UDC 65.012:656
DOI https://doi.org/10.32782/2663-5941/2024.5.1/34

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MODELLING THE DYNAMICS OF OCCUPATIONAL STRESS IN AIR TRAFFIC CONTROL

The subject matter of the article is occupational stress among air traffic controllers, the key factors causing it, and real-time management approaches. The research focuses on a comprehensive analysis of stressors and their impact on the overall stress level of air traffic controllers while performing their professional duties. The goal of the article is to develop a system dynamics model of work-related stress among air traffic controllers, taking into account various causes of stress and their interactions, as a basis for determining the overall stress level at air traffic controller workplaces and creating effective stress management strategies in the dynamic air traffic management environment. The tasks of the article: to investigate the primary sources of stress inherent in air traffic control work and analyze contemporary approaches to modeling the dynamic nature of professional stress; to identify and classify factors that contribute to the increase in the overall stress level at air traffic controller workplaces; to construct a graphical model of the relationships among stressor groups and to identify those that act as primary mediators in the transmission of information between other types of stressors; to develop a system dynamics model of occupational stress that illustrates both direct and feedback effects between the perceived overall stress level at air traffic controller workplaces and the relevant factors influencing it. The methods used are: logical analysis, cluster analysis, graph theory and graph analysis, and system dynamics modeling. The study defines and classifies a set of stressors (by their source) that increase the sense of overall stress among air traffic controllers, each with its corresponding controllability index and duration of impact. A system dynamics model of professional stress has been developed, consisting of a central component "air traffic controller's professional stress level" and several aggregator components that accumulate the impact of factors of different natures. Feedback loops in the model demonstrate potential reinforcing effects within the system. The scientific novelty of the results lies in the fact that the conceptual system dynamics model of professional stress among air traffic controllers provides a visual representation of the dynamic nature of stress experienced by air traffic controllers and the impact of key factors on their perceived stress at work. The presented model can serve as a basis for monitoring the dynamics of professional stress levels among air traffic controllers and enable effective stress management by supervisors of air traffic control shifts through the development and revision of operational, tactical, and strategic measures to address stress.

Key words: *air traffic controller specialists, occupational stress, stress management, stressors, system dynamic.*

Formulation of the problem. Air traffic control specialists (ATCs) work in a high-stress environment that requires constant vigilance, quick decision-making, and management of complex information. The demanding nature of ATC work can lead to occupational stress, fatigue, and potential impacts on job performance and safety [1]. Studies have found that even a 1% increase in air traffic can lead to a 10% increase in critical incidents for ATCs [2]. One study indicated that about 52% of air traffic management incidents were related to human error by controllers [3]. For instance, a survey among ATCs in China found that 77.4% reported experiencing stress in their work environment [4]. Given the critical role ATCs play in aviation safety, it is imperative to develop effective systems for managing occupational stress in this profession. Shift supervisors are in a key position to monitor and support ATCs, but may lack tools to systematically assess stress levels and determine appropriate interventions [5] A decision support system (DSS) tailored for ATC shift supervisors could help optimize stress management and maintain high levels of performance and safety. The development of the DSS is based on functional model of ATC stress management and main requirements, identified in our previous study [6].

The relevance of this research stems from the need to proactively address occupational stress in ATCs as air traffic grows, leveraging technology to support evidence-based decision making by supervisors. An effective DSS has the potential to enhance wellbeing of ATCs, reduce fatigue-related errors, and ultimately contribute to aviation safety.

Analysis of recent research and publications. Recent years have seen a growing body of research exploring the intricate relationships between mental workload, stress, and job performance in the ATC domain. Multiple studies have investigated how varying levels of mental workload impact ATCs' task performance. Metzger and Parasuraman (2005) found that high mental workload negatively affected ATCs' ability to detect conflicts and make timely decisions [7]. Similarly, Pant et al. (2012) reported that excessive mental workload could lead to diminished focus and increased likelihood of errors in ATC tasks [8]. ATC workload encompasses two dimensions: intrinsic complexity related to air traffic structure, and human factors associated with the controller's capabilities and vigilance [9]. While automation can reduce certain types of workloads, it may also introduce new challenges and sources of stress [10]. Endsley and Kiris (1995) cautioned that excessive automation could lead to reduced situational awareness and difficulties in problem-solving during system failures [11]. While ATCs will retain responsibility for air traffic safety in NextGen ATC systems, their direct control capabilities may be reduced. It could potentially lead to increased stress or workload [12].

