APPLICATION OF TOPOLOGICAL MODELLING METHODS FOR DETERMINING HUMAN FATIGUE

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Abstract. Fatigue is a complex concept that is simultaneously a physiological, psychological, and social phenomenon which pathophysiology is still not fully understood. Solutions offered by modern technologies are also still unable to prevent economic losses, but even more importantly not to lose human resources in high-risk sectors such as transport and operations. If the fatigue topological model (TM) is created in the form of a directed graph, the analysis provided by such a model in the main problem solution on the level of expression of human fatigue remains to be performed. First, the model makes it clear that in practice the often-combined terms fatigue (F) and drowsiness (D) are neither the same nor the opposite in nature. The graph configuration will clearly indicate the routes belonging solely to F and belonging solely to D, as well as the routes common to F and D. Secondly, based on the graph theory, a formal algorithm enables a selection task to be performed to select the most efficient set of parameters to measure fatigue. The method of selection is derived from the so-called table overlay method. In practice, this method is justified because there are no parameters that can be measured only under laboratory conditions, or the sensor is inconvenient to perform the work. The resulting parameters selected from TM can be obtained with one touch sensor placed on the head. The rest of the information comes from a remote camera, test results and self-survey data.

Keywords: topological modelling, graph theory, human fatigue.

Introduction

The knowledge about human fatigue includes a selection of latent observable indicators or manifest variables that are believed to reflect the latent constructs like fatigue, drowsiness, and workability. The analysis of large and complex data sets is crucial to all areas of science and industry and is needed to support artificial intelligence. The researchers select observable indicators or manifest variables that are believed to reflect the latent construct. The scientific problem proposed in this paper is to define a holistic approach which is based on expert methods for topological modelling and aims to comprehensively gather the knowledge about human functional systems, that have the domain expertise, but the individual experts have limited statistical information about the cross-domain relations. Existing methods for data analysis are often inadequate to deal with data that exhibit a great deal of complexity, because they are unable to express complicated “data shapes” [1]. Topological data analysis (TDA) extracts knowledge from data in a holistic approach via topological considerations [2]. The approach of expert methods is required to obtain the distance information to the topological representation given in the model without direct statistical information, which would otherwise require to experimentally rank or weight the links in a cross-disciplinary manner.

The heuristic way of solving problems and mathematical modelling can be used to analyse functioning systems to create the right working conditions. Topological modelling is an effective tool for developing mathematical models for heterogeneous systems if the available information is insufficient. A practical model-building process is tailored to use in medical tasks, where the conceptual model reflects the overall knowledge and consensus of the expert team knowledge, which is the source for further construction of fatigue component level statistical models. A similar problem is solved with a mechanism to model assessment criteria and multi-purpose optimisation methods, it is possible to prescribe an optimal treatment complex for a particular patient [3]. This exercise involves the use of topological modelling in biology [4] and medicine, which is associated with the problem of fatigue detection. Other authors use the stressor-strain-outcome (SSO) framework [5] to model the concept for mental fatigue component with antecedents and outcomes [6]. IBM AMOS software [7] for statistical modelling the research questions and hypotheses for the in-detail fatigue component relations implements Structural Equation Modelling (SEM) [8] and has significant results in the research of fatigue in cabin crew operators [9], physical exercise-induced fatigue [10] and mental fatigue [11]. The fatigue conceptual model was developed by scientists and experts of the Riga Technical University and Riga Stradins University together with experts from sleep medicine. The model is constructed with 3 levels of information, where A – causative and maintaining factors of disease, B – system internal functions and dysfunctions and C – manifestations of system states or measurable symptoms.

