INFORMATION TECHNOLOGIES

DOI: 10.15587/2706-5448.2026.352336

ASSESSMENT OF QUALITY DEGRADATION IN MODERN VOICE DEEPFAKE DETECTORS UNDER CROSS-LINGUISTIC SHIFT FROM ENGLISH TO UKRAINIAN

pages 6–10

Ivan Vynogradov, *PhD Student, Department of Cyber Security and Technical Information Protection, State University of Intelligent Technologies and Telecommunications, Odesa, Ukraine, e-mail: ipvinner@gmail.com, ORCID: https://orcid.org/0009-0000-9901-7811*

The research object is the processes and algorithms of automated discrimination between real and synthesized speech (anti-spoofing systems) when they function in conditions of a pronounced linguistic shift. The research solves the scientific and practical issue of quantitatively assessing the critical degradation of the precision of modern neurolinguistic detectors, using the example of the AASIST architecture with graph attention, when they encounter high-quality voice attacks in the Ukrainian. Special attention was paid to attacks formed using industrial new-generation neural vocoders, which are practically not represented in classic English training samples.

The essence of the obtained results lies in establishing and mathematically confirming the existence of a significant "generalization gap" in cross-language testing. It was experimentally proven that the transition from the English acoustic domain into the Ukrainian domain causes the growth of the equal error rate (EER) coefficient by 2.5–3.5 times. In the most advanced synthesis systems, the EER reached a critical threshold of 25.64%, which indicates the loss of the system's protective capabilities in this language domain.

These results were obtained through the usage of an experimental stand, which unites the AASIST model and closed-end commercial APIs of neural speech cloning. Unlike standard tests on archive databases, the suggested approach, using a specially EXT dataset that includes five independent attack groups, allowed for modeling real cyber threat scenarios.

In practice, these results can be used in the design of voice biometric authentication systems in the banking and governmental sectors of Ukraine and justify the mandatory necessity of linguistic adaptation and deep fine-tuning of classifiers using localized datasets to achieve the required level of information security.

Keywords: anti-spoofing, voice deepfakes, voice cloning, linguistic shift, biometric authentication.

References

1. Rabhi, M., Bakiras, S., Di Pietro, R. (2024). Audio-deepfake detection: Adversarial attacks and countermeasures. *Expert Systems with Applications, 250,* 123941. https://doi.org/10.1016/j.eswa.2024.123941
2. Vynogradov, I. (2025). Voice fake detection: modern techniques and applications for Ukrainian language. *Measuring and computing devices in technological processes, 82 (2),* 31–36. https://doi.org/10.31891/2219-9365-2025-82-5
3. Marek, B., Kawa, P., Syga, P. (2024). *Are audio DeepFake detection models polyglots?* arXiv preprint. https://doi.org/10.48550/arXiv.2412.17924
4. Liu, T., Kukanov, I., Pan, Z., Wang, Q., Sailor, H. B., Lee, K. A. (2024). Towards Quantifying and Reducing Language Mismatch Effects in Cross-Lingual Speech Anti-Spoofing. *2024 IEEE Spoken Language Technology Workshop (SLT),* 1185–1192. https://doi.org/10.1109/slt61566.2024.10832142
5. Moreno, V., Lima, J., Simões, F., Violato, R., Neto, M. U., Runstein, F., Costa, P. (2025). Revealing Cross-Lingual Bias in Synthetic Speech Detection under Controlled Conditions. *5th Symposium on Security and Privacy in Speech Communication,* 1–7. https://doi.org/10.21437/spsc.2025-1
6. Kong, J., Kim, J., Bae, J. H. (2020). HiFi-GAN: Generative Adversarial Networks for Efficient and High Fidelity Speech Synthesis. *Advances in Neural Information Processing Systems (NeurIPS),* 33. Available at: https://doi.org/arXiv:2010.05646
7. Wang, X., Delgado, H., Tak, H., Jung, J., Shim, H., Todisco, M. et al. (2024). ASVspoof 5: crowdsourced speech data, deepfakes, and adversarial attacks at scale. *The Automatic Speaker Verification Spoofing Countermeasures Workshop (ASVspoof 2024),* 1–8. https://doi.org/10.21437/asvspoof.2024-1
8. Delgado, H., Evans, N., Kinnunen, T., Lee, K. A., Liu, X., Nautsch, A. et al. (2021). *ASVspoof 2021 Evaluation Plan.* arXiv preprint. Available at: https://www.asvspoof.org/asvspoof2021/asvspoof2021_evaluation_plan.pdf
9. Todisco, M., Delgado, H., Evans, N. (2017). Constant Q cepstral coefficients: A spoofing countermeasure for automatic speaker verification. *Computer Speech & Language, 45,* 516–535. https://doi.org/10.1016/j.csl.2017.01.001
10. Tak, H., Patino, J., Todisco, M., Nautsch, A., Evans, N., Larcher, A. (2021). End-to-End anti-spoofing with RawNet2. *ICASSP 2021–2021 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP),* 6369–6373. https://doi.org/10.1109/icassp39728.2021.9414234
11. Tak, H., Jung, J., Patino, J., Kamble, M., Todisco, M., Evans, N. (2021). End-to-end spectro-temporal graph attention networks for speaker verification anti-spoofing and speech deepfake detection. *2021 Edition of the Automatic Speaker Verification and Spoofing Countermeasures Challenge,* 1–8. https://doi.org/10.21437/asvspoof.2021-1
12. Jung, J., Heo, H.-S., Tak, H., Shim, H., Chung, J. S., Lee, B.-J. et al. (2022). AASIST: Audio Anti-Spoofing Using Integrated Spectro-Temporal Graph Attention Networks. *ICASSP 2022–2022 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP),* 6367–6371. https://doi.org/10.1109/icassp43922.2022.9747766
13. Tak, H., Todisco, M., Wang, X., Jung, J., Yamagishi, J., Evans, N. (2022). Automatic Speaker Verification Spoofing and Deepfake Detection Using Wav2vec 2.0 and Data Augmentation. *The Speaker and Language Recognition Workshop (Odyssey 2022),* 112–119. https://doi.org/10.21437/odyssey.2022-16
14. Zhang, Q., Wen, S., Hu, T. (2024). Audio Deepfake Detection with Self-Supervised XLS-R and SLS Classifier. *Proceedings of the 32nd ACM International Conference on Multimedia,* 6765–6773. https://doi.org/10.1145/3664647.3681345
15. Models. *ElevenLabs.* Available at: https://elevenlabs.io/docs/models
16. Dubbing. *ElevenLabs.* Available at: https://elevenlabs.io/docs/capabilities/dubbing
17. Realtime Text-to-Speech AI Voice Generator built for Voice Agents. *Resemble AI.* Available at: https://www.resemble.ai/text-to-speech-converter/
18. Ukrainian Text-to-Speech and AI Voice Generator. *Resemble AI.* Available at: https://www.resemble.ai/ukrainian-tts/
19. What's new in Azure Speech in Foundry Tools? *Microsoft Learn.* Available at: https://learn.microsoft.com/azure/ai-services/speech-service/releasenotes
20. Gemini-TTS. Chirp 3 HD – Supported languages (uk-UA). *Google Cloud.* Available at: https://cloud.google.com/text-to-speech/docs/gemini-tts
21. Language Support – Languages supported by Speechify Text-to-Speech API. *Speechify.* Available at: https://docs.sws.speechify.com/docs/features/language-support
22. Bringing technology to life. *ElevenLabs.* Available at: https://elevenlabs.io
23. Bringing technology to life. *Resemble AI.* Available at: https://www.resemble.ai
24. Kinnunen, T., Lee, K. A., Delgado, H., Evans, N., Todisco, M., Sahidullah, M. et al. (2018). t-DCF: a Detection Cost Function for the Tandem Assessment of Spoofing Countermeasures and Automatic Speaker Verification. *The Speaker and Language Recognition Workshop (Odyssey 2018),* 312–319. https://doi.org/10.21437/odyssey.2018-44
25. Wang, X., Yamagishi, J., Todisco, M., Delgado, H., Nautsch, A., Evans, N. et al. (2020). ASVspoof 2019: A large-scale public database of synthesized, converted and replayed speech. *Computer Speech & Language, 64,* 101114. https://doi.org/10.1016/j.csl.2020.101114
26. Yi, J., Wang, C., Tao, J., Zhang, X., Zhang, C. Y., Zhao, Y. (2023). Audio Deepfake Detection: A Survey. *Journal of Latex Class Files, 14 (8).* https://doi.org/10.48550/arXiv.2308.14970
27. Yamagishi, J., Wang, X., Todisco, M., Sahidullah, M., Patino, J., Nautsch, A. et al. (2021). ASVspoof 2021: accelerating progress in spoofed and deepfake speech detection. *2021 Edition of the Automatic Speaker Verification and Spoofing Countermeasures Challenge,* 47–54. https://doi.org/10.21437/asvspoof.2021-8
28. Müller, N. M., Czempin, P., Dieckmann, J., Froghyar, A., Böttinger, K. (2022). *Does Audio Deepfake Detection Generalize?* https://doi.org/10.48550/arXiv.2203.16263

ISSN-L 2664-9969; E-ISSN 2706-5448

29. Liu, X., Wang, X., Sahidullah, M., Patino, J., Delgado, H., Kinnunen, T. et al. (2023). ASVspoof 2021: Towards Spoofed and Deepfake Speech Detection in the Wild. *IEEE/ACM Transactions on Audio, Speech, and Language Processing, 31,* 2507–2522. https://doi.org/10.1109/taslp.2023.3285283
30. Voicefakedetector. *GitHub repository.* Available at: https://github.com/ipvinner/voicefakedetector Last accessed: 22.12.2025

DOI: 10.15587/2706-5448.2026.352356

DEVELOPMENT OF A COMPLEX SOLUTION FOR A HUMAN-ROBOT INTERACTION AND OPERATORS TRAINING USING VR-INTEGRATED DT FRAMEWORK

pages 11–17

Yevhen Palazhchenko, *PhD Student, Department of Information Technologies, Sumy State University, Sumy, Ukraine, e-mail: e.palazhchenko@itp.sumdu.edu.ua, ORCID: https://orcid.org/0000-0003-4329-9447*

Vira Shendryk, *PhD, Associate Professor, Professor, Department of Information Technologies, Sumy State University, Sumy, Ukraine, ORCID: https://orcid.org/0000-0001-8325-3115*

Georg Meyer, *PhD in Technical Science, Associate Professor, Honorary Research Professor, Faculty of Engineering, University of Liverpool, Liverpool, United Kingdom, ORCID: https://orcid.org/0000-0002-3739-1653*

The object of research is the process of managing human-robot interaction through the virtual reality-integrated digital twin system. The problem addressed in the research is that, despite active development of architectural solutions, there are barriers to fundamental research and operator training due to the prohibitive costs, technical complexity, and proprietary restrictions of industrial-grade robotic hardware.