The primary source of stress for ATC controllers stems from their critical role in ensuring flight safety, where errors are not permissible. Concentration provokes stress, which leads to tension that cannot be overcome [13]. Zeier and Grubenmann (1990) identified key occupational stressors inherent to ATC work, including: dissatisfaction with management and organizational policies, workload control challenges, chronic fatigue and irregular work schedules [14]. In general, the main sources of stress reported by ATCs are related to both operational aspects (e.g. traffic load peaks, time pressure, equipment limitations) and organizational factors (e.g. shift schedules, role conflicts, lack of control over work). Paradoxically, many errors also occur during periods of light traffic due to understimulation [15]. These occupational stressors can have significant negative impacts on ATCs' health, wellbeing and job performance. Short-term effects include changes in physiological measures like hormone levels and heart rate, while long-term consequences may involve serious illnesses such as hypertension, heart disease and psychoneurotic disorders [16].

There are two main approaches to explaining stress in the workplace: unitary (causal) and multidimensional (integrative). The unitary approach explicates discrete aspects of workplace stress processes, often adopting a theoretical perspective that focuses on stress etiology, prevention methodologies, minimization strategies, or stress management techniques. This category encompasses causal models such as the "person-environment fit" and "job demands-control" frameworks. Intervention models are predicated on developing approaches integral to stress management, which can be conceptualized through primary, secondary, and tertiary prevention systems. Primary prevention entails the elimination of existing workplace stressors. Secondary prevention emphasizes enhancing individual awareness and providing coping mechanisms. Tertiary prevention targets the treatment and support of individuals presumed to suffer from severe stress-related disorders. The multidimensional approach typically amalgamates causation with intervention. Christian et al. (2009) proposed a holistic model incorporating both explanatory and action phases [17]. An exemplar of this integrative approach for healthcare professionals is Dunn's conceptual model of medical student well-being [18]. This model's "coping reservoir" illustrates the interaction between positive factors (psychosocial support, social engagement, mentorship, intellectual stimulation) and negative factors (stress, internal conflict, time and energy demands), while accounting for personality factors and potential outcomes (burnout or resilience). The authors proposed this model for individual-level application to identify potential intervention areas.

A pilot study conducted among Spanish ATCs found that mindfulness-based interventions led to improved memory, concentration, and reduced irritability and tension [19]. Li et al. (2020) reported that mindfulness techniques helped decrease anxiety levels among pilots, suggesting potential applicability to ATCs as well [20]. This research Bader Alaydi and Siew-Imm Ng (2024) confirmed that mindfulness played a moderating role: more mindful ATCs exhibited less performance degradation due to workload. Workplace social support also had a mitigating effect: controllers who perceived greater job support experienced reduced adverse effects of workload on their performance [21].

Workplace stress among ATCs represents a complex and dynamic phenomenon frequently reported by the majority of controllers. While current models in the field of human factors and ergonomics have identified individual, psychosocial, and organizational factors associated with occupational stress, they may not fully explore the dynamic feedback between these factors, which could be a source of complexity. From a dynamic systems modeling perspective, conceptualizing workplace stress perception among ATCs should be grounded in a sociotechnical systems approach.

Understanding occupational stress necessitates a systemic view based on a sociotechnical approach [22]. The application of system dynamics and simulation modeling techniques to complex systems, particularly human factors such as stress, proves computationally beneficial. There is a paucity of research examining workplace stress through the lens of a feedback model. The need for a systemic approach was acknowledged by Karasek, the originator of the Job Demands-Control model [23]. Dynamic feedback can reflect both the immediate consequences of specific workplace stressors and their corresponding causes. Researchers A. Morris, V. Ross, and M. Ulieru have proposed a stress model incorporating 17 feedback loops that either amplify or attenuate overall stress levels, while also elucidating the factors influencing stress [24]. P. A. Hancock's dynamic model of stress and attention is predicated on the concept of adaptability [25]. The model posits a general adaptive strategy at both physiological and psychological levels in response to stress. When adaptive capacities are exceeded, a transition from stable to unstable operational modes occurs. The model facilitates the visualization of interactions between various stress sources and their impact on adaptability through vector representations. Consequently, it elucidates the mechanisms underlying performance breakdown under stress due to the depletion of compensatory physiological resources. Another study presents a model simulating the dynamics of stress generation, accumulation, and reduction in oncology center nursing staff [26]. The model effectively represents the complex feedback mechanisms involved in nursing stress and absenteeism, provides managers a tool to dynamically monitor stress levels and test different policy interventions.