Materials and methods

The determination of the fatigue level is based on the topological model of fatigue (TM) in the appearance of the topological graph, where one of the most laborious processes for the experts is the numerical estimation of graph elements (nodes and links). This is made difficult by the fact that not many numerical values are used to characterise biological objects. There are many parameters of a subjective nature that have no numerical values, dimensions, or instruments, especially for describing conditions such as fatigue, drowsiness, self-esteem, etc. The group of experts were selected according to the voluntary method, and it consists of 10 domain experts from the Riga Stradins University sleep laboratory and the Latvian Sleep Medicine Society, where 10-20 experts are recommended by the used expert iteration method [12]. Expert assessments on conditional ball scales prevail. Expert assessments cover both the graph nodes and links. To obtain reliable expert assessments, the following steps should be taken: a team of experts should be drawn up, the degree of collective consensus of experts should be established, the statistical credibility of expert judgements should be calculated. One algorithm for creating a team of experts is the technique of self-evaluation and mutual evaluation. The degree of consensus of experts is determined by the concordance coefficient W based on the correlation of the Spearman rankings [13]. The W value range is 0-1. The threshold of consensus required in medicine is $W \geq 0.75$. For statistical reliability, the statistical hypothesis test method using the Pearson factor x^2 will be used. Confidence threshold values are 0.95; 0.99; 0.999. In the specific study, the degree of collective consensus among 10 experts varies from 0.831 to 0.874 in different tasks. The statistical credibility across all tasks is 0.99.

The selected team of experts will assess the nodes and circles of the TM, according to the criteria set and further develop an expert system for determining the degree of fatigue expression.

Topological model element rating method

Graph nodes represent parameters of physiological processes the values of which can vary depending on the duration and intensity of the process for a particular person at a given point in time. Since the purpose of the future expert system is to recognise the level of fatigue expression by the values of parameters called measurable or diagnostic parameters during the human labour, training or recovery process, a set of parameters is subject to several requirements or quality criteria. The main ones are:

- α_1 – good availability of the parameter for measurement, sensor placement, presence of processing equipment;
- α_2 – absence of human inconvenience during parameter determination.

The parameter or node weight λ [14] can be obtained by the weighted sum method (1):

$$\lambda i = \varepsilon_1 \alpha_1 + \varepsilon_2 \alpha_2 , \tag{1}$$

where ε_1, ε_2 – weight coefficients of the corresponding evaluation criteria

$$\sum_{j=1}^{2} \varepsilon_j = 1 .$$

According to expert judgement, the values of the coefficients are ε_1 = 0,3 and ε_2 = 0.7.

The numerical evaluation of graph links is more complex. The link from the node x_i goes to the node x_{i+1} when x_i value affects x_{i+1} value. A quantitative value, known as “link weight”, $I(x_i/x_{i+1})$, may be assigned to the link expressing the magnitude of this impression. In substance, it expresses the amount of information between two parameters within the meaning of information theory. The link weight shall be evaluated with the value 5 indicating the closest link between the parameters (greater amount of information transmitted). In other words, it can be expressed as link permeability, the sensitivity of the parameter x_{i+1} to x_i. The link weight shall have the highest rating if minor but still to be recorded changes in the values of parameter x_i are to be fixed in parameter x_{i+1}. The transmission of information over the entire route, rather than between adjacent nodes, plays a more important role in this task. The route in the graph is called an oriented chain of causes-effects consisting of nodes and links. One of the main characteristics of fatigue, or code nodes, can be considered as one end of the route. One of the possible diagnostic parameters is at the top of the other end of the route. In an orientated and evaluated graph, the route length or distance is called the size [14], which is defined as (2):

$$\rho\left(x_i, x_j\right) = \min \sum\nolimits_{i=1}^{j-1} \bar{I}\left(x_i / x_{i+1}\right), \tag{2}$$

where $\bar{I}(x_i/x_{i+1}) = I_{\min}(x_i/x_{i+1})_{\max}$ – inverted link weight required to avoid discrepancy between individual link weight and route length;
$I_{\max}$, $I_{\min}$ – maximum and minimum values of link weights for a given task.

The inverse of the distance or proximity measure (amount of information) between the top of the code and the route parameter is (3):

$$\bar{\rho}\left(x_i, x_0\right) = \rho_{kr} + \rho\left(x_i, x_0\right)_{\min}, \tag{3}$$

where $\rho_{\max}$, $\rho_{\min}$ – maximum and minimum value of the route length in this task.

