurance to waves than the Fishing Vessel discussed earlier while it is also mentioned in the report that its main voyages are within coastal waters due to the nature of short-trade shipping routing.

7.2.3.1 ACTUAL INCIDENT

1. Random Noise: Yes (e1)

"In the 24 hours preceding the grounding, his sleep pattern had been disturbed by the port call and cargo operations…".

It is implied that the watchkeeper's sleep was disrupted by random noises.

2. Circadian Rhythms Intermediate: Drowsy (e2)

"….although he had the opportunity to rest, his circadian rhythm was probably sufficiently disrupted to prevent him obtaining adequate rest during this period…".

Our interpretation of the fact mentioned above is that the watchkeeper was in the drowsy period of his Biological Clock. While, the report indicates that he might have experienced difficulties to obtain sufficient sleep, our network has the ability to take advantage of the evidence regarding Circadian Rhythms separately.

3. High Alert State: Yes (e3)

"Antari was trading around the North West coast of Europe and had made 21 port calls in the 2 months preceding the accident. Every port call required the master's and chief officer's intense involvement: preparations for arrival and departure, pilotage, supervision of cargo operations, official and cargo paperwork. Audits and statutory inspections are normally undertaken in port, and these additional demands cannot normally be contained within the 6 hours on/6 hours off watch pattern since they frequently occur during what would otherwise be regarded as rest periods".

The frequency of port calls resulting in exhaustive workload as well as limited time for rest and sleep has led into importing evidence in the *High Alert State* node. This time we have no specific information about hours of sleep or manning levels (although the watchkeeper was alone in the Bridge, that was not against the legislation of the flag state) but the evidence set in this state updates these nodes by taking advantage of the capabilities that a Bayesian network provides each user (High alert state→ heavy workload→ hours awake).

4. Type of Task: Tedious (e4)

"The atmosphere on the bridge would have been very quiet, and once he sat in the chair, with no lookout posted and the watch alarm turned off, there were no means of anyone knowing that the chief officer had fallen asleep".

Apart from the already monotonous nature of watchkeeping, the operator again remained seated and inactive.

5. Recent Change of Shift: Yes (e5)

"The master's records show that he worked the 6 to 12 watch regardless of whether or not he was actually working. In the case of the chief officer, the record shows that he was working between midnight and 0600 on 28 June, when it is known that he was

sleeping from 0200 until about 0700. Thus, they do not accurately reflect the change of routine experienced in port".

It can be implied that the watchkeeper had experienced a recent change of shift due to low manning levels (accepted by the flag state) and the nature of short sea trading.

Table 7. 7: Antari actual incident

Evidence	1.Fatigue Posterior Probability P(Fatigue = yes)
no evidence	0,777
e1	0,78
e2	0,86
e3	0,888
e4	0,913
e5	0,918

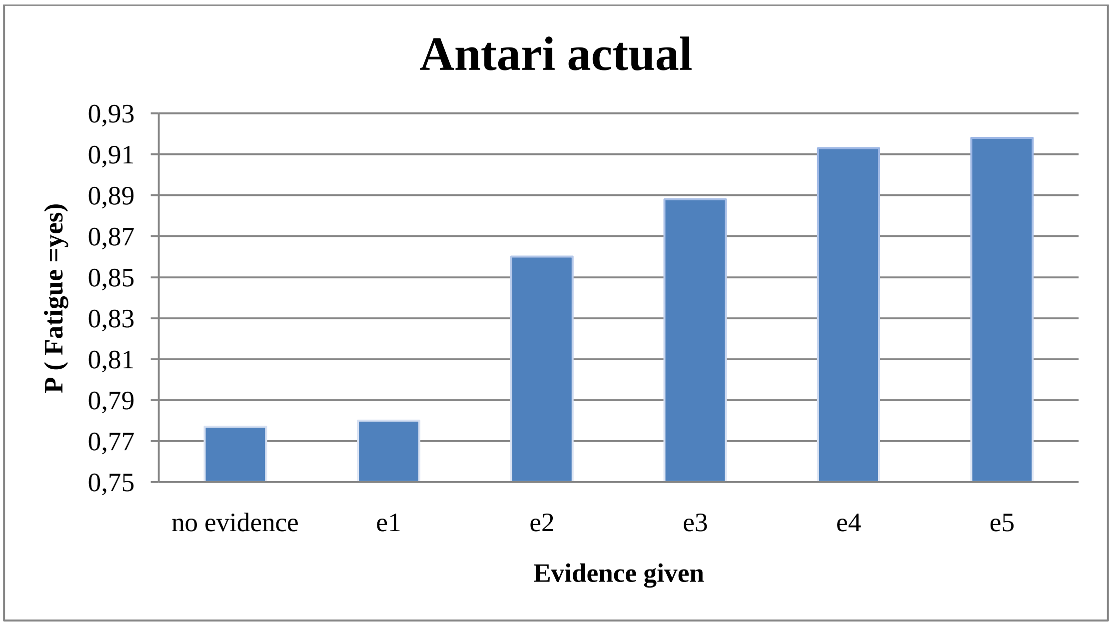


Figure 7. 14: Antari actual incident

The main finding of the figure above is the recognition of the Circadian Rhythms disruption as one of the most dangerous factors that lead to fatigue prevalence. The fact that the posterior probability does not seem to be affected by the import of (e5) is the result of the already disrupted biological clock. If there was no evidence regarding Circadian Rhythms the impact of abrupt shift rotation would be greater than shown above. For example if (e5) was the only evidence available, the updating of the network would produce a posterior probability of 0.848, which would be a significant change compared to the 0.777 prior probability.

7.2.3.2 OPTIMAL ALTERNATE SCENARIO

1. Random Noise: No (e1)

- Through better noise dampening and isolation techniques.

2. Circadian Rhythms Intermediate: Awake (e2)

- Through Higher manning levels and better shift rotation.

3. High Alert State: No (e3)

Through improved route planning and management policies.

4. Type of Task: Normal (e4)

- Similar to 7.2.1. And 7.2.2. A kind of practice that would keep the watchkeeper active and awake (e.g. music) while on duty, especially at night shifts.

5. Recent Change of Shift: No (e5)

- Through similar practices proposed for (e2) and (e3)

Table 7. 8: Antari alternate scenario

Evidence	1.Fatigue Posterior Probability P(Fatigue = yes)
no evidence	0,777
e1	0,776
e2	0,764
e3	0,762
e4	0,746
e5	0,73

The small change of the posterior probability after the import of all five evidences reflects that their prior distribution (for the fatigue mitigation states) was already low.

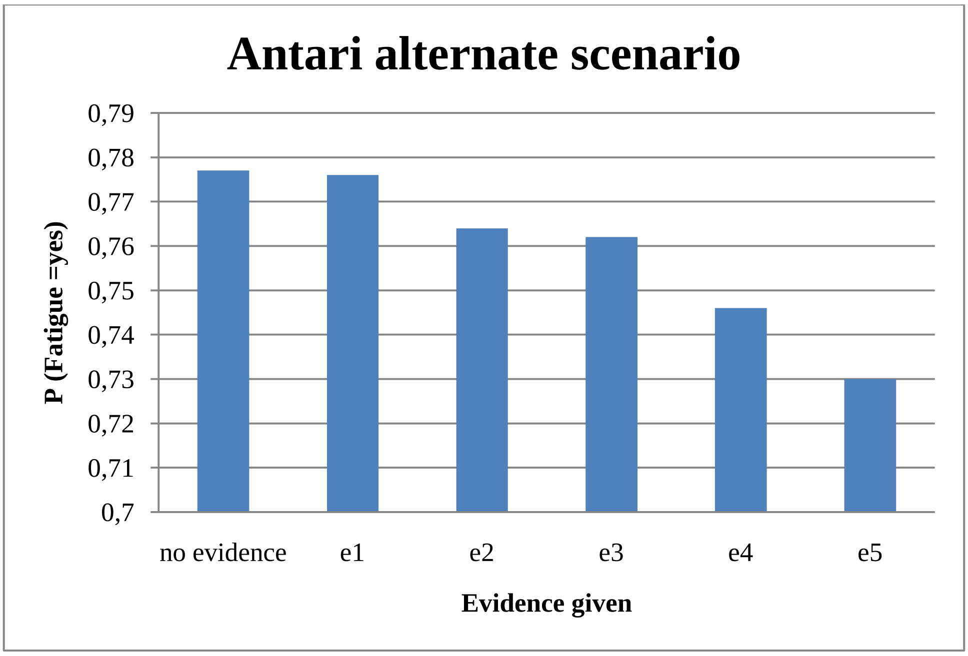


Figure 7. 15: Antari alternate scenario

In comparison to the actual incident scenario, the above graph indicates that even by making sure that all these factors are controlled, the posterior probability does not change dramatically. On the other hand, when these factors are at their hazardous states the fatigue posterior probability surpasses acceptable levels rather quickly while reaching extreme values close to 0.92. This observation is also visible in the following figure where the Actual Incident and the Alternate Scenario are presented together.