The obtained results are the creation of a comprehensive, scalable, and flexible digital twin architecture, implemented through a functional prototype. The prototype digital twin framework is an extensible tool for testing research strategies and can be adapted for specific tasks or equipment. The implementation synchronizes a low cost 6-degrees-of-freedom manipulator with its digital model using the Unreal Engine. Analysis of the application areas of the developed system highlights the potential of virtual reality to improve human-robot interaction.

These results were made possible by a complex approach combining architectural design and experimental prototyping. Unlike industrial solutions, which focus on specific technologies, a general approach to system design was applied. A significant advantage of focusing on general principles is that they can be developed without recourse to using complex real systems, which are associated with safety, accessibility, and cost issues.

The proposed solution is designed to enable systematic testing of a wide range of user interface designs, situational awareness tools, interaction, and collaboration strategies in a risk-free virtual environment. The underlying design and software will be publicly available, enabling researchers to use a standardized yet flexible approach to develop human-robot interaction systems based on the results presented in this research.

Keywords: digital twin, user interaction, immersive learning, virtual reality, augmented reality.

References

1. Grieves, M., Vickers, J. (2016). Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. *Transdisciplinary Perspectives on Complex Systems.* Springer International Publishing, 85–113. https://doi.org/10.1007/978-3-319-38756-7_4
2. Tao, F., Zhang, H., Liu, A., Nee, A. Y. C. (2019). Digital Twin in Industry: State-of-the-Art. *IEEE Transactions on Industrial Informatics, 15 (4),* 2405–2415. https://doi.org/10.1109/tii.2018.2873186
3. Bruynseels, K., Santoni de Sio, F., Van den Hoven, J. (2018). Digital Twins in Health Care: Ethical Implications of an Emerging Engineering Paradigm. *Frontiers in Genetics, 9.* https://doi.org/10.3389/fgene.2018.00031
4. Jeddoub, I., Nys, G.-A., Hajji, R., Billen, R. (2023). Digital Twins for cities: Analyzing the gap between concepts and current implementations with a specific focus on data integration. *International Journal of Applied Earth Observation and Geoinformation, 122,* 103440. https://doi.org/10.1016/j.jag.2023.103440
5. Lamagna, M., Groppi, D., Nezhad, M. M., Piras, G. (2021). A comprehensive review on digital twins for smart energy management system. *International Journal of Energy Production and Management, 6 (4),* 323–334. https://doi.org/10.2495/eq-v6-n4-323-334
6. Meyer, G. F., Wong, L. T., Timson, E., Perfect, P., White, M. D. (2012). Objective Fidelity Evaluation in Multisensory Virtual Environments: Auditory Cue Fidelity in Flight Simulation. *PLoS ONE, 7 (9),* e44381. https://doi.org/10.1371/journal.pone.0044381
7. Cooper, N., Millela, F., Cant, I., White, M. D., Meyer, G. (2021). Transfer of training – Virtual reality training with augmented multisensory cues improves user experience during training and task performance in the real world. *PLOS ONE, 16 (3),* e0248225. https://doi.org/10.1371/journal.pone.0248225
8. Cooper, N., Milella, F., Pinto, C., Cant, I., White, M., Meyer, G. (2018). The effects of substitute multisensory feedback on task performance and the sense of presence in a virtual reality environment. *PLOS ONE, 13 (2),* e0191846. https://doi.org/10.1371/journal.pone.0191846
9. Longo, F., Nicoletti, L., Padovano, A. (2017). Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context. *Computers & Industrial Engineering, 113,* 144–159. https://doi.org/10.1016/j.cie.2017.09.016
10. Palazhchenko, Y., Shendryk, V., Shendryk, S. (2023). Digital Twins Data Visualization Methods. Problems of Human Interaction: A Review. *New Technologies, Development and Application VI.* Springer Nature Switzerland, 478–485. https://doi.org/10.1007/978-3-031-31066-9_53
11. Ordaz, N., Romero, D., Gorecky, D., Siller, H. R. (2015). Serious Games and Virtual Simulator for Automotive Manufacturing Education & Training. *Procedia Computer Science, 75,* 267–274. https://doi.org/10.1016/j.procs.2015.12.247
12. Checa, D., Bustillo, A. (2019). A review of immersive virtual reality serious games to enhance learning and training. *Multimedia Tools and Applications, 79 (9-10),* 5501–5527. https://doi.org/10.1007/s11042-019-08348-9
13. Bucchiarone, A. (2022). Gamification and virtual reality for digital twin learning and training: architecture and challenges. *Virtual Reality & Intelligent Hardware, 4 (6),* 471–486. https://doi.org/10.1016/j.vrih.2022.08.001
14. Stark, R., Damerau, T. (2019). Digital Twin. *CIRP Encyclopedia of Production Engineering.* Berlin, Heidelberg: Springer, 1–8. https://doi.org/10.1007/978-3-642-35950-7_16870-1
15. Palazhchenko, Y., Shendryk, V., Ivanov, V., Hatala, M. (2023). Industry 5.0: Aspects of Collaboration Technologies. *Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems.* Springer Nature Switzerland, 609–617. https://doi.org/10.1007/978-3-031-38165-2_71
16. Wright, L., Davidson, S. (2020). How to tell the difference between a model and a digital twin. *Advanced Modeling and Simulation in Engineering Sciences, 7 (1).* https://doi.org/10.1186/s40323-020-00147-4
17. Jones, D., Snider, C., Nassehi, A., Yon, J., Hicks, B. (2020). Characterising the Digital Twin: A systematic literature review. *CIRP Journal of Manufacturing Science and Technology, 29,* 36–52. https://doi.org/10.1016/j.cirpj.2020.02.002
18. Tao, F., Xiao, B., Qi, Q., Cheng, J., Ji, P. (2022). Digital twin modeling. *Journal of Manufacturing Systems, 64,* 372–389. https://doi.org/10.1016/j.jmsy.2022.06.015
19. Garg, G., Kuts, V., Anbarjafari, G. (2021). Digital Twin for FANUC Robots: Industrial Robot Programming and Simulation Using Virtual Reality. *Sustainability, 13 (18),* 10336. https://doi.org/10.3390/su131810336
20. Wang, Z., OuYang, Y., Kochan, O. (2023). Bidirectional Linkage Robot Digital Twin System Based on ROS. *2023 17th International Conference on the Experience of Designing and Application of CAD Systems (CADSM),* 1–5. https://doi.org/10.1109/cadsm58174.2023.10076497
21. Inamura, T., Mizuchi, Y. (2021). SIGVerse: A Cloud-Based VR Platform for Research on Multimodal Human-Robot Interaction. *Frontiers in Robotics and AI, 8.* https://doi.org/10.3389/frobt.2021.549360
22. Acker, J., Rogers, I., Guerra-Zubiaga, D., Tanveer, M. H., Moghadam, A. A. A. (2023). Low-Cost Digital Twin Approach and Tools to Support Industry and

Academia: A Case Study Connecting High-Schools with High Degree Education. *Machines, 11 (9),* 860. https://doi.org/10.3390/machines11090860

23. Vairavasamy, S., J, N. I., MJ, H., Ahmed, S., N, S., MM Dean, R. (2022). Simulation And Real Time Of VR Controlled Robotic Manipulator Using ROS. *2022 IEEE Bombay Section Signature Conference (IBSSC).* IEEE, 1–6. https://doi.org/10.1109/ibssc56953.2022.10037520
24. Palazhchenko, Y. (2026). *Digital-twin-system-for_learning-strategies-development-in-VR*. Available at: https://github.com/palazhchenko/Digital-twin-system-for_learning-strategies-development-in-VR
25. Sailer, M., Homner, L. (2019). The Gamification of Learning: a Meta-analysis. *Educational Psychology Review, 32 (1),* 77–112. https://doi.org/10.1007/s10648-019-09498-w

DOI: 10.15587/2706-5448.2026.353067

DEVELOPMENT OF METHOD FOUNDATIONS FOR GENERATING NOISE-LIKE SIGNALS BASED ON DIRECT SEQUENCE SPREAD SPECTRUM OF TIMING SIGNAL STRUCTURES

pages 18–24

Volodymyr Korchynskyi, *Doctor of Technical Sciences, Professor, Head of the Department of Cybersecurity and Technical Information Protection, State University of Intelligent Technologies and Telecommunications, Odesa, Ukraine, e-mail: vladkorchin@ukr.net, ORCID: https://orcid.org/0000-0003-3972-0585*

Vitalii Kildishev, *PhD, Associate Professor, Department of Cybersecurity and Technical Information Protection, State University of Intelligent Technologies and Telecommunications, Odesa, Ukraine, ORCID: https://orcid.org/0000-0002-7121-4060*

Daniyar Bektursunov, *Doctor of Philosophy (PhD), General Director, NURSAT+ LLC, a subsidiary of Kazakhtelecom JSC, Almaty, Kazakhstan, ORCID: https://orcid.org/0000-0003-2491-0490*

Serhii Havel, *PhD Student, Department of Cybersecurity and Technical Information Protection, State University of Intelligent Technologies and Telecommunications, Odesa, Ukraine, ORCID: https://orcid.org/0000-0002-0484-5620*

Vadym Stepanov, *Lecturer, Military Academy, Odesa, Ukraine, ORCID: https://orcid.org/0009-0001-0851-4220*

Vasyl Slavych, *QA engineer, ValueTek, Kyiv, Ukraine, ORCID: https://orcid.org/0009-0000-8446-4061*

Ruslan Petrovskyi, *Lecturer, Lyceum "Fontansky", Odesa, Ukraine, ORCID: https://orcid.org/0009-0002-4605-9908*

The object of the research is the process of forming complex noise-like signals based on timer signal constructions in secure communication systems operating under conditions of electronic warfare and counteraction to electronic intelligence systems.

The problem addressed in the paper is the lack of a theoretical framework for spectrum spreading of non-positional signals. An example of such signals is timer signal constructions, which are characterized by a more complex and variable temporal pulse structure within a combination.

The research solves the problem of developing a direct-sequence spread spectrum method for non-positional signals with a variable temporal pulse structure. It is shown that the classical spread spectrum method, designed for positional signals with fixed bit interval duration, cannot be directly applied to timer signal constructions. The proposed method provides for spectrum spreading not of an individual time interval of a binary bit element, but of the entire timer signal combination. A necessary condition for spectrum spreading in this case is the optimal selection of timer signal design parameters. This ensures the required interference immunity of the signal constructions, taking into account the interference level in the channel and the assessment of structural concealment.

The obtained results made it possible to establish the relationship between interference immunity and the level of concealment of timer signal constructions. It is shown that varying the parameters of timer noise-like signal formation significantly complicates their detection, recognition, and analysis by electronic intelligence means. According to the results of correlation analysis, the correlation coefficient varies in the range from 0.125 to 0.516, indicating reduced predictability and an increased level of structural concealment of the generated signal constructions.