Task statement. The research purposes of the articles are to discover key causes of occupational stress among ATCs, to analyze modern real-time stress management approaches and to develop a system dynamics model of work-related stress among ATCs, taking into account various stressors and their interactions, as a basis for determining the overall stress level at ATC workplaces.

Outline of the main material of the study. Based on the conducted analysis of primary stress sources and specific stressors inherent to ATC' professional activities, a complex of factors leading to stress in ATCs' workplaces has been identified. It has been determined that ATCs' thorough understanding of stress impact specifics on their cognitive and psychophysiological state, as well as teamwork, is critical for managing stress during the performance of their professional duties at workplaces and, on a broader scale, their careers. Incidents become a potent source of stress, often requiring psychological support; therefore, it is crucial to skillfully manage stress both at individual and team levels. The lack of transparency and feedback tools, coupled with a punitive culture in control centers, exacerbates the psychological impact of serious incidents on ATCs. Background stress in the ATC job refers to the constant psychological stress and strain, that often occurs in this profession and can affect the psycho-emotional state of an aviation specialist.

The application of cluster analysis in constructing a system dynamics model of ATC stress can help identify groups of similar stress factors that may interact and influence ATC' stress levels. Typically, this method is applied using statistical analysis, but we employed a simplified version of cluster analysis based on a logical understanding of interrelationships between stressors. Six clusters of occupational stress among ATCs have been identified by source (Table 1). Each stressor from the presented categories has varying degrees of controllability and duration of impact (SC and TI indices, respectively).

The following abbreviations are used in the table 1: **SC –** stressor controllability (‘0’ – unmanageable stressor, ‘1’ – partly manageable, ‘2’ – manageable stressor); **TI** – time impact (‘0’ – short-term stressor (during one or several shifts), ‘1’ – long-term stressor, ‘2’ – throughout professional life).

The proposed classification helps identify which causes of stress are temporary and which may affect ATCs over an extended period, crucial for developing stress management strategies and improving working conditions. The classification by duration of impact, reflecting the temporal dimension of stress development, allows for differentiation of stress management measures at operational, tactical, and strategic levels.

Some stressors are only partially controllable by the ATC or aviation organization. For example, “fatigue” can be reduced through work-rest schedule management and support, but cannot be completely eliminated due to the high intensity and responsibility of the job. Similarly, shift work changes can be optimized but not fully eliminated as the service must operate continuously. Many key stressors are inherent to the nature of this profession and cannot be managed

Table 1

Classification key occupational stressors

Type of stress	Occupational stressor	SC	TI
I. Operational	1. Extreme weather conditions, large-scale temporary airspace restrictions, significant air traffic flow changes and flights with head of state status	0	0
	2. Discrepancies between actual airspace situations and data obtained from surveillance systems	1	0
	3. Emergency and unforeseen situations within the ATC's area of responsibility	0	0
	4. Technical malfunctions and failures	0	0
	5. Shift work	0	2
	6. Inability to fully accommodate the requirements and expectations of pilots, adjacent sector controllers, and other aviation professionals when addressing competing air traffic management tasks	1	2
II. Ergonomic-Life Safety	7. Ergonomic deficiencies in the workplace	1	1
	8. Physical limitations and adverse environmental factors in the workplace	1	2
III. Information-cognitive	9. High air traffic complexity and overload of the air traffic management system, or conversely, underload	1	1
	10. High demands on concentration and attention distribution	1	2
	11. Multitasking and the need to prioritize air traffic problem resolution	1	2
	12. Information overload or, conversely, lack of information in hazardous and rapidly changing situations	1	1
	13. Lack of time for decision-making (not just a time limit)	1	2
IV. Social	14. Necessity to maintain effective communication	2	2
	15. Interpersonal conflicts with supervisors and colleagues	1	1
	16. Need for adaptation to cultural differences among ATCs	1	1
	17. Insufficient recognition of real merits and achievements by managers	1	1
V. Psychological	18. Responsibility for flight safety and fear of failure	1	2
	19. Inability to influence certain factors in the professional environment	0	2
	20. Low self-efficacy	2	1
	21. Perception of poor occupational stress self-management	2	1
	22. Unrealistic expectations of oneself and others	2	1
	23. Changes in aviation laws, procedures and need for lifelong professional training	1	2
	24. Dependence of personal performance efficiency on other aviation professionals	1	2
	25. Necessity to adhere to standard procedures	1	2
	26. Processes related to aviation incident prevention (conducting internal investigations)	1	1
	27. Feelings of isolation from the external world and indirect nature of control	1	2
	28. Fatigue, depression, and burnout	1	1
VI. Organizational	29. Ineffective personnel management decisions	1	1
	30. Suboptimal changes in duty shift schedules	1	1
	31. Dissatisfaction with management and company policies	1	1
	32. Uncertainty regarding career advancement prospects	1	1