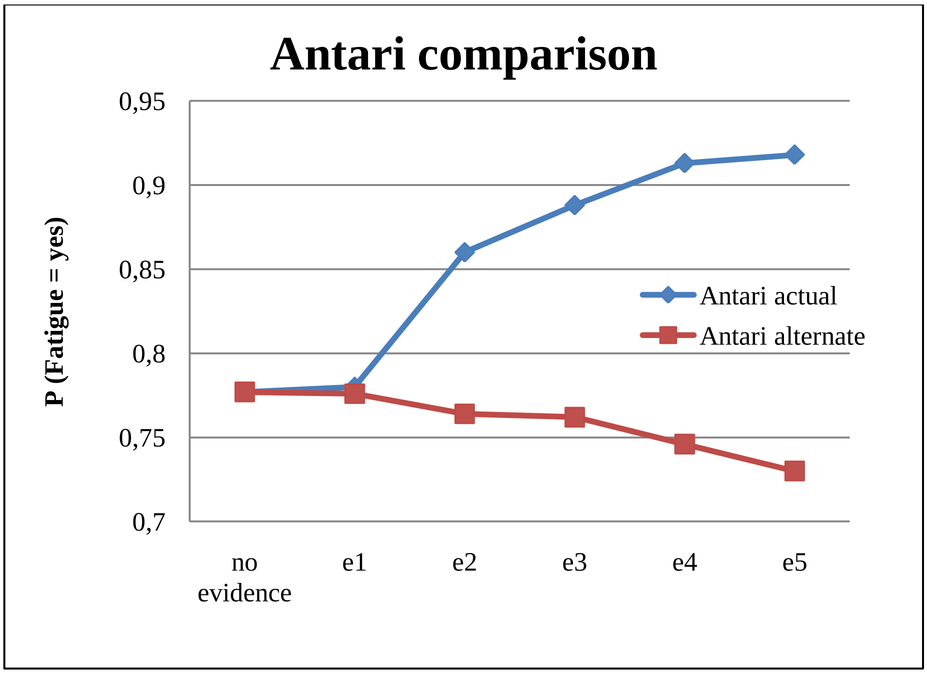


Figure 7. 16: Antari scenario comparison

7.3 HYPOTHETICAL SCENARIO OF 30000 G.T. CONTAINERSHIP

In this paragraph we discuss a hypothetical scenario of a 30000 G.T. containership in order to demonstrate our model’s full potential and capabilities. In the previous paragraphs factors such as sleep deprivation and shift rotation were mentioned numerous times. Unfortunately, factors regarding physical condition and working environment are rarely encountered in accident reports.

Container ships are considered high-risk vessels due to the nature of their cargo and work schedules. Some of the risks are linked to the loading and unloading of containers. The risks involved in these operations affect both the cargo being moved onto or off the ship, as well as the ship itself. Containers, due to their fairly nondescript nature and the small number handled in major ports, require complex organization to ensure they are not lost, stolen or misrouted. In addition, as the containers and the cargo they contain make up the vast majority of the total weight of a cargo ship, the loading and unloading is a delicate balancing act, as it directly affects the centre of mass for the whole ship.

In our hypothetical scenario we try to interpret the complex nature of a typical containership into a representative fatigue inducing example. Some common facts regarding containerships are listed below:

- High service speed
- Low Wave Endurance
- Low Block Coefficient
- Low Friction Resistance
- Regular Port Calls and Heavy Workloads

Figure 7. 17: An unfortunate incident aboard a containership

7.3.1 PROPOSED EVIDENCE

In similar approach to the previous examples, we will try to present a possible scenario regarding a watchkeeper working his shift in the bridge. The proposed evidence for our hypothetical example are listed and explained below:

1) Overweight watchkeeper → Physical exercise: No (e1)
Nutrition: Poor (e2)

A study conducted on Danish seafarers [34] provided the following results:

"The study comprised 1257 male seafarers. There were statistically significant more overweight seafarers in all age groups compared to a reference group ashore. Among those between 45 and 66 years of age 0.7% had a weight below normal, 22.7% had normal weight and 76.6% had a weight above normal, while 30.9% of this age group was obese".

These findings show that overweight issues are very common amongst marines so our proposing of this evidence is realistic enough.

2) Aged Watchkeeper → Age: 45 plus (e3)

For this node we propose a watchkeeper who is over forty years of age. Given the fact that several years of service are required in order to reach the rank of Captain, First, Second or even Third Mate, a watchkeeper can easily be over forty five years old, a fact also confirmed by the [110] questionnaire.

3) Lack of Quality Recreational Facilities → Recreational Facilities: Poor (e4)

According to ABS Crew Habitability Guide [61], mariners consider the following as vital parts of an ambient recreational environment:

- Internet access
- Access to a telephone
- Able to send/receive email
- Exercise equipment
- Satellite Television
- Library (DVDs & books)

The same guide also reports that better onboard living conditions (habitability and recreation facilities) as one of the main concerns when living at sea for long periods. In conclusion, we can assume that since this matter is still a common request amongst mariners, there is substantial probability that the overall quality of recreational facilities onboard is poor. Internet availability was recently made mandatory for

Greek merchant vessels and thought to be a great step forward. In reality, the importance of communicating with his social circle in the land is crucial for a mariner and his morale concluding that shipping companies do not yet approach the issue correctly.

4) High Humidity levels → Humidity: High (e5)

Crew Endurance Management system [103] identifies high humidity as a common issue aboard merchants vessels while it presents it as the main cause for Heat Exhaustion. The following excerpt is part of the chapter regarding sleep and circadian rhythms:

"Energy is restored optimally during uninterrupted sleep periods of 7 to 8 hours, with the sleeper reclined on a comfortable mattress in dark and quiet room at 65 - 70° F and 60 - 70% humidity".

5) Exhaustive workload, regular port calls and sleep deprivation→
Management Demands: Demanding (e6)
Hours Awake: Twenty four (e7)

The following passages by Martin Machado (AB seaman)[6] are part of his testimony regarding his months of service on a container ship:

"I have been living and working as a deckhand on a 906 foot container ship making 57 day runs from New York to Singapore, while hitting many ports in between".

"*Overtime is where a sailor makes his money, so we take as much as they'll give. I typically get around 12 hours work each day at sea, and in port I can work almost 24 hours straight at times. So any sleep is much appreciated".*

Note: At this point we could also import evidence regarding heavy workload and high alert state but decided against it since the Hours Awake evidence affect these nodes directly thus producing a realistic scenario nevertheless.

6) Bad weather → Weather: six_seven_considerable_waves (e8)

The *Containershipping.nl* website's containerships accident database indicates that in half of the 42 incidents that were investigated the last decade, weather was a major factor. A typical example is that of the containership MSC Napoli:

"*While en route from Belgium to Portugal, on January 18, 2007, during European windstorm Kyrill, severe gale force winds and huge waves caused serious damage to*

[6] Able Seamen's duties include standing watch as helmsman and lookout

Napoli's hull, including a crack in one side and a flooded engine room. The ship was then 50 miles (80 km) off the coast of The Lizard, Cornwall".

While we avoided importing evidence that would reflect an extreme weather incident, we felt that the six to seven B (Beaufort scale) sea state would be a representative example of a 'bad' weather scenario.

7.3.2 CALCULATING THE PROBABILITY FOR THE HYPOTHETICAL SCENARIO

7.3.2.1 ACCIDENT FRIENDLY SCENARIO

Table 7. 9: Containership accident friendly scenario

Evidence	1.Fatigue Posterior Probability P(Fatigue = yes)	Change (%)
No evidence	0,777	0.00
e1	0,789	1.54
e2	0,794	0.63
e3	0,805	1.39
e4	0,845	4.97
e5	0,859	1.66
e6	0,878	2.21
e7	0,91	3.64
e8	0,913	0.33

Even though the first three evidence do not seem to affect the posterior probability significantly, (e4) reaches the red zone by an almost 5% increase. This fact can be easily explained as the vessels recreational facilities is a micrographic representation of the vessel's overall facilities (as shown by the parent-child connection in our network). Another interesting finding is that weather seems to leave the posterior probability unaffected due to the fact that (e8) was imported last when the situation was already extreme and could hardly worsen.