The amount can be calculated for each node of the route. If the length of the route is shortened in advance so that is not needed to work with very distant nodes from the nodes of the code, then the critical value ρ_{kr} should be used instead of $\rho_{\max}$. For selecting a set of parameters to be measured, it is important to calculate the efficiency indicator Φ_i for each node (4):

$$\Phi_i = \alpha\lambda_i + \beta\bar{\rho}\left(x_i, x_j\right), \tag{4}$$

where α, β – coefficients of importance.

By expert decision, the values of the coefficients are $\alpha = 0.4$ and $\beta = 0.6$. TM of fatigue and drowsiness with element assessments is given in Figure 1.

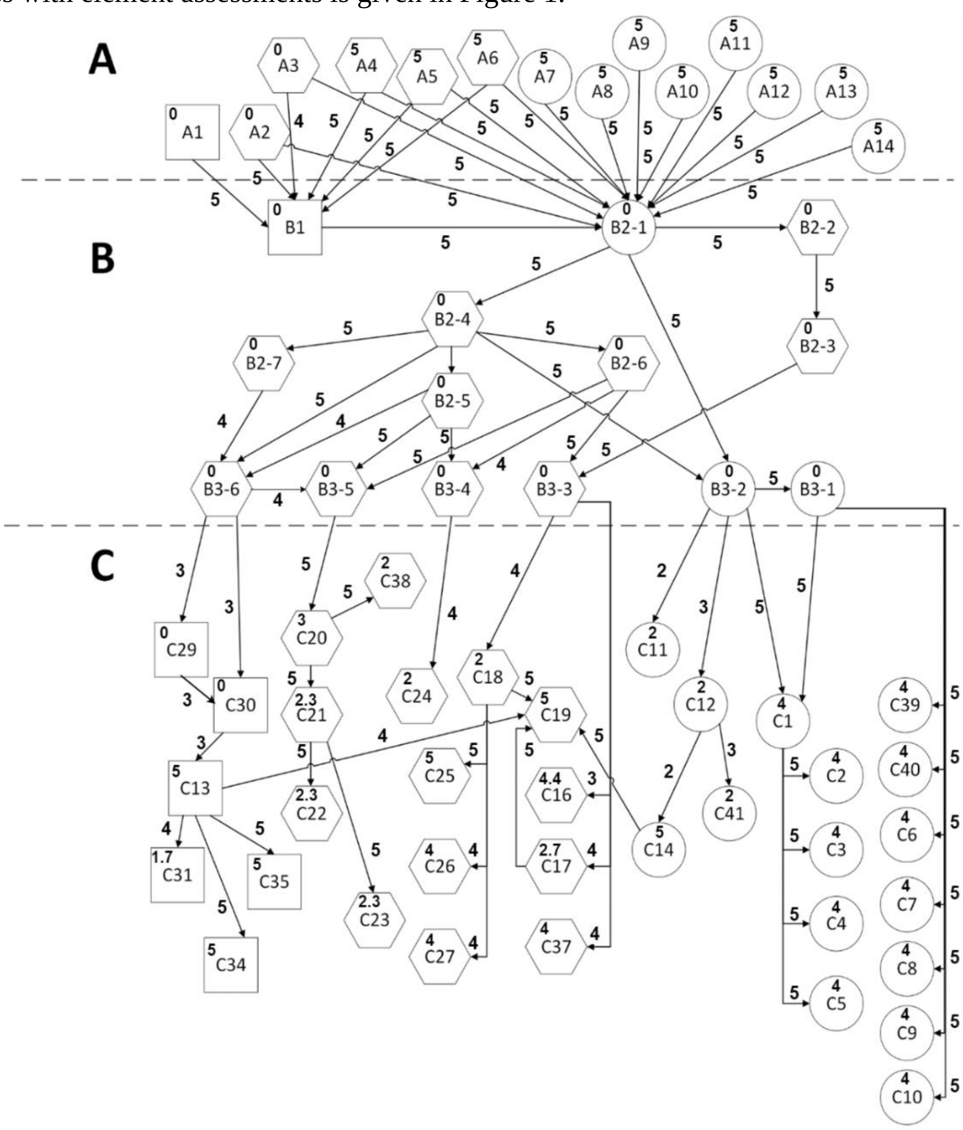

Fig. 1. **Topological model of fatigue and drowsiness with element assessments**

Node assessments (weights) in the Fig. 1 are given inside each node designation, link assessments at arrowhead ends. The circles represent parameters belonging to drowsiness, with squares – belonging only to fatigue, with hexagons – belonging to both states.