intrinsically, but can be partially compensated through organizational measures and development of the social and individual stress resilience resources.

The interrelationships between stress clusters are presented as a multi-connected directed graph (Fig. 1). In this model, each cluster of occupational stress is represented by a graph node, and the graph edges indicate connections between stressors.

The graph demonstrates the interaction and influence of separate stress factor groups on each other, facilitating a better understanding of the sources of ATCs' occupational stress and possible management approaches. The adjacency matrix (Table 2) reflects the connections of the resulting graph and can be applied in a knowledge-based system to create models that simulate the impact of various stress factors on the overall stress level of ATCs. However, the considered interrelationships may vary depending on the specific situation and individual characteristics of the ATC.

If the earlier mentioned graphical model is represented with graph nodes numbered from 1 to 6, and edges from 1 to 14, we obtain the graphical model shown in Fig. 2. To formalize the relationships between graph elements (edges and nodes), we construct an incidence matrix (Table 3).

The betweenness centrality calculations indicate that nodes №1 (0.075) and №5 (0.225) are key in this graph. Consequently, operational stress and

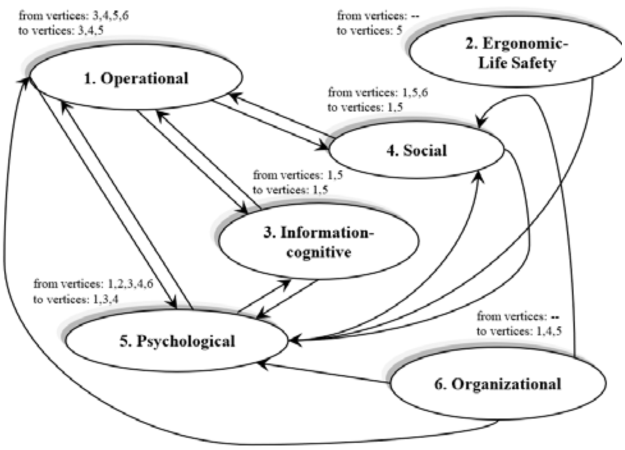

Fig. 1. The model of interrelationships of ATC occupational stressors groups

Table 2

The adjacency matrix of stress clusters

	3,4,5,6	-	1,5	1,5,6	1,2,3,4,6	-
	1	2	3	4	5	6
1	0	0	1	1	1	0
2	0	0	0	0	1	0
3	1	0	0	0	1	0
4	1	0	0	0	1	0
5	1	0	1	1	0	0
6	1	0	0	1	1	0

Table 3

Incident matrix of stress clusters

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	-1	1	-1	1	-1	0	0	0	0	0	-1	0	0
2	0	0	0	0	0	0	0	0	0	0	1	0	0	0
3	0	0	-1	1	0	0	1	-1	0	0	0	0	0	0
4	-1	1	0	0	0	0	0	0	1	-1	0	0	-1	0
5	0	0	0	0	-1	1	-1	1	-1	1	-1	0	0	-1
6	0	0	0	0	0	0	0	0	0	0	0	1	1	1

psychological clusters act as intermediaries in transmitting information (influence) between other clusters.

The system dynamics model of ATCs' occupational stress incorporates multidimensionality and involves several types of stressors, including perception of organizational conditions, workplace demands, control over work processes, organizational and social factors (Fig. 3).