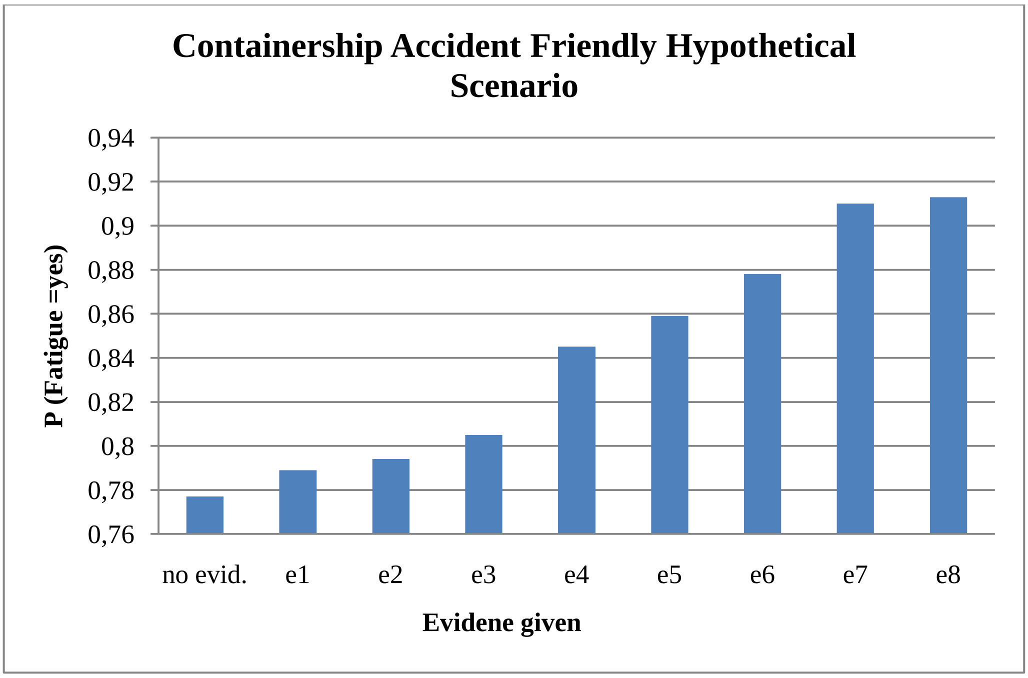


Figure 7. 18: Containership accident friendly scenario

7.3.3.2 OPTIMAL SCENARIO

1) Fit watchkeeper → Physical exercise: Regular (e1)
Nutrition: Fair (e2)

Through regular exercise and proper regulation regarding the mariners' physical condition.

2) Young watchkeeper → Age: 45 minus (e3)

3) High Quality Recreational Facilities → Recreational Facilities: Fair (e4)

By embracing the mariners' needs and complaints.

4) Low Humidity levels → Humidity: Low (e5)

5) Normal workload, improved shift planning, adequate sleep→
Management Demands: Normal (e6)
Hours Awake: Sixteen (e7)

6) Normal weather → Weather: three_calm__waves (e8)

Again, in similar manner to the Antari alternate scenario, after importing the first five evidences the posterior probability stays relatively high, due to the low prior distribution of the nodes' positive states. Finally, once again, sufficient sleep and proper management, manning and shift rotation seem to provide a quite improved context for battling fatigue. Weather on the other hand does not seem to be a major concern in such a healthy and ergonomic workplace.

Table 7. 10: Containership optimal scenario

Evidence	1.Fatigue Posterior Probability P(Fatigue = yes)	Change (%)
No evidence	0,777	0.00
e1	0,76	2.24
e2	0,758	0.26
e3	0,753	0.66
e4	0,725	3.86
e5	0,719	0.83
e6	0,656	9.60
e7	0,566	15.90
e8	0,559	1.25

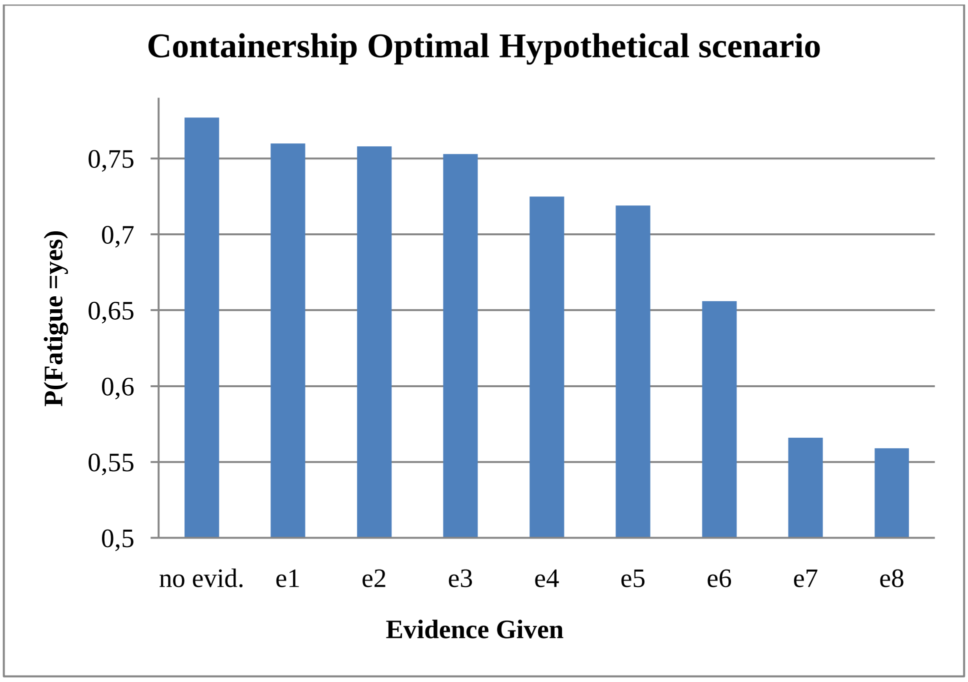


Figure 7. 19: Containership optimal scenario

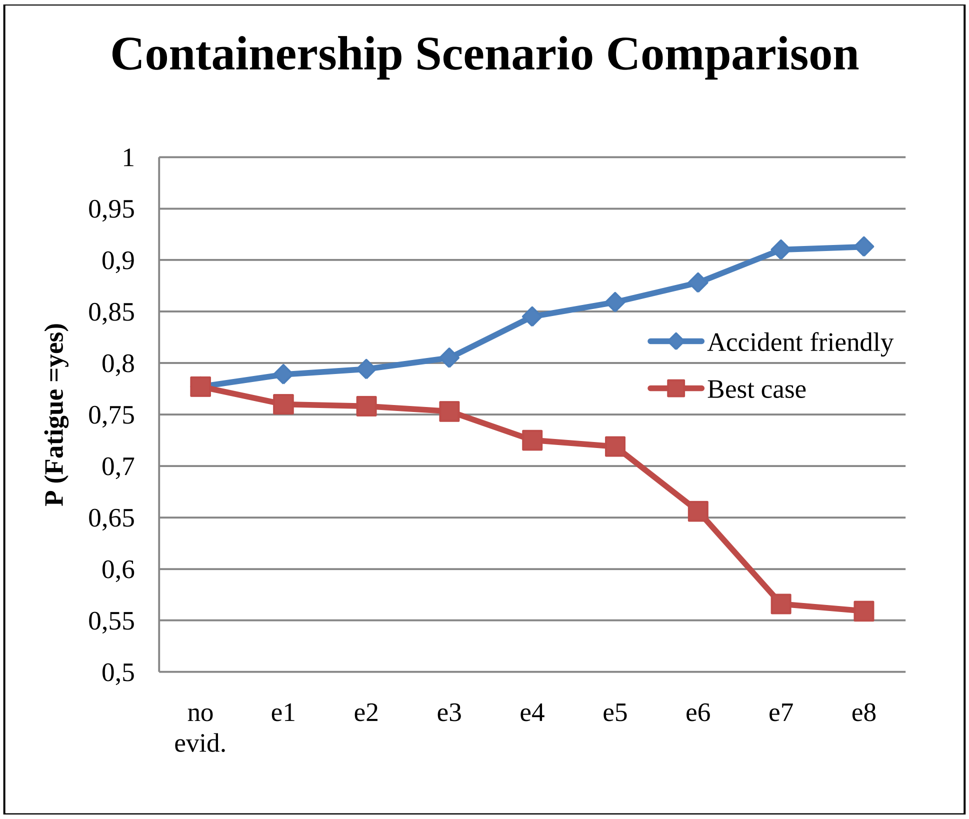


Figure 7. 20: Containership Scenario Comparison

CHAPTER 8

SENSITIVITY ANALYSIS

8 SENSITIVITY ANALYSIS

8.1 INTRODUCTION

Sensitivity analysis can be described as a method that defines how “sensitive” a mathematic model really is when the parameters and the overall structure of the model experience changes. The primary advantage that a sensitivity analysis provides is the studying of the uncertainties of parameters that are almost impossible to measure accurately in the real world.

This procedure helps to build confidence in the model by solving such precision and quantification issues thus improving the model’s reliability. Therefore, when building a system dynamics model, the modeler is usually at least somewhat uncertain about the parameter values he chooses and must use estimates or expert knowledge. Sensitivity analysis allows the researcher to find the accuracy needed for an accurate and functional model. If the analysis shows signs of insensitivity to parameter change, then it is probable that a rough estimation might serve as better information than an actual value. Sensitivity analysis can also pinpoint which parameter values are reasonable to use in the model. The ultimate objective of this procedure is to create a model that reflects the real world so the best way to determine that is by comparing the result to realistic scenarios. If these comparisons show similar findings then the model has both high precision and functionality.