The effectiveness of the proposed solution is explained by the fact that reception of broadband constructions is possible only when the correlation receiver is configured according to the timer signal design parameters. This practically prevents the reception of broadband timer signals generated with different design parameters, as well as by means of conventional classical correlation receivers.

The practical application of the results is possible in the design of secure special-purpose communication systems operating under conditions of intensive electronic countermeasures.

Keywords: timer constructions, noise-like signals, spectrum, stealth, interference immunity, radio electronic intelligence, correlation reception.

References

1. Zaitsev, D. V., Yafonkin, A. O., Yarema, V. V. (2021). *Osnovy zviazku ta radioelektronna borotba yak vyd boiovoho zabezpechennia.* Irpin: Universytet derzhavnoi fiskalnoi sluzhby Ukrainy, 279. Available at: https://ir.dpu.edu.ua/entities/publication/931c8879-4752-4096-a76d-6ab33b3b95e7/full
2. Sholokhov, S. M., Samborskyi, I. I., Vakulenko, O. V., Nikolaienko, B. A. (2021). *Zavadozakhyst radioelektronnykh zasobiv. Chastyna 1. Osnovy zavadozakhystu system zviazku.* Kyiv: ISZZI KPI im. Ihoria Sikorskoho, 210. Available at: https://ela.kpi.ua/handle/123456789/63622
3. Hurskyi, T. H., Zhuk, O. H., Klimovych, S. O. (2012). Napriamky zastosuvannia psevdovypadkovykh poslidovnostei v radiomerezhakh spetsialnoho pryznachennia. *Visnyk Khmelnytskoho natsionalnoho universytetu, 6,* 160–167. Available at: https://journals.khnu.km.ua/vestnik/pdf/tech/2012_6/54gur.pdf
4. Zakharchenko, M. V. (2009). *Systemy peredavannia danykh. Zavadostiike koduvannia.* Odesa: Feniks, 448. Available at: https://duikt.edu.ua/ua/lib/1/category/2234/view/502?lang=ua&act=view&page=1&category=2234&id=502
5. Korchinsky, V. V. (2012). Evaluation of structural stealth signal designs based on chaotic signals in the transmission systems of confidential information. *Naukovi pratsi ONAZ im. O. S. Popova, 1,* 77–81. Available at: https://ojs.suitt.edu.ua/index.php/sbornik_onat/article/view/481
6. Politanskyi, R. L., Hotra, Z. Yu. (2010). Doslidzhennia psevdovypadkovykh poslidovnostei, henerovanykh kartamy khaosu. *Problemy telekomunikatsii,* 127–128.
7. Burkinsky, B. V., Nazarenko, O., Laiko, O. I., Khadzhyradieva, S., Logvinov, V. (2024). *Sustainable development and digital innovations.* Odesa: DU "IREED NANU", 543. https://doi.org/10.31520/978-617-14-0253-9
8. Zakharchenko, M. V., Horokhov, Yu., S., Kril, A. S., Kovalchuk, S. V. (2015). Kodove ushchilnennia pry taimernykh syhnalakh. *Suchasni informatsiini tekhnolohii u sferi bezpeky ta oborony, 3 (24),* 38–42. Available at: file:///C:/Users/zimov/Downloads/61290-%D0%A2%D0%B5%D0%BA%D1%81%D1%82%20%D1%81%D1%82%D0%B0%D1%82%D1%82%D1%96-125862-1-10-20160229.pdf
9. Sklar, B. (2001). *Digital communications: Fundamentals and applications.* Prentice Hall, 1079.
10. Zakharchenko, M. V., Hadzhyev, M. M., Radzimovskyi, B. K., Horokhov, Yu. S., Shpak, D. O. (2014). Comparison of syndromic methods for correcting block positional and timing codes. *Eastern-European Journal of Enterprise Technologies, 2 (9 (68)),* 4–8. https://doi.org/10.15587/1729-4061.2014.23091
11. Zakharchenko, M. V. (2010). *Systemy peredavannya danykh. Tom 2: Poelementne ta Z–38 tsyklove fazuvannya v systemakh z blokovym koduvannyam.* Odesa: 264. Available at: https://duikt.edu.ua/uploads/l_502_87152646.pdf
12. Hordiichuk, V., Shyshatskyi, A., Korchinskyi, V., Kildishev, V., Pozdniakov, P. (2021). Timing pulse code modulation as a tool for quantization noise reduction in special-purpose IT systems. *Journal of Physics: Conference Series, 1839 (1),* 012005. https://doi.org/10.1088/1742-6596/1839/1/012005
13. Hordiichuk, V., Korchynskyi, V., Kildishev, V., Molodetskyi, B., Staikutsa, S., Alfaiomi, K. (2024). Adaptive Synthesis of Wideband Timer Signals in the Conditions of Radio-Electronic Warfare. *2024 IEEE 17th International Conference*

ISSN-L 2664-9969; E-ISSN 2706-5448

on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET). Lviv, 1–4. https://doi.org/10.1109/tcset64720.2024.10755658

14. Gorokhov, S. M., Zakharchenko, N. V., Korchinsky, V. V. (2012). Criteria of efficiency of hidden communication techniques. *Tsyfrovi tekhnolohii, 12,* 147–150. Available at: https://ojs.suitt.edu.ua/index.php/digitech/article/view/761/759

DOI: 10.15587/2706-5448.2026.352027

DEVELOPMENT OF A SYSTEMOLOGICAL METHOD FOR MEASURING INTELLECTUAL CAPITAL OF IT COMPANIES USING THE FIBONACCI SEQUENCE

pages 25–35

Oleksandr Andreichikov, *PhD Student, Department of Cyber Security and Information Technologies, Simon Kuznets Kharkiv National University of Economics, Kharkiv, Ukraine, e-mail: andreychenkov.oleksandr@hneu.net, ORCID: https://orcid.org/0009-0009-8496-6139*

The object of research is the intellectual capital (IC) of IT companies. From the perspective of systemology, IC is conceptualized as a system formed from sub-systems and embedded within a meta-system. The ability of a system to adapt to the functional need of the meta-system, within the framework of systemology, is described by the key characteristic of the degree of systemization (μ_s), which reflects the degree of correspondence between the system's current properties and the functional need of the meta-system. That is, it serves as a criterion for the adaptability of the object (the IT company) to the functional need of the meta-object (the IT market). Thus, it is not simply the IC as a set of elements that is being studied, but rather their capacity for functional adaptation, which enables IT companies to meet current market demands.

The problem addressed lies in the absence of an objective and systemically coherent method for measuring IC of IT companies. The key methodological contradiction within extant approaches manifests as a discrepancy between component and holistic methods.

In the course of this research, a systemological Fibonacci-oriented method for measuring IC was developed and substantiated. A nonlinear weighting function, constructed upon the harmonic ratios of the Fibonacci sequence. The final measurement is based on determining the measure of degree of systemization (μ_s), which constitutes a one-dimensional projection of the multidimensional state-space of IC onto a scale within the range [0; 1] ($\mu_s \in [0; 1]$). This provides for the objective classification of any unique IC profile of IT companies.

The primary practical value of the method lies in its applicability for constructing an adaptive rating system for IT companies, featuring full automation and integration into expert-analytical software complexes.

Keywords: intellectual capital measurement, degree of systemization, systemological assessment method, IT companies, Fibonacci sequence.

References

1. Starkova, O., Andreichikov, O. (2024). Intellectual capital of IT companies in the development processes of innovative technologies and digital transformations: Historical and genetic analysis. *Development Management, 23 (4),* 64–75. https://doi.org/10.57111/devt/4.2024.64
2. Investment in Intangible Assets Surges, led by Funding for Software and Databases Amid AI Boom (2025). *Wipo.* Available at: https://www.wipo.int/pressroom/en/articles/2025/article_0005.html
3. Bagna, E., Cotta Ramusino, E., Denicolai, S., Strange, R. (2024). Intangible assets and firm performance: The relative effects of recognized and unrecognized assets. *Journal of Open Innovation: Technology, Market, and Complexity, 10 (3),* 100356. https://doi.org/10.1016/j.joitmc.2024.100356
4. Top Ten list of firms with the most Intellectual Capital in United States. *Attainix Consulting.* Available at: https://www.attainix.com/ICTopTen.aspx?TTP=ICP_IC
5. Ali, M. A., Hussin, N., Haddad, H., Al-Araj, R., Abed, I. A. (2021). A Multidimensional View of Intellectual Capital: The Impact on Innovation Performance. *Journal of Open Innovation: Technology, Market, and Complexity, 7 (4),* 216. https://doi.org/10.3390/joitmc7040216
6. Fan, C., Liao, X., Yang, X. (2025). Artificial intelligence and enterprise total factor productivity: A human capital requirement perspective. *International Review of Economics & Finance, 104,* 104661. https://doi.org/10.1016/j.iref.2025.104661
7. Cosa, M., Pedro, E., Urban, B. (2023). How to assess the intellectual capital of firms in uncertain times: a systematic literature review and a proposed model for practical adoption. *Journal of Intellectual Capital, 25 (7),* 1–22. https://doi.org/10.1108/jic-05-2023-0096
8. Popov, E., Vlasov, M. (1992). Assessment of Intellectual Development of the Human Capital of Hi-Tech Productions. *Montenegrin Journal of Economics, 14 (1),* 121–131. https://doi.org/10.14254/1800-5845/2018.14-1.9
9. Vo, D. H., Tran, N. P. (2024). Sectoral Intellectual Capital and Sector Performance in an Emerging Market. *Montenegrin Journal of Economics, 20 (2),* 209–220. https://doi.org/10.14254/1800-5845/2024.20-2.17
10. de Frutos-Belizón, J., Martín-Alcázar, F., Sánchez-Gardey, G. (2019). Conceptualizing academic intellectual capital: definition and proposal of a measurement scale. *Journal of Intellectual Capital, 20 (3),* 306–334. https://doi.org/10.1108/jic-09-2018-0152
11. Kianto, A., Ritala, P., Vanhala, M., Hussinki, H. (2020). Reflections on the criteria for the sound measurement of intellectual capital: A knowledge-based perspective. *Critical Perspectives on Accounting, 70,* 102046. https://doi.org/10.1016/j.cpa.2018.05.002
12. Helitha Muchtar, N., Palar, M. R. A., Amirulloh, M. (2023). Development of a valuation system of technology for the enhancement of innovation in Indonesia. *Heliyon, 9 (2),* e13124. https://doi.org/10.1016/j.heliyon.2023.e13124
13. Pryimak, V., Kornilova, I. (2025). Intellectual capital in the age of artificial intelligence. *Economy and Society, 71.* https://doi.org/10.32782/2524-0072/2025-71-55
14. Perić, N., Mamula NIkolić, T., Arsenijević, O. (2025). Intellectual Capital Evaluation Methods in Business Systems. *Journal of Soft Computing and Decision Analytics, 3 (1),* 136–145. https://doi.org/10.31181/jscda31202568
15. Semenchuk, T. B., Boniar, S. M., Osypova, Ye. L. et al. (2024). Management of creative industries. *History of Science and Technology.* Kyiv: DUIT, 340. https://doi.org/10.32703/978-617-7449-27-9
16. Wudhikarn, R. (2020). The hybrid intellectual capital valuation method. *Economic Research-Ekonomska Istraživanja, 34 (1),* 2115–2134. https://doi.org/10.1080/1331677x.2020.1860798
17. Jardon, C. M., Martinez-Cobas, X. (2021). Measuring intellectual capital with financial data. *PLOS ONE, 16 (5),* e0249989. https://doi.org/10.1371/journal.pone.0249989
18. Melnikov, G. P. (1988). *Systemology and Linguistic Aspects of Cybernetics.* New York, Paris, Monterey, Tokyo, Melbourne: Gordon and Breach, 433.
19. Starkova, O., Andreichikov, O. (2025). Conceptualizing a unit of measure of the intellectual capital of IT companies. *Proceedings of the XXII International Scientific and Practical Conference.* Hamburg, 36–39. https://doi.org/10.46299/ISG.2025.1.22
20. Hegel, G. W. F. (1969). *Science of Logic.* Routledge.