The central component of the system dynamics model of ATCs' occupational stress is the "perceived overall job stress" – a base variable, that either increases or decreases over time depending on changes in the model's aggregator values. The level of perceived overall occupational stress is determined by five component-aggregators of the model, which accumulate the impact of job stressors

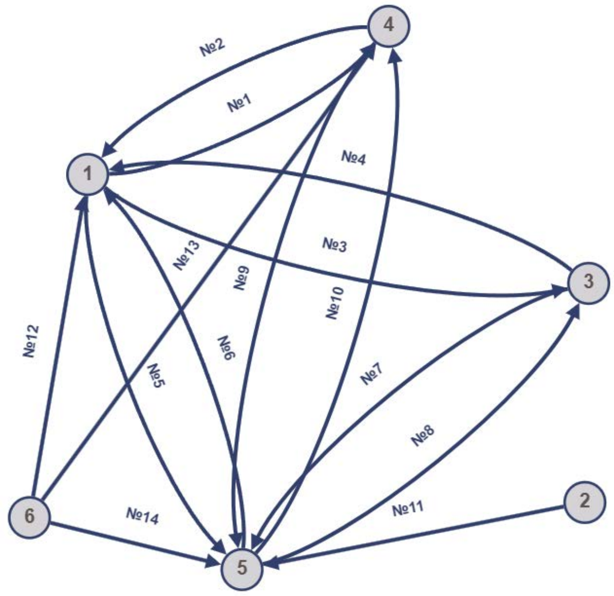

Fig. 2. Graph of interconnections of ATCs' occupational stress clusters

of various sources, the cumulative effect of which can be quantitatively measured – "level of perceived personal control over the work situations", "level of perceived the teamwork quality", "level of perceived job demands", "level of perceived background stress", and "level of perceived stress manageability". Numbers from 1 to 32 on the edges of the model graph denote occupational causes of stress (their numbering corresponds to the defined list of stressors presented in Table 1) affecting the components of the model.

The '+/-' signs in the model indicate the type of relationship between different stress clusters and the model's component aggregators: '+' denotes a direct relationship, '-' – an inverse relationship. Stressors of the operational, information-cognitive, and psychological clusters decrease the level of work controllability perceived by the ATCs. Conversely, stressors from the operational, information-cognitive, psychological, and social clusters heighten the level of perceived job demands.

The identified relationships of the impact of certain types of stressors on the corresponding component-aggregators of ATCs' job stress are presented in Table 4. The structural matrix indicates the presence of a relationship between stressors and the model's component-aggregators.

Similarly, the model represents the impact of various levels of job stress aggregators on the level of overall occupational stress experienced by the ATCs. An increase in the perception of job demand level and background stress level leads to an increase in the perceived overall occupational stress indicator (shown by '+'). Conversely, an increase in the perception of work situation controllability, teamwork effectiveness, and stress manageability positively affects the overall occupational stress indicator among ATCs, reducing the level of perceived overall job stress. (shown by '-').

Feedback loops (R1, R2, R3, R4, R5), indicated by "bold" edges on the graph, demonstrate the feedback between the five "component aggregators" and the level of overall occupational stress perceived by the ATC:

1. **R1** (connection between "work situation controllability level" and "overall occupational stress level") demonstrates the following situation: an increase in the ATC's perception of work controllability leads to a decrease in their overall occupational stress level ('-'), but if the overall stress level increases, it will reduce the perception of work situation controllability ('-').

2. **R2** (connection between job demand level and overall occupational stress level) shows that an increase in the perception of job demands will increase the ATC's overall occupational stress level ('+'), and in turn, an increase in the perceived overall occupational stress level will lead to a feeling of increased job demands ('+').

3. **R3** (connection between teamwork level and overall occupational stress level) demonstrates the following effect: improved teamwork effectiveness reduces the overall stress level, while an increase in the overall stress level negatively impacts teamwork effectiveness.