Finally, sensitivity analysis can also provide knowledge about the overall tests dynamics of a system. Experimenting with a wide range of values can offer insights into behavior of a system in extreme situations. Through these experimentations the modeler can track down where the system behavior greatly changes after a specific parameter alters. To conclude, this method identifies a leverage point in the model, a parameter whose specific value can significantly influence the behavior mode of the system [10].

8.2. BAYESIAN NETWORK SENSITIVITY ANALYSIS

8.2.1 PARAMETER DESICION

In this paragraph we perform a sensitivity analysis on our Bayesian Network regarding fatigue in the maritime domain. Through this procedure, we hope to test our model in reliability, precision and ‘real world’ reflection (see paragraph 8.1). In the previous chapter our network was used in order to calculate the posterior probability of fatigue in real accidents and hypothetical scenarios with the use of evidence. To perform a sensitivity analysis we will change the prior probability distributions of certain nodes by a 100% range (+ 50% to -50%) in order to test the model’s sensitivity to these alternations.

In chapter 4, we discussed in depth the ship specific fatigue factors in order to present the situation from the naval architect/ designer's view. It is undeniable that, most of the times fatigue aboard ships is the result of the mariner's personal decisions. For example, STCW proposes 8 hours of uninterrupted sleep within twenty four hours; if a mariner has the chance to sleep but decides to spend this time on a different activity then the possible accumulation of fatigue would be primarily the result of his own personal choice.

A naval architect has little jurisdiction over the crew's actions during a trip but has the opportunity to provide a healthy, non-hazardous environment according to the principles of Human Factors and Applied Ergonomics. After a thorough search on existing literature and our own subjective knowledge we decided to focus on the following parameters which we feel can be managed and improved by proper design in accordance to the science of Naval Architecture and Marine Engineering:

- 1.Noise

The presence of noise is a common issue in the Maritime domain, especially for those working in a large engine room where crew members can hardly communicate with each other. Guidelines and regulations about noise tend to neglect its impact on fatigue inducing since they focus on the prevention of potential hearing loss. Temporary loss of hearing can be the result of even short-term exposure to noise and can eventually lead to permanent hearing loss. Moreover, guidelines about noise fail to address important physiological outcomes that may appear years after working in a noisy workplace. Our goal as engineers is to find ways to reduce the noise levels aboard the ship and isolate its prevalence.

- 2. Light

Light is an integral part of an ergonomic environment. While the importance of light is rather obvious the importance of light as far as visibility is concerned, its primary purpose is to maintain the regular pace of the Circadian Rhythms. Solar light is essential in calibrating our biological clock making the exposure to natural daylight a great need. Most mariners have to work night shifts while other crew members perform their tasks in places where no sunlight illumination is available even at daytime.(e.g. engine room).

- 3. Vessel Motions

Working in a constantly moving environment can often induce muscle fatigue since the vessel's motions would probably raise the average energy expenditure of the crew members. This can be easily explained by the need of a crew member to maintain his position/stance while performing a specific task at the same time. When the vessel experiences extreme motions due to severe weather phenomena, the crew member has to work and rest in an extremely hazardous and fatigue inducing environment. The Naval Architect can enhance the vessel's endurance to these situations by applying hydrostatic and hydrodynamics principles.

- 4. Vibrations

According to Calhoun [14], mariners experience shipboard vibrations caused by machinery, marine equipment and the ship's response to the environment. Vibrations resonate throughout the hull structure and the entire crew can be affected. The propagation of these vibrations along the decks and bulkheads subject the crew to whole body vibration and noise. Short-term exposure can lead to headaches, stress, and fatigue. Long-term exposure leads to hearing loss and causes constant body agitation. Maritime vibration guidelines keep levels low enough to prevent bodily injury but the recommended levels can cause fatigue and disrupt sleeping patterns.

- 5. Management demands

We decided to include this node in our sensitivity analysis as it is a common trend for engineers nowadays to participate in transportation and operations research procedures and even receive managerial posts in shipping companies. At this point our definition of management demands includes arranging shifts and routing, dealing with the optimization of maritime transport (e.g. classification societies) and the compliance of legislation on company policies (e.g. ISM code).

8.2.2 SENSITIVITY ANALYSIS

In this paragraph we are going to perform a sensitivity analysis for each of the parameters discussed in the preceding conversation by changing the prior probability distribution for a 100% range.

1. NOISE

Table 8. 1: Noise sensitivity analysis

State	Prior Probability Distribution	Posterior Probability for Fatigue	C (%)[7]
-50%	0.075	0.775	0.25
0	0.150	0.777	0.00
+50%	0.225	0.780	0.38
W.S.[8]	1.000	0.808	3.90

[7] % change of the posterior probability

[8] This state describes the worst possible scenario for Noise. We include this option to show what would be the highest possible value of the posterior probability for this evidence only.

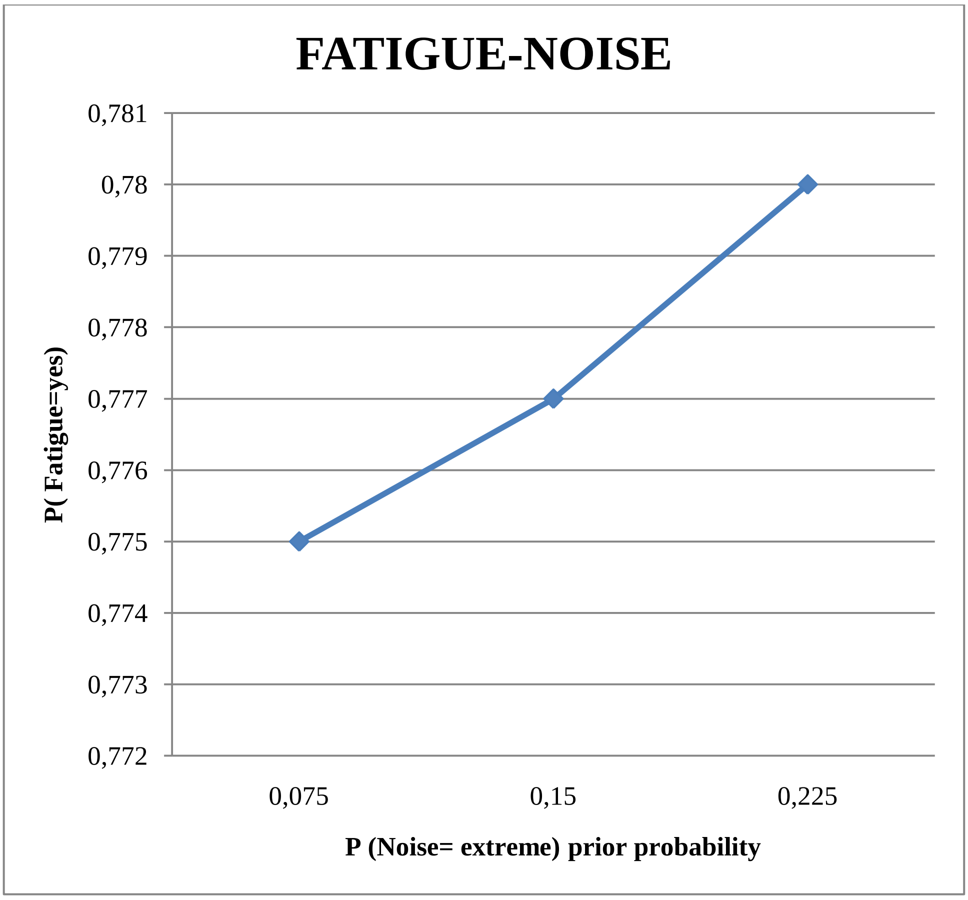


Figure 8. 1: Noise sensitivity analysis

The figure above shows that our model is rather insensitive to the noise parameter. Since we used estimation when setting the prior distribution for this node, the outcome of the sensitivity analysis serves to the model's reliability and 'real word' reflection. Even though intensive noises can disrupt sleeping patterns severely and create a fatigue inducing workplace, this evidence cannot raise the posterior probability by itself.