SYSTEMS AND CONTROL PROCESSES

DOI: 10.15587/2706-5448.2026.349558

COMBINED OPTIMIZATION OF COUNTERACTING ENEMY AMPHIBIOUS OPERATIONS IN COMPUTER MODELING

pages 36–42

Maksym Maksymov, *Doctor of Technical Sciences, Professor, Chief Researcher of Research Department, Scientific Research Center of the Armed Forces of Ukraine "State Oceanarium" of the Institute of the Naval Forces, Odesa, Ukraine, ORCID: https://orcid.org/0000-0002-3292-3112*

Maksym Grishyn, *PhD, Department of Computer Technologies of Automation, Odesa Polytechnic National University, Odesa, Ukraine, ORCID: https://orcid.org/0000-0002-9268-8994, e-mail: grishyn.m.v@opu.ua*

Oleksii Neizhpapa, *Vice Admiral, Commander of the Ukrainian Navy, Odesa, Ukraine, ORCID: https://orcid.org/0009-0007-0037-0166*

The object of research is an integrated coastal defense system using mine barriers and artillery batteries. The research was conducted for a typical landing force and uniform mining within the fairway.

Among the most challenging issues are accounting for heterogeneous weapons and uncertainties in the combat environment. Another challenge is choosing between the speed of completing the operation and the cost of resources.

The paper presents a combined model for countering amphibious assaults, which combines the effects of sea mine barriers and artillery fire in a single scale of relative explosive effectiveness. This allows for the optimization of resource and time expenditure. Additionally, robustness to disturbances due to the loss of mines and guns (Δm, Δg) is taken into account.

The research employs: standardization of ammunition nomenclature, Markov model of shelling, probabilistic model of detonation, and two-criterion optimization.

A unified model of combined optimization (ρ, G) in a common metric was developed. The operation was simulated in different modes. Robust corrections were introduced to the effective number of mines and guns in case of disturbances. For the practical selection of parameters, the ε-constraint method was applied, and tactical modes of use were outlined.

The results of modelling the response time of the operation T_{tot} and resource costs S were obtained. T_{tot} depends more on G and ρ (minimum 26 minutes) than on S, which has a dominant influence to a greater extent than ρ (minimum 80 tons). This is due to the fact that as G increases, the operation time is reduced due to parallelism. Meanwhile, an increase in ρ will lead to a high probability of disruption, reducing the need for shells.

Accordingly, the proposed model enables rapid selection of parameters to meet prescribed time thresholds and risks of enemy breakthrough.

Keywords: combined optimization, counter-amphibious operation, artillery support, minefield modeling, resource minimization.

References

1. Trail, C. D., Schmiedekamp, M. D., Phoha, S., Sustersic, J. P. (2013). Multiobjective planning for naval mine counter measures missions. *International Journal of Operational Research, 16 (1),* 113. https://doi.org/10.1504/ijor.2013.050626
2. Ftemov, Yu. (2021). Recommendations for creating specialized software for calculation the engineering barrier systems. *Systems of Arms and Military Equipment, 1 (65),* 131–136. https://doi.org/10.30748/soivt.2021.65.19
3. Neroba, V. (2019). The role of mining weapons in the modern wars and border conflicts. *Collection of scientific works of the National Academy of the State Border Guard Service of Ukraine. Series: Military and Technical Sciences, 81 (3),* 155–171. https://doi.org/10.32453/3.v81i3.444
4. Grishyn, M., Maksymova, O., Kirkopulo, K., Klymchuk, O. (2025). Development of methods of artillery control for suppression of an enemy amphibious operation in video game simulations. *Technology Audit and Production Reserves, 1 (2 (81)),* 26–33. https://doi.org/10.15587/2706-5448.2025.321797
5. Boltenkov, V., Brunetkin, O., Dobrynin, Y., Maksymova, O., Kuzmenko, V., Gultsov, P. et al. (2021). Devising a method for improving the efficiency of artillery shooting based on the Markov model. *Eastern-European Journal of Enterprise Technologies, 6 (3 (114)),* 6–17. https://doi.org/10.15587/1729-4061.2021.245854
6. Dobrynin, Y. V., Boltenkov, V. O., Maksymov, M. V. (2020). Information technology for automated assessment of the artillery barrels wear based on SVM classifier. *Applied Aspects of Information Technology, 3 (3),* 117–132. https://doi.org/10.15276/aait.03.2020.1
7. Zacks, S. (1979). Survival distributions in crossing fields containing clusters of mines with possible detection and uncertain activation or kill. *Naval Research Logistics Quarterly, 26 (3),* 423–435. https://doi.org/10.1002/nav.3800260306
8. Mjelde, K. M. (1977). An analytical minefield evaluation model without space averages. *Naval Research Logistics Quarterly, 24 (4),* 639–650. https://doi.org/10.1002/nav.3800240411
9. Cressie, N., Collins, L. B. (2001). Patterns in spatial point locations: Local indicators of spatial association in a minefield with clutter. *Naval Research Logistics, 48 (5),* 333–347. https://doi.org/10.1002/nav.1022
10. Qian, L., Chen, G., Tong, M., Tang, J. (2022). General design principle of artillery for firing accuracy. *Defence Technology, 18 (12),* 2125–2140. https://doi.org/10.1016/j.dt.2022.09.001
11. Dobrynin, Y., Volkov, V., Maksymov, M., Boltenkov, V. (2020). Development of physical models for the formation of acoustic waves at artillery shots and study of the possibility of separate registration of waves of various types. *Eastern-European Journal of Enterprise Technologies, 4 (5 (106)),* 6–15. https://doi.org/10.15587/1729-4061.2020.209847
12. Shim, Y., Atkinson, M. P. (2018). Analysis of artillery shoot-and-scoot tactics. *Naval Research Logistics, 65 (3),* 242–274. https://doi.org/10.1002/nav.21803
13. Świętochowski, N. (2019). Rules of artillery employment in combat operations. *Scientific Journal of the Military University of Land Forces, 192 (2),* 280–293. https://doi.org/10.5604/01.3001.0013.2599
14. Krzyzanowski, S. (2018). How to assess the accuracy of artillery fire. *Scientific Journal of the Military University of Land Forces, 187 (1),* 25–39. https://doi.org/10.5604/01.3001.0011.7355
15. Amorim, C. B., Augusto, A. da S., Gonçalves, R. F. B. (2025). A Constant Trinitrotoluene Equivalence Fit for Blast Wave Position Versus Time Data. *Propellants, Explosives, Pyrotechnics, 50 (7),* 44–54. https://doi.org/10.1002/prep.12071
16. Hammond, T. R., Midtgaard, Ø., Connors, W. A. (2021). A Bayesian Network Approach to Evaluating the Effectiveness of Modern Mine Hunting. *Remote Sensing, 13 (21),* 4359. https://doi.org/10.3390/rs13214359

DOI: 10.15587/2706-5448.2026.349943

DEVELOPMENT OF SYSTEM-TYPE-CENTRIC PARADIGM OF COMPUTER-SOFTWARE SYSTEMS ARCHITECTURAL DESIGN FOR AUTOMATION SYSTEMS

pages 43–56

Ihor Polataiko, *PhD Student, Department of Information and Telecommunication Technology and Systems, Ivano-Frankivsk National Technical University of Oil and Gas, Ivano-Frankivsk, Ukraine, ORCID: https://orcid.org/0000-0002-9111-0162*

Leonid Zamikhovskyi, *Doctor of Technical Sciences, Professor, Head of Department of Information and Telecommunication Technology and Systems, Ivano-Frankivsk National Technical University of Oil and Gas, Ivano-Frankivsk, Ukraine, e-mail: leozam@ukr.net, ORCID: https://orcid.org/0000-0002-6374-8580*

The object of research is the design processes of computer-software systems in the automation domain. Computer-software systems are considered as a combination of software and hardware.

This research focuses on addressing the lack of a formal methodology that differentiates the architectural design of computer-software systems for automation systems, including in hybrid Information Technology/Operational Technology environments.

Existing approaches, methods, and models for designing the architecture of computer-software systems do not account for the differentiation of approaches based on the fundamental differences in the nature of various system types used in the automation domain. This precludes the establishment of standardized and differentiated processes and methods for designing the architecture of such systems.

The main result is a new type-centric paradigm of architectural design, based on a taxonomy that classifies computer-software systems into fundamental types by their architectural nature. Furthermore, within the scope of the research, the levels and elements of computer-software systems are defined, which forms a standardized vision of the systems' constituent parts.

In contrast to existing models, approaches, and methodologies, the proposed type-centric paradigm for the architectural design of computer-software systems incorporates the fundamental aspects of the systems' nature that are important for architectural design, classifying systems based on this factor.

The proposed paradigm provides a foundation for systematized, specialized, and differentiated architectural design processes adapted to the specifics

ISSN-L 2664-9969; E-ISSN 2706-5448

of the systems' nature. This ensures standardization, interoperability, and systematicity in the design of computer-software systems for automation systems, potentially forming a basis for automated architectural design systems.

Keywords: software architecture, automation systems, system taxonomy, computer systems, architectural design.