4. **R4** (connection between background stress level and overall occupational stress level) shows that

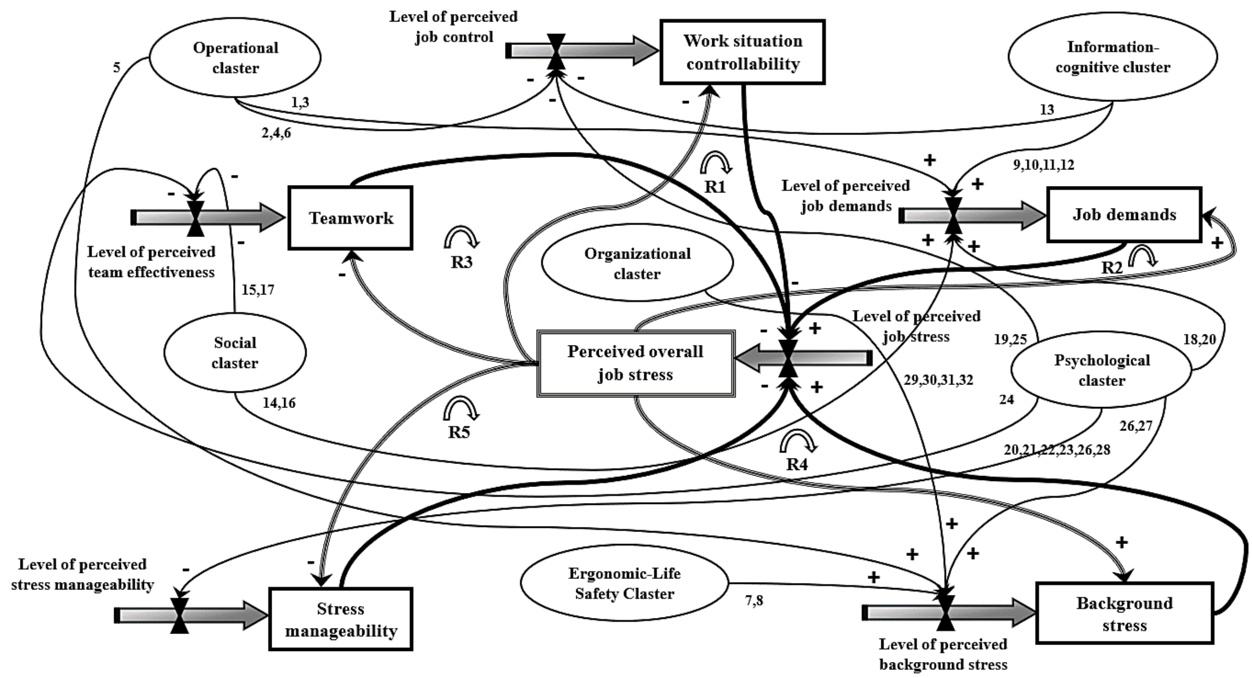

Fig. 3. System dynamics model of ATCs' job stress components

Table 4

Structural matrix of the impact of occupational stressor clusters on its key components

Stress clusters	Stress components				
	1. Level of perceived job control	2. Level of perceived job demands	3. Level of perceived team effectiveness	4. Level of perceived background stress	5. Level of perceived stress management
1. Operational	+	+	-	+	-
2. Information-cognitive	+	+	-	-	-
3. Social	-	+	+	+	-
4. Psychological	+	+	+	+	+
5. Organizational	-	-	-	+	-
6. Ergonomic-Life Safety Claster	-	-	-	+	-

an increase in background stress level increases the overall stress level. On the other hand, an increase in the overall stress level leads to an increase in the background stress level.

5. **R5** (connection between stress management level and overall occupational stress level) reflects the following effect: an increase in the perception of stress manageability reduces the overall stress level, while an increase in the overall stress level reduces the perception of ability to manage stress by ATC.

Thus, the feedback loops demonstrate the mutual influence of different model components on the overall occupational stress level of ATCs. By altering the values of various variables (occurrence of stressors of different sources) and assessing their impact on the perceived rate of corresponding work stress type, it is possible to model the dynamics of the overall occupational stress level of ATCs over time. This allows for testing different scenarios and intervention options to reduce stress in the workplace.

Ignoring stress sources can lead to greater stress and catastrophic consequences. Stress from one of these sources may be difficult to overcome, but stress from multiple sources can be destructive. An effective stress reduction strategy should aim to eliminate both its causes and consequences, acting on all factors related to work organization, as well as personal resources and conditions in which ATCs operate.

Conclusions. The categorization of ATCs' occupational stressors proposed in this work, based on their nature of occurrence, rate of controllability, and duration of impact, organically complements and specifies the system dynamics model of job stress management. The system dynamics model of occupational stress among ATCs allows for considering various stress sources, their interaction, and serves as a basis for monitoring stress level dynamics. Quantitative assessment of individual stressors' impact on the overall stress level of ATCs will allow determining the actually achieved stress level and predicting its changes under the influence of known factors, particularly in real-time.