2. LIGHT

Table 8. 2: Light sensitivity analysis

State	Prior Probability Distribution	Posterior Probability for Fatigue	C (%)
-50%	0.100	0.770	0.90
0	0.200	0.777	0.00
+50%	0.300	0.785	1.01
W.S.	1.000	0.835	7.46

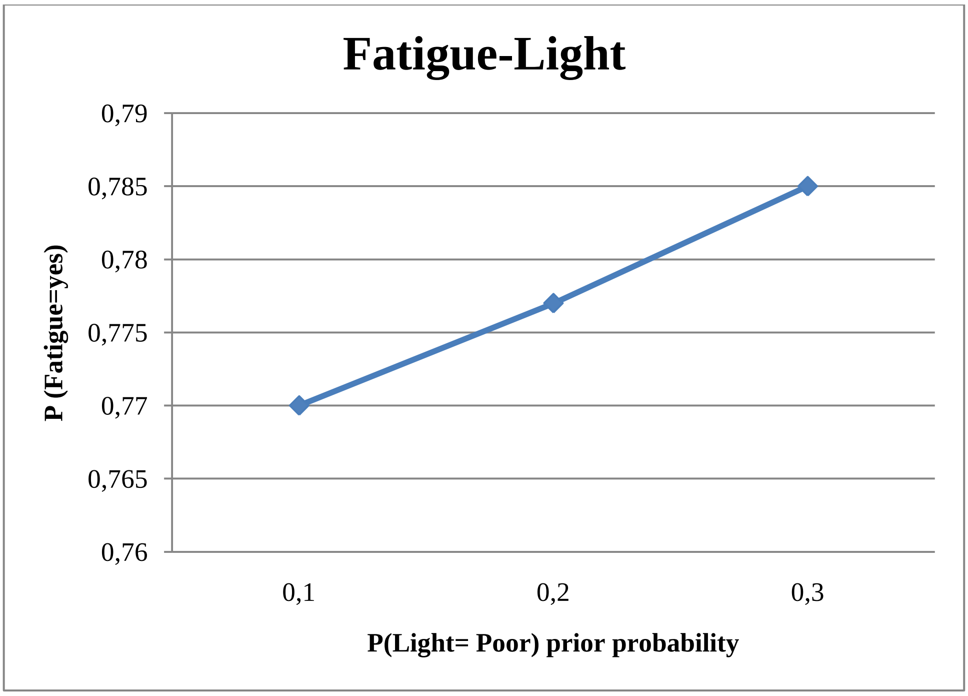


Figure 8. 2: Light sensitivity analysis

Contrary to noise, light seems to affect the posterior probability in a more profound way, a fact that is also shown by the 7.46% increase when poor light is imported as evidence. We can reasonably assume that this is both the result of a poor working environment as well as the disruption of the circadian rhythms.

3. VESSEL MOTIONS

Note: Because the Vessels Motions node is a child to the Weather node, we imported information by removing the parent node in order to assign prior probabilities to this node.

It is obvious that our model is more sensitive to this parameter than any other discussed in this chapter. This fact works to our advantage as it was anticipated due to the vessel's motions effect on both working and sleeping environment. To conclude, this is the field where the naval architect should focus in order to provide a non-fatigue inducing workplace. The 8.10% overall change is an indicator of this conclusion.

Table 8. 3: Vessel Motions sensitivity analysis

State	Prior Probability Distribution	Posterior Probability for Fatigue	C (%)
-50%	0.105	0.769	1.04
0	0.210	0.777	0.00
+50%	0.315	0.786	1.15
W.S.	1.000	0.840	8.10

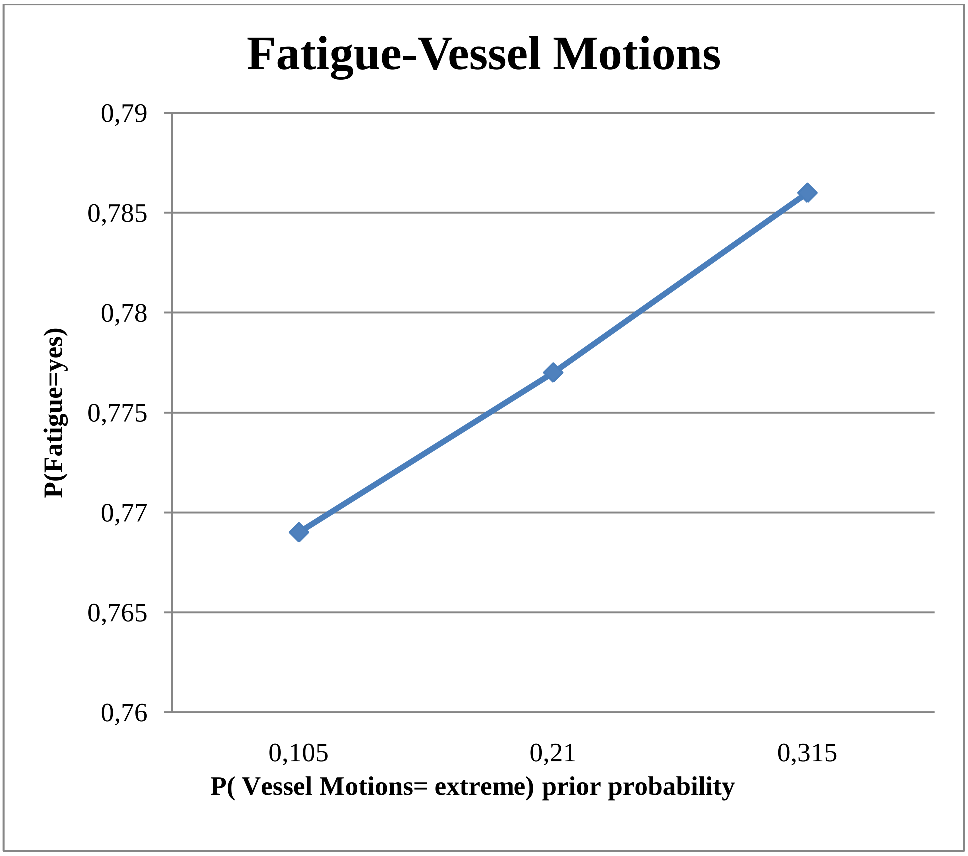


Figure 8. 3: Vessels Motions sensitivity analysis

4. VIBRATIONS

Table 8. 4: Vibrations sensitivity analysis

State	Prior Probability Distribution	Posterior Probability for Fatigue	C (%)
-50%	0.025	0,776	0.128
0	0.050	0,777	0.00
+50%	0.075	0,778	0.127
W.S.	1.000	0,822	5.70

Our previous discussion concerning the *noise* node applies for vibrations as well. The model's insensitivity to this parameter change proves that estimation for the prior probability distribution is preferred compared to that of an actual measurement. Finally, it is essential to point out that since the actual measurement for these parameters is difficult and often imprecise, the sensitivity analysis vindicates our choosing Bayesian Network to deal with this uncertainty problem.