References

1. Williams, T. J. (1990). A Reference Model for Computer Integrated Manufacturing from the Viewpoint of Industrial Automation. *IFAC Proceedings Volumes, 23 (8),* 281–291. https://doi.org/10.1016/s1474-6670(17)51748-6
2. *IEC 62264-1:2013 Enterprise-control system integration – Part 1: Models and terminology* (2013). International Electrotechnical Commission. Available at: https://webstore.iec.ch/en/publication/6675
3. *The Industrial Internet Reference Architecture (IIRA), Version 1.10: An Industry IoT Consortium foundational document* (2022). Boston: Industry IoT Consortium. Available at: https://www.iiconsortium.org/wp-content/uploads/sites/2/2022/11/IIRA-v1.10.pdf Last accessed: 16.10.2025
4. Controllers. *Kubernetes.* Available at: https://kubernetes.io/docs/concepts/architecture/controller Last accessed: 16.10.2025
5. Kruchten, P. B. (1995). The 4+1 View Model of architecture. *IEEE Software, 12 (6),* 42–50. https://doi.org/10.1109/52.469759
6. Starke, G., Simons, M., Zörner, S., Müller, R. D., Losch, H. (2019). *arc42 by Example: Software architecture documentation in practice.* Birmingham: Packt Publishing.
7. *arc42.* arc42. Available at: https://arc42.org Last accessed: 16.10.2025
8. ISO/IEC/IEEE 42010:2022. Software, systems and enterprise – Architecture description (2022). *ISO/IEC/IEEE.* Available at: https://www.iso.org/standard/74393.html Last accessed: 16.10.2025
9. ISO/IEC/IEEE 42020:2019. Systems and software engineering – Architecture processes (2019). *ISO/IEC/IEEE.* Available at: https://www.iso.org/standard/68982.html Last accessed: 16.10.2025
10. Bass, L., Clements, P., Kazman, R. (2021). *Software Architecture in Practice.* Boston: Addison-Wesley Professional.
11. Cervantes, H., Kazman, R. (2016). *Designing Software Architectures: A Practical Approach.* Boston: Addison-Wesley Professional.
12. Rozanski, N., Woods, E. (2012). *Software Systems Architecture: Working With Stakeholders Using Viewpoints and Perspectives.* Boston: Addison-Wesley.
13. Bauer, M., Boussard, M., Bui, N., Carrez, F., Siemens, C., Alube, J. et al. (2013). *Internet of Things – Architecture IoT-A Deliverable D1.5 – Final architectural reference model for the IoT v3.0.* Available at: https://www.researchgate.net/publication/272814818_Internet_of_Things_-_Architecture_IoT-A_Deliverable_D15_-_Final_architectural_reference_model_for_the_IoT_v30
14. Fornés-Leal, A., Lacalle, I., Palau, C. E., Szmeja, P., Ganzha, M., Paprzycki, M. et al. (2022). ASSIST-IoT: A Reference Architecture for Next Generation Internet of Things. *New Trends in Intelligent Software Methodologies, Tools and Techniques.* https://doi.org/10.3233/faia220243
15. Szmeja, P., Fornés-Leal, A., Lacalle, I., Palau, C. E., Ganzha, M., Pawłowski, W. et al. (2023). ASSIST-IoT: A Modular Implementation of a Reference Architecture for the Next Generation Internet of Things. *Electronics, 12 (4),* 854. https://doi.org/10.3390/electronics12040854
16. Megow, J. (2020). *Reference architecture models for Industry 4.0, smart manufacturing and IoT: An introduction.* Berlin: Begleitforschung PAiCE; iit – Institut für Innovation und Technik in der VDI / VDE Innovation + Technik GmbH.
17. ANSI/ISA-88.00.01-2010 Batch Control Part 1: Models and Terminology (2010). *International Society of Automation.* Available at: https://www.isa.org/products/isa-88-00-01-2010-batch-control-part-1-models Last accessed: 16.10.2025
18. AUTOSAR (AUTomotive Open System ARchitecture). *AUTOSAR Consortium.* Available at: https://www.autosar.org Last accessed: 16.10.2025
19. Evans, E. (2003). *Domain-Driven Design: Tackling Complexity in the Heart of Software.* Boston: Addison-Wesley Professional.
20. Lamm, J. G., Weilkiens, T. (2013). Method for Deriving Functional Architectures from Use Cases. *Systems Engineering, 17 (2),* 225–236. https://doi.org/10.1002/sys.21265
21. Forlingieri, M., Lamm, J. G., Roth, S., Walker, M. (2022). *Model-based system architecture.* Hoboken: Wiley. https://doi.org/10.1002/9781119746683
22. Eichmann, O. C., Lamm, J. G., Melzer, S., Weilkiens, T., God, R. (2024). Development of functional architectures for cyber-physical systems using interconnectable models. *Systems Engineering, 27 (6),* 993–1011. https://doi.org/10.1002/sys.21761
23. Griffor, E. R., Greer, C., Wollman, D. A., Burns, M. J. (2017). *Framework for Cyber-Physical Systems: Volume 1, Overview (NIST Special Publication 1500-201).* National Institute of Standards and Technology. Available at: https://doi.org/10.6028/NIST.SP.1500-201
24. NASA Systems Engineering Handbook (NASA/SP-2016-6105 Rev2) (2017). *National Aeronautics and Space Administration.* Available at: https://ntrs.nasa.gov/citations/20170001761 Last accessed: 16.10.2025
25. The DoDAF Architecture Framework Version 2.02 (2010). *The U.S. Department of Defense.* Available at: https://dodcio.defense.gov/Library/DoD-Architecture-Framework Last accessed: 16.10.2025
26. MOD Architecture Framework (2012). *Ministry of Defence.* Available at: https://www.gov.uk/guidance/mod-architecture-framework Last accessed: 16.10.2025
27. About the Unified Architecture Framework Specification Version 1.2 (2022). *Object Management Group.* Available at: https://www.omg.org/spec/UAF/1.2/About-UAF Last accessed: 16.10.2025
28. Plum, N. (2025). *TRAK Enterprise architecture framework.* Available at: https://sourceforge.net/projects/trak Last accessed: 16.10.2025
29. NATO Architecture Framework Version 4 (NAFv4) (2020). *NATO.* Available at: https://www.nato.int/content/dam/nato/webready/documents/publications-and-reports/NAFv4_2020.09.pdf Last accessed: 16.10.2025
30. *The TOGAF® Standard* (2022). The Open Group. Zaltbommel: Van Haren Publishing.
31. *Gesellschaft für Systems Engineering e.V.* (GfSE). System Architecture Framework. Available at: https://saf.gfse.org/ Last accessed: 16.10.2025
32. Dömel, A. (2025). *The Robot Architecture Framework: A systematic approach for describing the architecture of complex, autonomous robotic systems.* [Doctoral dissertation; University of Bremen].
33. Hatebur, D., Heisel, M. (2009). Deriving Software Architectures from Problem Descriptions. *Software Engineering,* 383–392.
34. Alebrahim, A., Hatebur, D., Heisel, M. (2011). A Method to Derive Software Architectures from Quality Requirements. *2011 18th Asia-Pacific Software Engineering Conference.* IEEE, 322–330. https://doi.org/10.1109/apsec.2011.29
35. Fitzgerald, J., Gamble, C., Larsen, P. G., Pierce, K., Woodcock, J. (2015). Cyber-Physical Systems Design: Formal Foundations, Methods and Integrated Tool Chains. *2015 IEEE/ACM 3rd FME Workshop on Formal Methods in Software Engineering.* Florence 40–46. https://doi.org/10.1109/formalise.2015.14
36. Rama, A., Reddy, M., Govindarajulu, P., Naidu, M. M. (2007). A Process Model for Software Architecture. *International Journal of Computer Science and Network Security, 7 (4),* 272–280.
37. Liu, L. (2018). The Process to Design an Automation System. *Journal of Physics: Conference Series, 1087*, 042001. https://doi.org/10.1088/1742-6596/1087/4/042001
38. Cantor, M. (2003). Rational Unified Process for Systems Engineering: Part 1. *Journal of Systems Architecture – JSA.*
39. Sas, C., Capiluppi, A. (2022). Antipatterns in software classification taxonomies. *Journal of Systems and Software, 190,* 111343. https://doi.org/10.1016/j.jss.2022.111343
40. Britto, R., Wohlin, C., Mendes, E. (2016). An extended global software engineering taxonomy. *Journal of Software Engineering Research and Development, 4 (1).* https://doi.org/10.1186/s40411-016-0029-2
41. Usman, M., Britto, R., Börstler, J., Mendes, E. (2017). Taxonomies in software engineering: A Systematic mapping study and a revised taxonomy devel-

opment method. *Information and Software Technology, 85,* 43–59. https://doi.org/10.1016/j.infsof.2017.01.006

42. Guenther, J., Falk, I., Cole, M. J. (2023). Theory building from qualitative evaluation. *Evaluation, 29 (4),* 410–427. https://doi.org/10.1177/13563890231196603

43. Lukka, K. (2003). *Case study research in logistics.* Turku: Turku School of Economics and Business Administration, 83–101.

44. Kwasnik, B. (1999). The role of classification in knowledge representation and discovery. *Library Trends, 48 (1).*

45. Mohammed, S. S. (2024). Deductive and inductive research. *Introduction to Research Methods.* Japan Bilingual Publishing Co., 203.

46. Iovino, M., Förster, J., Falco, P., Chung, J., Siegwart, R., Smith, C. (2024). *Comparison between Behavior Trees and Finite State Machines.* arXiv:2405.16137. https://doi.org/10.48550/arXiv.2405.16137

47. Zhang, Y., Li, R., Liang, P., Sun, W., Liu, Y. (2025). Knowledge-Based Multi-Agent Framework for Automated Software Architecture Design. *Proceedings of the 33rd ACM International Conference on the Foundations of Software Engineering,* 530–534. https://doi.org/10.1145/3696630.3728493

48. Guo, X., Keivan, D., Syed, U., Qin, L., Zhang, H., Dullerud, G. et al. (2024). *ControlAgent: Automating Control System Design via Novel Integration of LLM Agents and Domain Expertise.* arXiv:2410.19811. https://doi.org/10.48550/arXiv.2410.19811

DOI: 10.15587/2706-5448.2026.350994

DEVELOPMENT OF A SYSTEM OF INDICES FOR MONITORING AND ASSESSING THE SUSTAINABILITY OF UNDERGROUND UTILITIES

pages 57–65

Olha Starkova, *Doctor of Technical Sciences, Professor, Head of Department of Cybersecurity and Information Technologies, Simon Kuznets Kharkiv National University of Economics, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-9034-8830*

Olena Shapovalova, *PhD, Associate Professor, Department of Cybersecurity and Information Technologies, Simon Kuznets Kharkiv National University of Economics, Kharkiv, Ukraine, e-mail: olena.shapovalova@hneu.net, ORCID: https://orcid.org/0000-0003-4566-6634*

Alevtyna Aleinikova, *Doctor of Technical Sciences, Associate Professor, Department of Construction Technology and Organization, O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-2486-4263*

Ganna Solodovnyk, *PhD, Associate Professor, Department of Cybersecurity and Information Technologies, Simon Kuznets Kharkiv National University of Economics, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0001-6323-5083*

Petro Liubynskyi, *PhD Student, Department of Cybersecurity and Information Technologies, Simon Kuznets Kharkiv National University of Economics, Kharkiv, Ukraine, ORCID: https://orcid.org/0009-0004-3471-2206*

The object of research is the exploitative sustainability of the urban underground utility system. The subject of research is performance indices and methodological approaches to assess the sustainability and performance of urban underground utility systems.