Diagnostic parameter selection algorithm

A table overlay method is chosen from a large range of parameter selection methods, which is well aligned with topological modelling, a multi-critical environment and allows variation with the number of parameters selected. To apply this method, one must find the most significant, so-called code nodes of the functional states. This allows to analyse routes by TM and to find out which parameters on the periphery of the model are most closely associated with code nodes. The drowsiness code consists of changes in neurohumoral regulation at several levels:

- B 2-1 Changes in CNS functionality;
- B 2-2 Changes of Peripheral Nervous System Activity;
- B 2-3 Changes of Peripheral Nervous System Activity;
- B 2-4 Changes of Vegetative Nervous System Activity.

A more detailed analysis of the fatigue pattern by separating 4 fatigue types (mental, physical, sensory, emotional), has shown that the mental fatigue code coincides with the drowsiness code. This indicates the sphere of covering drowsiness and fatigue.

Table 1

Table coverage method fragment

Nodes at level A and C	Node short description	Effectivity Φ_i	Code node B2-1	Code node B2-2	Code node B2-3	Code node B2-4
A4, A5, A6, A7	History data	5	5	4	3	4
A8, A9, A10, A11	History data	5	5	4	3	4
A12, A13, A14	Survey data	5	5	4	3	4
C25	Eye blink frequency	3.8	-	2	3	-
C2, C3, C4, C5	Test activities	3.4	3	2	-	3
C6, C7, C8, C9, C10, C39, C40	EEG α, β, θ frequency, indexes J1 -J4	3.4	3	2	-	3
…						
C21	Hypertensia	3.32	-	-	-	2
C20	Heart rate frequency	3.3	-	-	-	3
C18	Muscle amplitude	3.2	-	3	4	-
C26, C28	Facial muscle tonus	2.8	-	1	2	-
C19	Reduced workability	1.68	-	-	1	-
C11	Adenosine levels increase	1.4	-	-	-	1

A table is created that vertically displays process parameters ranked by the efficiency generator Φ_i in the first column reflected in Table 1. The nodes of recognized or evaluable process, state, or diagnosis codes are placed horizontally on the top line. Table boxes display values calculated for parameters $\overline{\rho}(x_i, x_j)$, called proximity measure, for each possible route that links the possible symptom to the top of the code. The table coverage shall be the minimum by number and the maximum by efficiency Φ_i parameter set having the highest positive numbers at the intersections with the code nodes. This ensures that the most characteristic parameters are found for each node of the code. The application of the table overlay method in the fatigue detection task has some differences from the classic differential diagnostics variant [15]. The classic variant searches for a recipe to differentiate between possible nosologies, so parameter resolution is important. Fatigue and drowsiness are not competing states in each task, they can be simultaneous, and the aim of the method is to determine their level of expression. Therefore, coverage not for each state, but for all the nodes of the code is evaluated. The other difference is as follows: in the classic variant, the overlay nodes are only at symptom level C, but in the case of fatigue, most of the suggestive values at level A may be included in the diagnostic parameter set, especially due to their mild finding.

Short algorithm for finding the table coverage:

1. The nodes (parameters) of the model are analysed for certainty in the order starting with the highest value of the efficiency indicator Φ_i calculated for the nearest code node;
2. Analyse the values $\overline{\rho}$ at the intersections of the line and code nodes, which characterize the proximity of the node to each code node from B 2-1 to B 2-4 if such routes exist;
3. If there is at least one significant number in the line, the node is included in the set of parameters to be determined (measured);
4. Analyse the node next in size to Φ_i, include it or not in the set of parameters to be determined;
5. The minimum set of lines (links) that provides at least one positive number for each node of the code is the coverage of the table. In the given example, the table coverage ends with row C6, C7, C8, C9, C10, C39, C40.