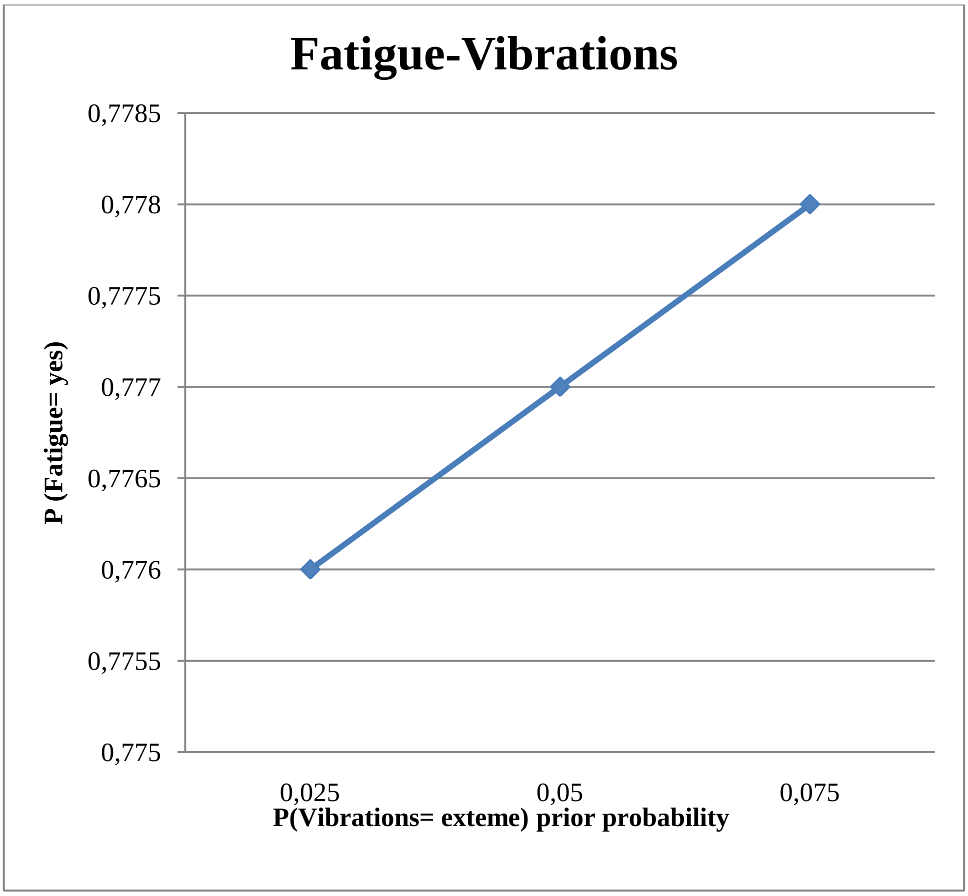


Figure 8. 4: Vibrations sensitivity analysis

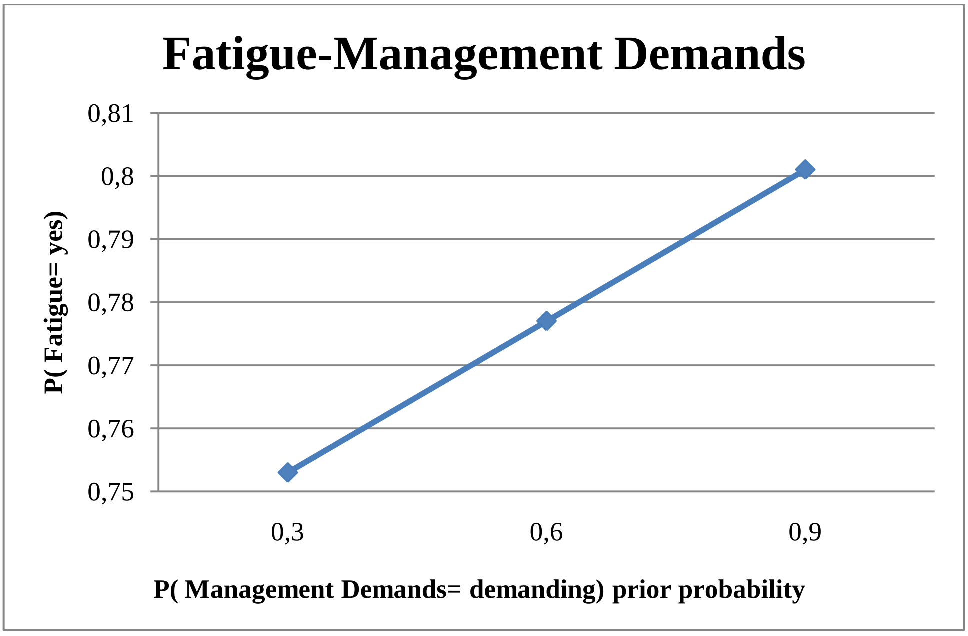
5. MANAGEMENT DEMANDS

Table 8. 5: Management Demands sensitivity analysis

State	Prior Probability Distribution	Posterior Probability for Fatigue	C (%)
-50%	0.300	0.753	3.18
0	0.600	0.777	0.00
+50%	0.900	0.801	3.08
W.S.	1.000	0.809	4.11

It was expected that our model would be sensitive to Management Demands for the following reasons:

- The prior probabilities distribution was already high due to the fact that the maritime industry is a highly demanding domain.
- Management Demands affect directly or indirectly workload, sleeping hours, work condition and overall living quality onboard.



<u>Figure 8. 5:</u> Management Demands sensitivity analysis

8.2.3 NAVAL ARCHITECT OPTIMAL AND WORST SCENARIO

In this paragraph we will present two scenarios in similar approach to that of Chapter 7. The nodes where evidence will be imported are those discussed in our sensitivity analysis. The order of the information inserted in our network is not random; evidence was imported according to the following rule:

- Evidence was imported in weighing order. The first evidence is the factor that the sensitivity analysis proved that affects the posterior probability less than the other nodes investigated.

The actual sequence that we followed is listed below:

- ❖ Noise (e1)
- ❖ Management Demands (e2)
- ❖ Vibrations (e3)
- ❖ Light (e4)
- ❖ Vessel Motions (e5)

8.2.3.1 OPTIMAL SCENARIO

- Noise (e1) : Normal
- Management Demands (e2) : Normal
- Vibrations (e3) : Normal
- Light (e4) : Sufficient

- Vessel Motions (e5) : Normal

Table 8. 6: Naval Architect Optimal scenario

Evidence	1.Fatigue Posterior Probability P(Fatigue = yes)	Change (%)
No evidence	0,777	0,00
e1	0,772	0,65
e2	0,722	6,93
e3	0,719	0,42
e4	0,700	2,71
e5	0,674	3,86

It is made clear in the following graph that by improving shift rotation, work schedules and reducing the huge amount of paperwork that a mariner must withstand while onboard, fatigue levels could drop more in comparison to the rest of the factors discussed in our sensitivity analysis. Finally, vessel motion seems to come second in importance.

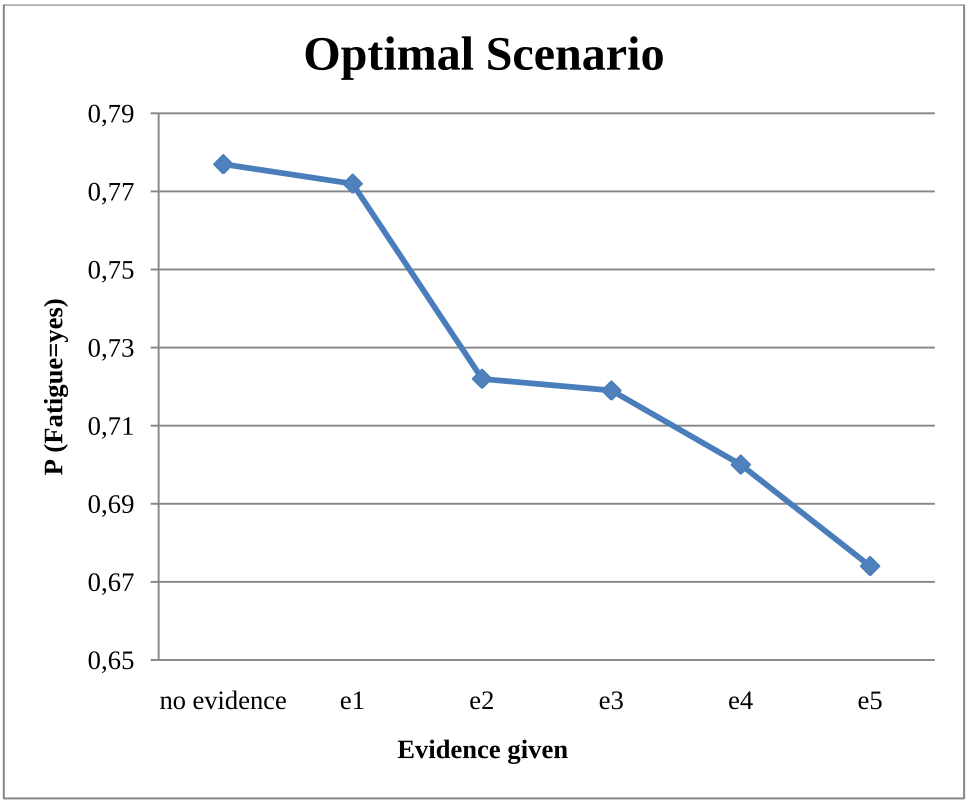


Figure 8. 6: Naval Architect Optimal scenario

8.2.3.2 WORST SCENARIO

- Noise (e1) : Extreme
- Management Demands (e2) : Demanding
- Vibrations (e3) : Extreme
- Light (e4) : Poor
- Vessel Motions (e5) : Extreme

Table 8. 7: Naval Architect worst scenario

Evidence	1.Fatigue Posterior Probability P(Fatigue = yes)	Change (%)
No evidence	0,777	0,00
e1	0,808	3,99
e2	0,836	3,47
e3	0,856	2,39
e4	0,881	2,92
e5	0,891	1,14