The research study proposes a comprehensive system of indices to monitor and assess the sustainability of urban underground utilities and address critical issues such as aging infrastructure, aggressive operating environments, and financial constraints. The research study identifies seven categories of performance indices such as availability, funding sources, effectiveness of rehabilitation work, accident mitigation, environmental safety, efficient use of funds and efficiency of monitoring implementation. Each index is intended to measure a specific aspect of utility performance and provide a clearly defined basis to assess operational reliability and sustainability. Each of these indexes serves to evaluate a certain aspect of engineering networks functioning. This creates a firmly formalized foundation to the following analysis of the exploitation reliability and network durability. The methodology used regulations the calculation of these indexes, establishes the range of values and their possible variations; also, defines correlations between indexes and characteristics of sustainability of engineering communications. Indexes presented in this research provide an opportunity to predictive planning, increase efficiency of reconstruction and modernization strategies and ensure optimal resource allocation, which increases the operational safety. The methodology used regulations the calculation of these indexes, establishes the range of values and their possible variations; also, defines correlations between indexes and characteristics of sustainability of engineering communications. Indexes presented in this research provide an opportunity to predictive planning, increase efficiency of reconstruction and modernization strategies and ensure optimal resource allocation, which increases the operational safety.

Practical value of the results obtained in this research consists in the possibility of the heads of municipal utilities to take grounded management decisions. The research shows the level of impact of synergistic combination modern technology and financial planning on forming long-term stability of engineering structures. The proposed research allows improving the quality of urban infrastructure management. The application of the developed tools contributes to the stability of service provision and reduces the level of risks associated with the aging of engineering networks.

Keywords: indicator, operational sustainability, indicative planning, technical condition of networks, organizational and technological monitoring.

References

1. Aleinikova, A., Bondarenko, D., Goncharenko, D., Starkova, O. (2022). *Methodological principles for informational and technological monitoring of the stable operation of the sewerage networks.* Kharkiv, 272. Available at: http://repository.hneu.edu.ua/handle/123456789/29772

2. Hojjati, A., Jefferson, I., Metje, N., Rogers, C. D. F. (2018). Sustainability assessment for urban underground utility infrastructure projects. *Proceedings of the Institution of Civil Engineers – Engineering Sustainability, 171 (2),* 68–80. https://doi.org/10.1680/jensu.16.00050

3. Huang, H., Zhang, D., Huang, Z. (2022). Resilience of city underground infrastructure under multi-hazards impact: From structural level to network level. *Resilient Cities and Structures, 1 (2),* 76–86. https://doi.org/10.1016/j.rcns.2022.07.003

4. Sakai, H. (2024). Review of research on performance indicators for water utilities. *AQUA – Water Infrastructure, Ecosystems and Society, 73 (2),* 167–182. https://doi.org/10.2166/aqua.2024.224

5. Fares, H., Zayed, T. (2010). Hierarchical Fuzzy Expert System for Risk of Failure of Water Mains. *Journal of Pipeline Systems Engineering and Practice, 1 (1),* 53–62. https://doi.org/10.1061/(asce)ps.1949-1204.0000037

6. Shoaei, A., Sousa, V., Cruz, C. O. (2024). Literature review on the evaluation of resilience in infrastructure projects. *Journal of Infrastructure Policy and Development, 8 (15),* 9984. https://doi.org/10.24294/jipd9984

7. Suprayoga, G. B., Bakker, M., Witte, P., Spit, T. (2020). A systematic review of indicators to assess the sustainability of road infrastructure projects. *European Transport Research Review, 12 (1).* https://doi.org/10.1186/s12544-020-0400-6

8. Yang, Z., Barroca, B., Mebarki, A., Laffréchine, K., Dolidon, H., Lilas, L. (2024). Critical infrastructure resilience: a guide for building indicator systems based on a multi-criteria framework with a focus on implementable actions. *Natural Hazards and Earth System Sciences, 24 (11),* 3723–3753. https://doi.org/10.5194/nhess-24-3723-2024

9. Zhu, Y., Zhang, Q.-B. (2025). Modelling and assessing lifetime resilience of underground infrastructure to multiple hazards: Toward a unified approach. *Tunnelling and Underground Space Technology, 156,* 106212. https://doi.org/10.1016/j.tust.2024.106212

ISSN-L 2664-9969; E-ISSN 2706-5448

10. De Matos, B., Salles, R., Mendes, J., Gouveia, J. R., Baptista, A. J., Moura, P. (2022). A Review of Energy and Sustainability KPI-Based Monitoring and Control Methodologies on WWTPs. *Mathematics, 11 (1),* 173. https://doi.org/10.3390/math11010173
11. Carluccio, S., Mian, J., Andrews, L. et al. (2021). A review of the landscape of guidance, tools and standards for sustainable and resilient infrastructure. *PreventionWeb.* Available at: https://www.preventionweb.net/publication/review-landscape-guidance-tools-and-standards-sustainable-and-resilient-infrastructure
12. Endrodi-Kovacs, V., Tankovsky, O. (2022). A composite indicator for economic integration maturity: the case of Western Balkan countries. *Eastern Journal of European Studies, 13 (1),* 148–166. https://doi.org/10.47743/ejes-2022-0107
13. Nam, S.-N., Yun, H., Park, K., Oh, J. (2020). Proposed Framework of Performance Indicators for Evaluation of Sewerage Services: A Case Study of Seoul Metropolitan Government. *Journal of Korean Society of Environmental Engineers, 42 (8),* 393–404. https://doi.org/10.4491/ksee.2020.42.8.393
14. He, Y., Yang, L., Xu, H., Han, X., Sun, C., Di, Y., Zhao, T. (2024). Construction of an evaluation system for the effectiveness of rural sewage treatment facilities and empirical research. *Frontiers in Environmental Science, 12.* https://doi.org/10.3389/fenvs.2024.1430068
15. Shapovalova, O., Starkova, O., Solodovnyk, G. (2021). Automated system for determining a damage class for sections of a wastewater disposal network. *CEUR Workshop Proceedings.* Available at: http://ceur-ws.org/Vol-3039/short5.pdf
16. Xiao, X. (2022). Evaluation of operation cost control of urban sewage treatment plants in China. *Modern Salt Chemical Industry, 49,* 111–112. https://doi.org/10.19465/j.cnki.2095-9710.2022.05.021

DOI: 10.15587/2706-5448.2026.344218

THE IDENTIFICATION OF CRITICAL OCCUPATIONAL RISKS AND THE DETERMINATION OF PRIORITY PREVENTIVE MEASURES IN THE ROTARY KILN AREA OF CEMENT

pages 66–74

Razika Aouad, *Doctor of Technical Sciences, Associate Professor, Department of Transport Engineering, Laboratory of Transports and Environment Engineering, Mentouri Brothers University Constantine1, Constantine, Algeria, ORCID: https://orcid.org/0009-0004-5479-4157*

Samira Belhour, *Doctor of Technical Sciences, Associate Professor, Department of Transport Engineering, Laboratory of Transports and Environment Engineering, Mentouri Brothers University Constantine1, Constantine, Algeria, ORCID: https://orcid.org/0000-0001-9719-4646*

Rachid Chaib, *Doctor of Technical Sciences, Professor, Department of Transport Engineering, Laboratory of Transports and Environment Engineering, Mentouri Brothers University Constantine1, Constantine, Algeria, ORCID: https://orcid.org/0000-0001-8680-1906*

Djamel Nettour, *Doctor of Technical Sciences, Associate Professor, Department of Mining Engineering, Metallurgy and Materials, LAVAMINE Laboratory, Higher National School of Technology and Engineering ENSTI, Sidi Amar, Algeria, e-mail: djnettour@gmail.com, ORCID: https://orcid.org/0000-0003-0056-5389*

The objects of this research are occupational risks and priority preventive measures in the zone of the rotary kiln used in cement production. The identification of these objects is essential for housing development and infrastructure, but cement production is involving serious professional risks. Consequently, an evaluation of these is necessary; it is a critical stage in prevention process, aiming to prioritize actions in order to implement preventive measures. Therefore, an evaluation was triggered following a noticeable increase of five (05) accidents compared with 2021, with 16 accidents in 2022, to which workers in the rotary kiln zone were exposed. The adopted methodology, namely risk mapping, constitutes a strategic management tool that enables the identification, assessment, prioritization, and visualization of potential threats affecting the study area. Widely applied in industrial contexts, it offers a comprehensive representation and a systematic inventory of existing and potential hazards in both temporal and spatial dimensions. This facilitates risk management in a more informed and effective way. Furthermore, this offers decision-makers a clear overview to develop proactive action plans and allows them to monitor the effectiveness of implemented strategies. To obtain good results, qualitative and quantitative methods were applied, including the Ishikawa diagram, FMEA, and root cause analysis. These tools enabled the identification of the root causes of accidents in the studied zone. The survey results prove that gas leaks constitute the most critical hazards because of their potential to initiate fires. The findings offer a clear and comprehensive overview of occupational hazard distribution in the study zone, supporting the development of a planned prevention strategy to safeguard workers' health, enhance operational safety, and foster a sustainable safety culture.

Keywords: risk mapping, management, cement plant, safety, decision support tools and prevention.