The ATC shift supervisor's awareness of current and anticipated stressors, their present and potential effects on ATCs' stress levels, combined with data on existing occupational stress and alerts about approaching critical thresholds, can facilitate effective stress management in ATC workplaces. Such data and alerts will allow for swift adjustments to ATCs' occupational stress management strategies by on-duty supervisors. These strategies may encompass actions to enhance operational processes, improve the work environment, boost team collaboration, refine organizational policies, support professional growth, provide psychological assistance, and promote individual well-being among ATCs.

The directions for future research in five important areas will be outlined: (1) development methodology for quantitatively measuring the impact of specific stressors on ATCs' overall stress levels, (2) creation method for dynamically adjusting stress level thresholds based on various factors such as traffic complexity, weather conditions, and individual ATC experience levels, (3) development method for creating and updating individual stress management profiles for each ATC, allowing for more tailored interventions and support, (4) utilization of machine learning techniques and data analytics to build intelligent real-time monitoring and predictive models that can forecast changes in ATC stress levels based on known stressors and historical data (for individual ATCs and the team), (5) development framework of an AI-powered system that can suggest appropriate interventions to the supervisor based on current stress levels, predicted trends, and past effectiveness of various strategies (particularly in simulation mode).

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Пальоний А.С., Нечипуренко А.Г. МОДЕЛЮВАННЯ ДИНАМІКИ ПРОФЕСІЙНОГО СТРЕСУ В УПРАВЛІННІ ПОВІТРЯНИМ РУХОМ

Предметом статті є професійний стрес серед авіадиспетчерів, ключові фактори, що його спричиняють, та підходи до управління ним у режимі реального часу. Дослідження зосереджене на комплек-

сному аналізі стресогенних чинників та їх впливу на загальний рівень стресу авіадиспетчерів під час виконання професійних обов'язків. Метою статті є розробка системно-динамічної моделі професійного стресу серед авіадиспетчерів, що враховує різні причини стресу та їх взаємодію, як основи для визначення загального рівня стресу на робочих місцях авіадиспетчерів та створення ефективних стратегій управління стресом в умовах динамічного середовища управління повітряним рухом. Завдання статті: дослідити первинні джерела стресу, притаманні роботі фахівців з управління повітряним рухом, та проаналізувати сучасні підходи до моделювання динамічної природи професійного стресу; виявити та класифікувати фактори, що сприяють підвищенню загального рівня стресу на робочих місцях авіадиспетчерів; побудувати графічну модель взаємозв'язків між групами стресорів та виявити ті з них, що виступають основними посередниками у передачі інформації між іншими типами стресорів; розробити системно-динамічну модель професійного стресу, що ілюструє як прямі, так і зворотні зв'язки між сприйманим загальним рівнем стресу на робочих місцях авіадиспетчерів та факторами, що на нього впливають. Використані методи: логічний аналіз, кластерний аналіз, теорія графів та графоаналітичний аналіз, а також системно-динамічне моделювання. У дослідженні визначено та класифіковано сукупність стресорів (за їх джерелом), що підвищують відчуття загального стресу серед авіадиспетчерів, кожен з яких має відповідний індекс контрольованості та тривалість впливу. Розроблено системно-динамічну модель професійного стресу, що складається з центрального компонента «рівень професійного стресу авіадиспетчера» та кількох компонентів-агрегаторів, які акумулюють вплив чинників різної природи. Петлі зворотного зв'язку в моделі демонструють потенційні посилюючі ефекти в системі. Наукова новизна одержаних результатів полягає в тому, що концептуальна модель системної динаміки професійного стресу авіадиспетчерів дає наочне уявлення про динамічну природу стресу, якого зазнають авіадиспетчери, та вплив ключових чинників на сприйняття ними стресу під час роботи. Представлена модель може слугувати основою для моніторингу динаміки рівня професійного стресу серед авіадиспетчерів та уможливити ефективне управління стресом з боку керівників змін управління повітряним рухом шляхом розробки та перегляду оперативних, тактичних та стратегічних заходів з подолання стресу.

Ключові слова: *авіадиспетчери, професійний стрес, стрес-менеджмент, стресогенні чинники, системна динаміка.*