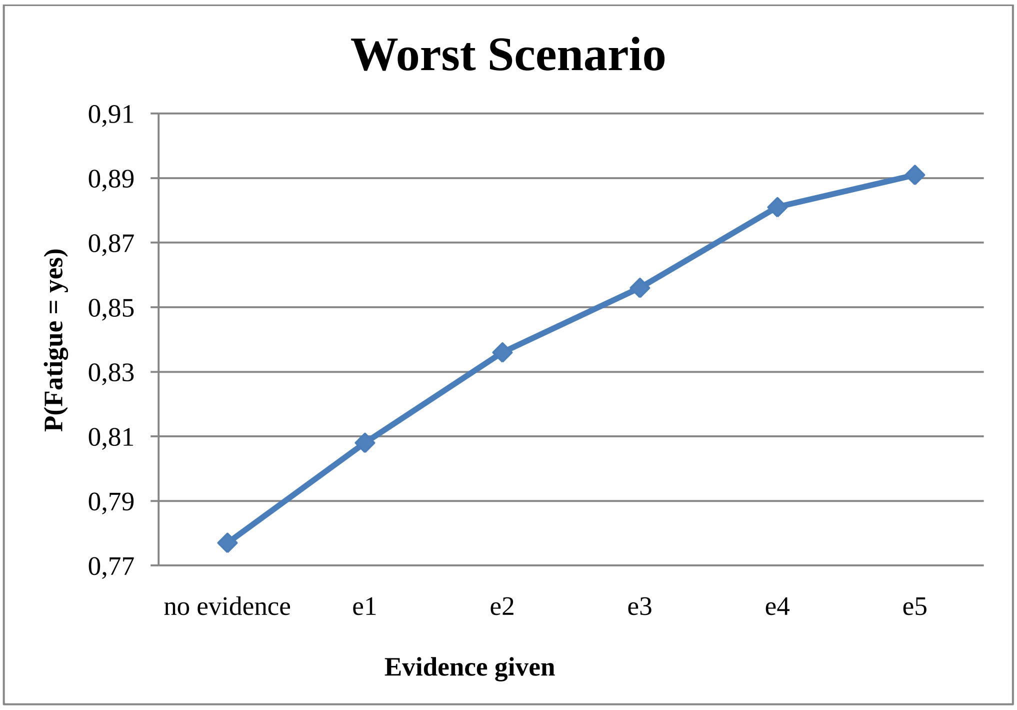
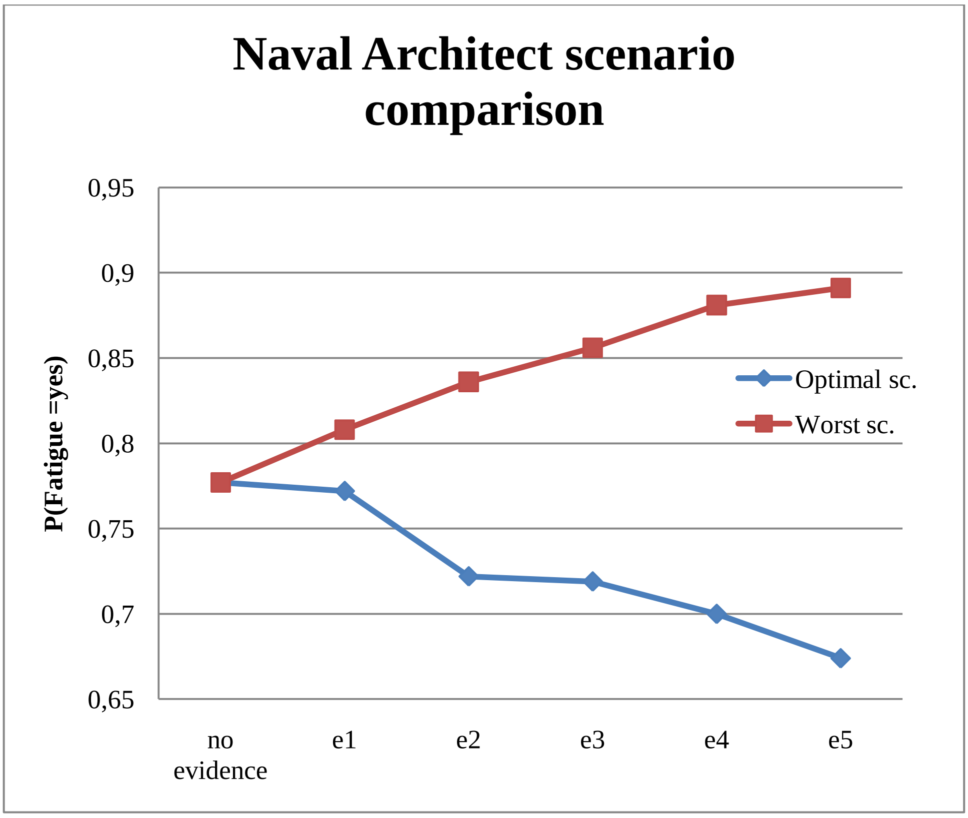


Figure 8. 7: Naval Architect worst scenario

Contrary to the optimal scenario, we can assume by the form of the figure, that all factors affect the posterior fatigue probability in a much similar way. The overall % change drops after the import of each evidence thus proving that when the situation is already dangerous it is difficult to worsen more.



<u>Figure 8. 8:</u> Naval Architect scenario comparison

CHAPTER 9

CONCLUSIONS

9 CONCLUSIONS

9.1 GENERAL LITERATURE

In this paragraph we will list our general conclusions that are the product of our extended research upon existing literature. The most important presumption can be found below:

- Even though Human Factors are responsible for almost 80% of maritime accidents and casualties, our industry is way behind in terms of research and ergonomics implementation compared to more advanced industries such as aviation and railroad. While constant effort is made towards proper integration of ergonomic principles on ships, the maritime domain has a long road ahead in order to fully benefit from Human Factors. Consequently, fatigue is under researched as part of HF science while it also underrated compared to other ergonomic issues such as human-machine interaction. We can only explain this tendency as a result of constant economic pressures and the need of shipping companies to reduce manning levels and operational costs. An interesting finding is that the United States Coast Guard, a nonprofit government organization, is a pioneer in the field of Human Factors engineering and fatigue mechanisms understanding and countermeasures in particular. This fact leads to the conclusion that fatigue should be properly researched firstly from the mariner's perspective and then of that of the shipping company in order to provide beneficial solutions for both parties.

- IMO has provided guidelines regarding fatigue mitigation aboard ship but the majority of scholars consider these propositions outdated. It took more than fifteen years to revise STCW, fifteen years where manning levels became even lower and the maritime domain became even more competitive and demanding. Most critics agree IMO's existing approaches seem largely inadequate while their improvement is clearly regarded as one strategy that could reduce the problem. IMO has the means and the authority to make fatigue awareness mandatory for mariners and shipping companies. The introduction of the Human Element working group and its interplay with various maritime organizations and parties (e.g. the FSA group) has provided an improved framework in order to properly eliminate fatigue-related hazardous outcomes.

- It is very common to regard fatigue as the main factor behind impaired performance and reduced safety aboard ships. While this is undeniably true, accumulative fatigue can have long term consequence that few mariners are aware of. A common example is the exposure to low density noises or vibrations which are not regarded as a potential threat in the workplace. However, scientific research has shown that constant exposure to vibrations and noises, even if their density does not seem threatening, can result to chronic fatigue and other long term deceases (e.g. spastic colitis). At this point, it is essential to indicate that almost every guideline or regulation addresses only short term issues while long term outcomes are completely neglected. In order to understand the preceding discussion we will provide a representative example of a common incident aboard a merchant vessel:

The regulation regarding permitted noise levels in the engine room were compiled in order to prevent permanent loss of hearing and difficulties in communication amongst crew members. However, studies have shown that exposure to noises of half the density proposed in the regulations is sufficient enough to induce fatigue and result in medical problems that may appear long after the mariners years of service. The question remains: How many mariners are aware of this fact and how many owners can understand that even these seemingly minor problems can result in casualties and compensations?

- Most surveys regarding mariners' fatigue have proved that the vessel's type and scheduling is a critical factor regarding fatigue. Questionnaires' findings show that crew member working on mini bulkers or small general cargo vessels tend to get tired more quickly than those who serve on large oil tankers. A logical explanation for these findings is the fact that the workload on short sea shipping vessels is heavier due to the regularity of port calls and the difficulty to adjust the mariner's lifestyle to the short trip-land-short trip sequence. Therefore, it is easier for a seafarer working on VLCC to adjust his daily routine in a 20 year trip than a crew member working on a 5000 DWT general cargo vessel that may have 10 port calls within a calendar month. It is crucial to mention that whenever a ship is at port work shift routines are often abolished while crew members rest for very small periods thus resulting in sleep deprivation and circadian disruption. Finally, we must add that mariners working on containerships and RO/RO carriers, independently of size, also experience similar issues due to the nature of the vessel's trading schedules.

- The implementation of advanced technology aboard ships has resulted in the constant decrease of manning levels while the need to cut operating costs has provided as a fertile field for this practice. The majority of mariners complain about working hours and insufficient time for rest or the poor quality of onboard recreational activities. A typical example of this practice would be the disaster of Exxon Valdez .Whereas tankers in the 1950s carried a crew of 40 to 42 to manage about 6.3 million gallons of oil; the *Exxon Valdez* carried a crew of 19 to transport 53 million gallons of oil. In 2010, the complements policies are more flexible than ever. While certain Flag States try to keep strict policies regarding manning levels, the majority allows vessels to sail with minimum complements. In addition, the integration of highly complex and sophisticated machinery aboard ships has created the need for extensive training while it impaired the mariner's initiative and understanding of his surroundings.

- The issue that we feel is of the outmost importance when addressing fatigue, is the proper knowledge and understanding of the subject. Most people working aboard merchant ships are unaware of fatigue mechanisms and its causes. While various organizations (e.g. STCW and Classification societies) have tried to provide sufficient information about fatigue, sleeping patterns and circadian rhythms, questionnaire findings and several other interviews indicate that seafarers' overestimate their capabilities and exceed theirlimitations thus making themselves vulnerable to fatigue prevalence. Whether they knew what they were up against, they would probably think twice before endangering their personal safety and the ship's as well. Where legislation and guidelines focus on what might cause fatigue, they rarely mention the effects on general well being and performance. Finally, since fatigue cannot be measured precisely, the importance of proper fatigue perception is integral for an individual to understand when his limitations have been surpassed and further effort will eventually result in underperformance and dangerous incidents.