References

1. Bouzerara, R., Chaib, R., Verzea, I. (2023). For better governance of harmfulness in companies: a case study. *Procedia Structural Integrity, 48,* 4–11. https://doi.org/10.1016/j.prostr.2023.07.103
2. Burtan, Z., Nowak-Senderowska, D., Szczepański, P. (2025). Methodology for Identification of Occupational Hazards Using Their Characteristic Features in Hard Coal Mining. *Applied Sciences, 15 (13),* 7079. https://doi.org/10.3390/app15137079
3. Kharzi, R., Chaib, R., Verzea, I., Akni, A. (2020). Safe and Sustainable Development in a hygiene and healthy company using decision matrix risk assessment technique: a case study. *Journal of Mining and Environment, 11 (2),* 363–373. https://doi.org/10.22044/jme.2020.9156.1807
4. Aouragh, L., Ouazraoui, N., Boubaker, L., Bourmada, N., Sekhri, A. (2025). Integrating Human Performance Factors to Improve Occupational Risk Assessment. *International Journal of Safety and Security Engineering, 15 (3),* 609–619. https://doi.org/10.18280/ijsse.150319
5. Mounia, T., Chaib, R., Samira, B., Djamel, N. (2024). The use of risk mapping for sustainable management of harmful effects in business: Case study. *XX International May Conference on Strategic Management – IMCSM24 Proceedings – Zbornik Radova,* 191–199. https://doi.org/10.5937/imcsm24070m
6. Kabiesz, P., Tutak, M. (2024). Developing a Culture of Safety for Sustainable Development and Public Health in Manufacturing Companies – A Case Study. *Sustainability, 16 (17),* 7557. https://doi.org/10.3390/su16177557
7. Abdelatif, A., Rachid, C., Smain, A., Ion, V. (2015). Promoting a sustainable organizational culture in a company: The National Railway Transport Company. *Journal of Rail Transport Planning & Management, 5 (1),* 23–30. https://doi.org/10.1016/j.jrtpm.2015.01.001
8. Revilla, A. J., Pérez-Luño, A., Nieto, M. J. (2016). Does Family Involvement in Management Reduce the Risk of Business Failure? The Moderating Role of Entrepreneurial Orientation. *Family Business Review, 29 (4),* 365–379. https://doi.org/10.1177/0894486516671075
9. Bakhuys Roozeboom, M. C., Wiezer, N. M., Boot, C. R. L., Bongers, P. M., Schelvis, R. M. C. (2021). Use of Intervention Mapping for Occupational Risk Prevention and Health Promotion: A Systematic Review of Literature. *International Journal of Environmental Research and Public Health, 18 (4),* 1775. https://doi.org/10.3390/ijerph18041775
10. Tremblay, A., Badri, A. (2018). Assessment of occupational health and safety performance evaluation tools: State of the art and challenges for small and medium-sized enterprises. *Safety Science, 101,* 260–267. https://doi.org/10.1016/j.ssci.2017.09.016
11. Figueroa-Maldonado, J., Herrera-Franco, G., Moreno-Alcívar, L., Bravo-Montero, L. (2024). Comparative Analysis of Methodologies for Occupational Safety Risk Assessment in an Artisanal Woodworking Industry. *International Journal of*

Safety and Security Engineering, 14 (6), 1825–1835. https://doi.org/10.18280/ijsse.140617

12. Gamboa-Sánchez, M. C., Cotrina-Teatino, M. A., Vega-Gonzalez, J. A., Noriega-Vidal, E. M., Arango-Retamozo, S. M., Marquina-Araujo, J. J. (2024). Effective Critical Risk Management in Welding Operations for Mining: A Case Study on Incident Reduction. *International Journal of Safety and Security Engineering, 14 (4),* 1039–1047. https://doi.org/10.18280/ijsse.140403
13. Bautista-Bernal, I., Quintana-García, C., Marchante-Lara, M. (2024). Safety culture, safety performance and financial performance. A longitudinal study. *Safety Science, 172,* 106409. https://doi.org/10.1016/j.ssci.2023.106409
14. Cooper, M. D.; Gilbert, C. et al. (Eds.) (2018). The safety culture construct: theory and practice. *Safety cultures, safety models: Taking stock and moving forward*. Cham: Springer International Publishing. Safety Cultures, Safety Models, SpringerBriefs in Safety Management, 47–61. https://doi.org/10.1007/978-3-319-95129-4_5
15. Moradi, M., Malmasi, S., Babaei Pouya, A. (2020). Identification Of Health, Safety, and Environment Aspects in Cement Factory Using AHP And FMEA Techniques. *Iranian Journal of Health Sciences, 8 (1),* 1–10. https://doi.org/10.18502/jhs.v8i1.4020
16. Pandeya, P., Mishra, D. K., Khanal, S. P., Joshi, Y. P., Marahatta, S. B., Neupane, A. et al. (2021). Occupational Health Risk among Selected Cement Factory Workers in Dang District of Nepal. *International Journal of Health Sciences and Research, 11 (5),* 8–22. https://doi.org/10.52403/ijhsr.20210502
17. Mohammadfam, I., Kamalinia, M., Momeni, M., Golmohammadi, R., Hamidi, Y., Soltanian, A. (2017). Evaluation of the Quality of Occupational Health and Safety Management Systems Based on Key Performance Indicators in Certified Organizations. *Safety and Health at Work, 8 (2),* 156–161. https://doi.org/10.1016/j.shaw.2016.09.001
18. Koskela, M. (2014). Occupational health and safety in corporate social responsibility reports. *Safety Science, 68,* 294–308. https://doi.org/10.1016/j.ssci.2014.04.011
19. Kim, Y., Jeong, S. S., Yiu, D. W., Moon, J. (2020). Frequent CEO Turnover and Firm Performance: The Resilience Effect of Workforce Diversity. *Journal of Business Ethics, 173 (1),* 185–203. https://doi.org/10.1007/s10551-020-04534-0
20. Ssemuddu, J. B., Olupot, P. W., Kirabira, J. B., Okure, M., Kayenga, T. J. (2025). Strengthening occupational safety, health, and environment risk assessments in cement manufacturing under stochastic production pressure using hybrid predictive models. *Discover Applied Sciences, 7 (9).* https://doi.org/10.1007/s42452-025-07594-x
21. Fresenbet, D. S., Olana, A. T., Tulu, A. S., Danusa, K. T. (2022). Occupational injury and associated factors among cement factories workers in central Ethiopia. *Journal of Occupational Medicine and Toxicology, 17 (1).* https://doi.org/10.1186/s12995-022-00348-0
22. Maqsoom, A., Khan, K., Musarat, M. A., Mubasit, H., Umer, M. (2020). Influence of Internal Workforce Diversity Factors on Labor Productivity in Construction Projects: Empirical Evidence from Pakistan. *2020 Second International Sustainability and Resilience Conference: Technology and Innovation in Building Designs.* IEEE, 1–7. https://doi.org/10.1109/ieeeconf51154.2020.9319935
23. Glendon, A. I., Clarke, S., McKenna, E. (2016). *Human Safety and Risk Management.* Boca Raton: CRC Press. https://doi.org/10.1201/9781420004687
24. Rachid, C., Ion, V., Irina, C., Mohamed, B. (2015). Preserving and improving the safety and health at work: Case of Hamma Bouziane cement plant (Algeria). *Safety Science, 76,* 145–150. https://doi.org/10.1016/j.ssci.2015.01.014
25. Kanti Bose, T. (2012). Application of Fishbone Analysis for Evaluating Supply Chain and Business Process – A Case Study on the ST James Hospital. *International Journal of Managing Value and Supply Chains, 3 (2),* 17–24. https://doi.org/10.5121/ijmvsc.2012.3202
26. Taleb, M, Belhour, S, Chaib, R, Kahoul, H. (2025). Applied approach for sustainable management and operation of the Constantine tramway. *Journal of Dalian University of Technology, 32 (9),* 24–34. Available at: https://drive.google.com/file/d/15_du9HTBvMhV9fESq6izihpWMMTuPv4l/view
27. *Custom Cement Production Line Cement Rotary Kiln Burner 300tpd Cement Plant Cement Clinker Biochar Rotary Kiln Gas Burner.* Available at: https://bntet-burner.en.made-in-china.com/product/SJNpdzfVYRYL/China-Custom-Cement-Production-Line-Cement-Rotary-Kiln-Burner-300tpd-Cement-Plant-Cement-Clinker-Biochar-Rotary-Kiln-Gas-Burner.html
28. Chaib, R., Verzea, I., Benidir, M., Taleb, M. (2012). Promoting a culture of health and safety at work: safety – a permanent priority. *Risk Analysis VIII, 44 (9),* 405–413. https://doi.org/10.2495/risk120341

DOI: 10.15587/2706-5448.2026.352435

IMPROVING THE EFFECTIVENESS OF MEDICAL DECISION SUPPORT SYSTEMS BASED ON MACHINE LEARNING AND CLOUD SERVICES

pages 75–84

Dmytro Buhai, *Automation Hardware and Software Department, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine, ORCID: https://orcid.org/0009-0001-0112-1432*

Anatolii Zhuchenko, *Doctor of Technical Sciences, Professor, Automation Hardware and Software Department, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine, ORCID: https://orcid.org/0000-0002-1552-8372*

Oleksii Zhuchenko, *Doctor of Technical Sciences, Professor, Automation Hardware and Software Department, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine, ORCID: https://orcid.org/0000-0001-5611-6529*

Dmytro Kovaliuk, *PhD, Associate Professor, Automation Hardware and Software Department, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine, ORCID: https://orcid.org/0000-0002-9729-1443*

Denys Skladannyy, *PhD, Associate Professor, Automation Hardware and Software Department, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine, e-mail: skl_den@ukr.net, ORCID: https://orcid.org/0000-0003-3624-5336*

The object of research is the process of developing and deploying decision support systems using ML models and cloud infrastructure. A significant problem solved in this research is the software implementation of such DSSs with ML models, as well as their further deployment for end-user access. As a result, a multipurpose scheme that combines the stages of local development and publication in a cloud infrastructure is proposed. Such approach is relevant for small companies and government agencies as it allows them to save financial resources on maintaining permanent IT specialists, maintenance and support. Its distinctive feature is that model training and its integration into a web application are performed at the local stage, while the publication stage uses cloud services to automatically update the project.

The research implements a comprehensive data preprocessing pipeline for stroke risk prediction, including KNN-based imputation for missing values and SMOTE + NCL for class balancing. Following a correlation analysis and data augmentation four classification algorithms: logistic regression, SVM, Random Forest, and eXtreme Gradient Boosting were evaluated. Logistic regression is identified as the top-performing model regarding recall after data augmentation. The final model is integrated into a Flask application via serialization and a dedicated inference module.

The application is published automatically from GitHub to Amazon's cloud environment using such services as EC2, S3, ECR, and Secrets Manager. The cost of maintaining such a project is significantly lower than using dedicated servers or third-party software with a subscription fee per user. The results can be used in various industries to create DSSs that require high availability and minimal maintenance costs.

ISSN-L 2664-9969; E-ISSN 2706-5448

Keywords: stroke prediction, data analysis, machine learning, DSS, web-programming, cloud infrastructure.