Results and discussion

A set of parameters has been derived from the fatigue topological model, by using the table overlay method, which is input information for the decision support computer system. It is divided into 2 parts – subjective and objective or measurable. Subjective information shall consist of the following 4 groups, which are further described in Table 2:

1. History data obtained by completing the questionnaire when the employee starts using the computer system to assess fatigue in the performance of his or her tasks;
2. Pre-shift survey data obtained at the beginning of each shift;
3. Test results obtained during the shift, during the pause or interruption of the monitoring process [16];
4. Measured objective parameters (EEG waves and blink frequency) obtained by a single sensor.

Table 2

Resulting diagnostic parameters

Parameter name	Description	Parameter group
A4	Shift work	1
A5	Stress at home/job	1
A6	Use of tonic drinks	1
A7	Head trauma	1
A8	Hypertension	1
A9	Use of sedative	1
A10	Apnoea	1
A11	Microsleep episodes	1
A12	Previous sleep quality	2
A13	Assessment of feeling	2
A14	Sleepiness self-assessment on Karolinska scale	2
C2	Memory test	3
C3	Reaction time test	3
C4	Attention test	3
C5	Arithmetic test	3
C6	EEG α wave amplitude duration deviations	4
C7	Change in index J1 (involvement in task)	4
C8	Change in index J2 (attention)	4
C9	Change in index J3 (stress level)	4
C10	Change in index J4 (alertness)	4

The resulting parameter set enables the creation of an expert decision support system that assesses the level of drowsiness and fatigue of an employee at the same time in professions requiring attention, focus and responsible decision-making which is a part of a more extensive decision-making system, where Mamdani fuzzy logic expert-systems [16; 17] apply the expert decision rules derived from the topological model.

Decision support system is an interactive system that helps decision-makers utilize data and models to solve unstructured or semi-structured problems like human fatigue and drowsiness. Similar research with the mental tasks [18] identifies the relationship between neural activity during the driving simulation tasks and human reaction time. However, the usage of expert methods, which is the aim of the current research, provides the necessary methods to specify the required decision-making parameters and provides the necessary tooling for the experts of sleep research to produce the knowledge in a human readable transparent format and to combine the subjective, objective information as well as the task results and the sensor data. The first level of parameter acquisition is combined with machine-learning algorithms to perform signal processing and the parameter acquisition for the expert system objective parameters from the human wearable sensors. Other authors [19] also emphasize that AI with fuzzy rules, machine learning or deep learning algorithms, as well as the methods of model explanation can be a valuable tool for creating accurate models of mental fatigue. The application of the Thurstonian models [20] accompanying structural equation modelling is a useful approach in modelling and analysing ranking data that have the subjective nature of the latent variables.

Conclusions

Several important characteristics should be highlighted when assessing the established fatigue TM. The first is the nature, sequence and interdependence of the investigational processes that are easily recognisable in the model. For the current application, it enables experts to recognize processes that are characteristic only of fatigue, which are characteristic only of drowsiness, and which are attributable to both states. This simultaneously allows them to see the benefits of drowsiness parameters over fatigue parameters in a particular application area. For the drowsiness value scale, both extremes are detectable, such as total vigour and the fact of falling asleep (the arrival of an easily detectable EEG alpha wave). Fatigue extreme is not fixable in comparison.

Secondly, it is possible to assess human fatigue using an expert knowledge model based on topological modelling and complex system theory, which involves analysing the regularities between the main functional systems of the body. The decision-making structure consists of several levels.

The third positive characteristic is that the representation of the model in the form of a graph and the numerical assessment of its elements make it possible to apply mathematical methods in discreet environments and to apply computer hardware to the implementation of algorithms. The applicability of the proposed method of selecting parameters is demonstrated by the fact that the set of parameters to be measured contains only the most informative and convenient ones to be determined. The parameter set does not contain any parameter that would inconvenience the employee, such as electrodes on the body, a head helmet with sensors, cuffs on extremities, front-facing video cameras.

Author contributions

Conceptualization, M.E and Z.M.; methodology, Z.M.; investigation, M.E.; writing – original draft preparation, Z.M. and M.E.; writing – review and editing, M.E.; funding acquisition, M.E. All authors have read and agreed to the published version of the manuscript.

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