- Recent statistical data show that fatigue related incidents are almost 20% of all maritime accidents. We think that this percentage is an underestimation since most errors recorded, even if there is no direct connection to fatigue, are often result of a tired individual. For example, in a conversation between two sleep deprived officers, if there is a misunderstanding in a specific command, the error will be recorded as a communication error. Knowing that fatigue can impair an individual's hearing ability, this error now seems more of a fatigue error than a communicational one. Therefore, most reports fail to recognize this fact thus neglecting fatigue's actual importance. In addition to the preceding conclusion, since most mariners cannot recognize the actual effects of fatigue, it is logical that many slips and errors are recorded in a different manner. Our rough estimation is that fatigue related accidents are over 50% of the overall maritime incidents given the fact that the maritime industry is often connected to heavy workloads, pressing deadlines and other demands.

- Furthermore, it is rather profound that there is difficulty in understanding and implementing fatigue related human factors in ship design. Naval architects focus on the vessels endurance to waves, its overall stability and the optimization of its service speed. When it comes to designing the superstructure, their top priority is to ensure its structural resilience and overall interaction with the hull. However, the proper designing of the sleeping quarters and recreational facilities, naval architects neglect the importance of the working and sleeping environment in order to reduce costs and enhance the vessel's performance at sea. For example the fact that the sleeping quarters are just above the engine room can prove a risk factor for fatigue. The engine room is the source of extreme noises, vibrations and even high temperatures and humidity which, with the lack of proper dampening, make their way to the superstructure and into the sleeping quarters creating an unhealthy sleeping/living environment for crew members. Finally, few studies have highlighted the impact of the vessel's motions on the mariner's performance and the difficulties that may come with working in a constantly moving environment.

- Proper lighting aboard ships has been highlighted as a major issue regarding fatigue, lack of alertness and the circadian rhythms. Most guidelines focus on visibility issues while the impact of poor lighting on the disruption of the circadian rhythms pattern is addressed with desultoriness. Crew members working in the engine room, even during daytime, lack the salutary effect of sunlight. Watchkeepers who perform night shifts in a regular basis tend to have alertness issues due to their biological clock malfunctioning. In conclusion, lighting quality is not yet regarded as major contributing fatigue risk factor by IMO or the ISM code. Nevertheless, our thesis, in accordance to the existing literature, pinpoints the need for improvement and more thorough revision on existing legislation.

9.2 CONCLUSION FROM OUR BAYESIAN NETWORK APPLICATION ON MARITIME SCENARIOS

The following conclusions are products of our Bayesian Network application analysis on real and hypothetical scenarios:

Note: Some of the findings were general and therefore were included in the previous paragraph (e.g. vessels motions)

- Our major finding was that human physiology (sleep and circadian rhythms) is the milestone in any discussion or study regarding fatigue. The safeguard of sleeping quality and the proper function of the biological clock is the integral step towards fatigue mitigation. Even if all other factors such as environment and work condition are favorable, poor sleeping quality and drowsiness will always result in fatigued individuals and underperformance. Taking this general rule into consideration, we realize that our best chance to enhance sleep quality is by providing better work schedules, sufficient rest opportunities and heavy workload discharging. As far as the naval architect's perspective is concerned, there is a great potential for improvement in both working and sleeping conditions, the most prominent being the opportunity to ameliorate the connectedness between the vessel's motion and limitations (e.g. difficulty to sleep in a moving environment).

- All examples investigated proved to be sensitive to one specific parameter: the monotonous nature of watchkeeping. While examining the figures provided by each scenario, one thing was made perfectly clear; tedious jobs can radically increase the fatigue posterior probability. The situation could easily get out of hand when working night shifts. On the other hand, any attempts made to provide a more interesting kind of task (e.g. Betty James) often result in distracting environments. Finally, even if most concerned parties agree that the nature of that task can hardly change, we believe that it is of the outmost importance to provide a less tedious task when it comes to watchkeeping.

- Another interesting fact that came to our knowledge is that mariners often lie on official documents about rest times. These facts often come into prominence after a major disaster, when investigations find serious contradictions between official documents and mariners' actual testimonies. This practice is a typical procedure of underreporting/misreporting which allows mariners to infringe policies and regulations. This also confirms the fact we discussed earlier about the seafarers' ignorance and poor knowledge regarding fatigue mechanisms and its possible outcomes. Our main assumption about this practice is the following: The seafarers are risking much more than they wish to avoid.

- Most of the accidents related to fatigue involve a sole watchkeeper on the bridge. Flag state policies and other legislation make the presence of at least two watchkeepers on the bridge mandatory at all times. Unfortunately, the tendency to reduce operating cost has led shipping companies to reduce manning levels as well, making this situation unavoidable. After many years of debating, most parties agree that extra watchkeepers should be made mandatory in order to avoid further disasters in the maritime domain.

- At this point we must indicate that our graphical model was generally compiled having indoors activities in mind. Our Bayesian Network makes the assumption that most crew members work indoors so they are not exposed to weather and temperature. In a real time scenario, this could not be true as many duties on-board require outdoor activities (e.g. small fishing vessels). Therefore, it would be correct to assume that the major findings of this thesis are addressed to mariner's working mostly indoors (especially officers and engineers). However, our general approach to fatigue and our thorough description of its consequences could serve as useful instrument for any mariner serving on a merchant vessel.

- While most seafarers believe that their training is sufficient to overcome any obstacle during a day at work, our study has found that: a) crew members tend to overestimate the level of their training and general competence b) older, more experienced mariners have lesser stress and anxiety problems. Finally, we must mention that the presence of fatigue and the lack of proper training can be a rather lethal combination that may result in major disaster.

- More and more mariners complain about the quality and availability of recreational facilities aboard ship. The presence of such installations has proven to be an effective measure to reduce stress levels and enhance the crew members' morale. Furthermore, internet availability is essential, especially for those serving on deep sea shipping vessels that spend months away from families and friends.

9.3 SUGGESTIONS

In this paragraph we will present our suggestion for each of the conclusions discussed in this paragraph and several other methods that may proven to be useful for mitigating fatigue in the maritime domain:

- Proper integration of Human Factors Engineering into Maritime Transport and Ship design

- Emphasis on physiology and the Circadian Rhythms through further research and recognition of fatigue as a primary factor in maritime casualties

- Research from the seafarer's perspective instead of the shipping company's

- Further improvement and revision of the Guidelines proposed by IMO and the amendments made by STCW with emphasis on working/rest hours

- Stricter Flag State legislation regarding manning and watchkeeping

- Better understanding of the long term effects of fatigue and exposure to low density noises and vibration. Assistance from the medical field

- Revision of Guidelines and regulations regarding habitability with specific emphasis on permitted noise, vibrations, humidity levels and lighting quality

- Higher manning levels, especially for short sea shipping vessels and containerships. Port assistance during discharging (especially for large tankerd and containerships)

- Recognition of the fact that a human could not be replaced by any machine or software

- Proper education about fatigue in general. Crew seminars with emphasis on fatigue prevalence, personal choices and countermeasures. Identify fatigue perception as a major concern

- Improved in-depth techniques for categorization of human error in order to highlight the importance of fatigue at sea

- The implementation of fatigue related issues into the principles of Naval Architecture and Marine Engineering. The naval architect should not neglect habitability issues in favor of the vessel's performance. Both aspects should be treated with similar interest and graveness

- Installation of more efficient lighting systems with emphasis on the Circadian Rhythms mechanism

- Improved, ergonomic sleeping quarters. Sleep is fundamental when discussing fatigue so there should be constant effort for improving sleeping environments and the overall sleeping quality

- The watchkeeper's task has to become less monotonous and passive while two crew members must remain on the bridge at all times. Legislation should be even stricter regarding this matter

- Countermeasures for underreporting errors and non-compliance to regulations through more regular inspections and thorough investigations of official documents regarding rest hours and work schedules

- Introduction of improved and ergonomic recreational facilities. Sufficient spaces for accommodation for all crew members and implementation of contemporary facilities such as internet connection and DVD's

- Proper training with emphasis in emergency situations and human-machine interaction through simulation procedures

- Last but not least, fatigue can be eliminated by adjusting to a healthy life style. Personal decisions and situation awareness is very important in order not to overestimate the human body's capabilities and exceed its limitation. Mariners should understand that by not reporting fatigue or by infringing regulations regarding rest hours, they are putting themselves and the ship in great danger while embracing a hazardous practice that has led the maritime industry into major catastrophes, fatalities and large ecological disasters.

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