References

1. Kubat, M. (2017). *An Introduction to Machine Learning.* Springer International Publishing, 348. https://doi.org/10.1007/978-3-319-63913-0
2. Shalev-Shwartz, S., Ben-David, S. (2014). *Understanding Machine Learning.* Cambridge University Press, 449. https://doi.org/10.1017/cbo9781107298019
3. Chowdary, M. N., Sankeerth, B., Chowdary, C. K., Gupta, M. (2022). Accelerating the Machine Learning Model Deployment using MLOps. *Journal of Physics: Conference Series, 2327 (1),* 012027. https://doi.org/10.1088/1742-6596/2327/1/012027
4. Paleyes, A., Urma, R.-G., Lawrence, N. D. (2022). Challenges in Deploying Machine Learning: A Survey of Case Studies. *ACM Computing Surveys, 55 (6),* 1–29. https://doi.org/10.1145/3533378
5. Treveil, M., Omont, N., Stenac, C., Lefevre, K., Phan, D., Zentici, J. et al. (2020). *Introducing MLOps How to Scale Machine Learning in the Enterprise.* O'Reilly Media, Inc. Available at: https://itsocial.fr/wp-content/uploads/2021/04/Comment-mettre-%C3%A0-l%E2%80%99%C3%A9chelle-le-Machine-Learning-en-entreprise.pdf
6. Heymann, H., Kies, A. D., Frye, M., Schmitt, R. H., Boza, A. (2022). Guideline for Deployment of Machine Learning Models for Predictive Quality in Production. *Procedia CIRP, 107,* 815–820. https://doi.org/10.1016/j.procir.2022.05.068
7. Corbin, C. K., Maclay, R., Acharya, A., Mony, S., Punnathanam, S., Thapa, R. et al. (2023). DEPLOYR: a technical framework for deploying custom real-time machine learning models into the electronic medical record. *Journal of the American Medical Informatics Association, 30 (9),* 1532–1542. https://doi.org/10.1093/jamia/ocad114
8. Heymann, H., Schmitt, R. H. (2023). Machine Learning Pipeline for Predictive Maintenance in Polymer 3D Printing. *Procedia CIRP, 117,* 341–346. https://doi.org/10.1016/j.procir.2023.03.058
9. Kozak, Ye. B. (2021). Data Analysis and Machine Learning in Cloud and Fog Platforms as a Basis for Efficient Data Transfer. *Scientific Notes of Taurida National V. I. Vernadsky University. Series: Technical Sciences, 5,* 100–107. https://doi.org/10.32838/2663-5941/2021.5/16
10. Panchenko, T., Tuzova, I., Tuzov, O., Chumak, O. (2024). Khmarni servisy ta ohliad yikh postachalnykiv. *InterConf, 43 (193),* 550–559. https://doi.org/10.51582/interconf.19-20.03.2024.053
11. Report on Situational Analysis Results of Acute Stroke Care in Ukraine (2024). *World Health Organization.* Available at: https://www.who.int/ukraine/publications/WHO-EURO-2024-9677-49449-73972
12. Stroke Prediction Dataset. *Kaggle Inc.* Available at: https://www.kaggle.com/datasets/fedesoriano/stroke-prediction-dataset
13. SMOTE. *Imbalanced-learn.* Available at: https://imbalanced-learn.org/stable/references/generated/imblearn.over_sampling.SMOTE.html
14. Kovaliuk, D. O., Kovaliuk, O. O., Pinaieva, O. Y., Kotyra, A., Kalizhanova, A. (2019). Optimization of web-application performance. *Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2019,* 210. https://doi.org/10.1117/12.2537163
15. Singh, C. (2023). Automate deployment (CI/CD) of React JS application in AWS by using CodePipeline and EBS. *L&G Consultancy.* Available at: https://lng-consultancy.com/automate-deployment-ci-cd-of-react-js-application/

DOI: 10.15587/2706-5448.2026.352787

COMPARATIVE ASSESSMENT OF COMMONLY USED COLOR LOOKUP TABLES TO DETERMINE KEY PERFORMANCE INDICATORS FOR PERFUSION MAP DATA VISUALIZATION

pages 85–92

Svitlana Alkhimova, *PhD, Department of Biomedical Cybernetics, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine, e-mail: alkhimova.svitlana@lll.kpi.ua, ORCID: http://orcid.org/0000-0002-9749-7388*

Viktoriia Sorokina, *Department of Biomedical Cybernetics, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine, ORCID: https://orcid.org/0009-0005-8911-9765*

Illia Kabala, *Department of Biomedical Cybernetics, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine, ORCID: https://orcid.org/0009-0006-3450-9472*

The object of this research is color lookup table schemes that are most commonly used to visualize perfusion maps in the scope of assessment of brain hemodynamic parameters. The problem is that such color schemes differ significantly in the number of colors, their distribution, and the rules for converting grayscale image data into color. As a result, the same perfusion map may appear different depending on the selected scheme, which complicates the visual assessment of hemodynamic parameters and significantly biases the precision of their interpretation.

The research provides a comprehensive analysis of the ten commonly used color lookup table schemes for perfusion map visualization. Assessment of both direct schemes and patient-derived data is provided. Among quantitative metrics are RMSE, PSNR, SSIM, FSIM, ISSM, SRE, SAM, and UIQ. The CIELAB color space is used to provide a perceptual assessment of the color impact across neighboring levels in the schemes. It also used to analyze the relationship between local intensity differences in greyscale perfusion maps and resulting color perceptual differences once the lookup table is applied. Analysis reveals that the selection of color lookup table schemes is critical for preserving signal intensity and structural integrity. Spectral rainbow and block-structured schemes lag behind others in performance, making them less effective due to distorted structural features.

The results can be applied in practice to visualize perfusion map data in medical software to assess key hemodynamic parameters, such as blood volume, blood flow, and mean transit time. Also, the results can be helpful for standardization and selecting optimal color lookup table schemes in clinical practice, and for validating algorithms used to calculate perfusion maps during medical software development.

Keywords: colormap, color perception, color visualization, hemodynamic parameters, perfusion-weighted images.

References

1. Putowski, Z., Bakker, J., Kattan, E., Hernández, G., Ait-Oufella, H., Szczeklik, W., Guerci, P. (2025). Tissue perfusion as the ultimate target of hemodynamic interventions in the perioperative period. *Journal of Clinical Anesthesia, 107,* 112009. https://doi.org/10.1016/j.jclinane.2025.112009
2. Lipiński, S. (2024). Creation of a Simulated Sequence of Dynamic Susceptibility Contrast–Magnetic Resonance Imaging Brain Scans as a Tool to Verify the Quality of Methods for Diagnosing Diseases Affecting Brain Tissue Perfusion. *Computation, 12 (3),* 54. https://doi.org/10.3390/computation12030054
3. Sobhan, R., Gkogkou, P., Johnson, G., Cameron, D. (2023). *Model-based deconvolution for DSC-MRI: A comparison of accuracy, precision, and computational complexity of parametric transit time distributions.* https://doi.org/10.1101/2023.02.12.528216
4. Sorokina, V. V., Alkhimova, S. M. (2024). Analiz zastosuvannia tablyts vidpovidnosti koloriv dlia vizualizatsii danykh perfuziinykh kart. *World Ways and Methods of Improving Outdated Theories and Trends*, 380–385. Available at: https://isg-konf.com/world-ways-and-methods-of-improving-outdated-theories-and-trends/
5. Căiniceanu, A.-M.-A., Alexa, F. (2025). Application of Color Theory in Graphic Design. *2025 18th International Conference on Engineering of Modern Electric Systems (EMES).* IEEE 1–6. https://doi.org/10.1109/emes65692.2025.11045619
6. Furmanová, K., Kozlíková, B., Höllt, T., Gröller, M. E., Preim, B., Raidou, R. G. (2025). *BioMedical Visualization. Synthesis Lectures on Visualization.* Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-66789-3

7. Preim, B., Oeltze, S., Mlejnek, M., Groeller, E., Hennemuth, A., Behrens, S. (2009). Survey of the Visual Exploration and Analysis of Perfusion Data. *IEEE Transactions on Visualization and Computer Graphics, 15 (2),* 205–220. https://doi.org/10.1109/tvcg.2008.95
8. Garrison, L. A., Kolesar, I., Viola, I., Hauser, H., Bruckner, S. (2022). Trends & Opportunities in Visualization for Physiology: A Multiscale Overview. *Computer Graphics Forum, 41 (3),* 609–643. https://doi.org/10.1111/cgf.14575
9. Crameri, F., Shephard, G. E., Heron, P. J. (2020). The misuse of colour in science communication. *Nature Communications, 11 (1).* https://doi.org/10.1038/s41467-020-19160-7
10. Moreland, K. (2016). Why We Use Bad Color Maps and What You Can Do About It. *Electronic Imaging, 28 (16),* 1–6. https://doi.org/10.2352/issn.2470-1173.2016.16.hvei-133
11. Reda, K. (2023). Rainbow Colormaps: What are They Good and Bad for? *IEEE Transactions on Visualization and Computer Graphics, 29 (12),* 5496–5510. https://doi.org/10.1109/tvcg.2022.3214771
12. Liu, Y., Heer, J. (2018). Somewhere Over the Rainbow. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems,* 1–12. https://doi.org/10.1145/3173574.3174172
13. Stoelzle, M., Stein, L. (2021). Rainbow color map distorts and misleads research in hydrology – guidance for better visualizations and science communication. *Hydrology and Earth System Sciences, 25 (8),* 4549–4565. https://doi.org/10.5194/hess-25-4549-2021
14. Silva, S., Sousa Santos, B., Madeira, J. (2011). Using color in visualization: A survey. *Computers & Graphics, 35 (2),* 320–333. https://doi.org/10.1016/j.cag.2010.11.015
15. Sibrel, S. C., Rathore, R., Lessard, L., Schloss, K. B. (2020). The relation between color and spatial structure for interpreting colormap data visualizations. *Journal of Vision, 20 (12),* 7. https://doi.org/10.1167/jov.20.12.7
16. Zabala-Travers, S., Choi, M., Cheng, W.-C., Badano, A. (2015). Effect of color visualization and display hardware on the visual assessment of pseudocolor medical images. *Medical Physics, 42 (6),* 2942–2954. https://doi.org/10.1118/1.4921125
17. Nuñez, J. R., Anderton, C. R., Renslow, R. S. (2018). Optimizing colormaps with consideration for color vision deficiency to enable accurate interpretation of scientific data. *PLOS ONE, 13 (7),* e0199239. https://doi.org/10.1371/journal.pone.0199239
18. Ware, C., Turton, T. L., Bujack, R., Samsel, F., Shrivastava, P., Rogers, D. H. (2019). Measuring and Modeling the Feature Detection Threshold Functions of Colormaps. *IEEE Transactions on Visualization and Computer Graphics, 25 (9),* 2777–2790. https://doi.org/10.1109/tvcg.2018.2855742
19. Sollmann, N., Fuderer, M., Crameri, F., Weingärtner, S., Baeßler, B., Gulani, V. et al. (2024). Color Maps: Facilitating the Clinical Impact of Quantitative MRI. *Journal of Magnetic Resonance Imaging, 61 (4),* 1572–1579. https://doi.org/10.1002/jmri.29573
20. deSouza, N. M., Fuderer, M., Sollmann, N., Wichtmann, B. D., Golay, X. (2025). Colour map displays. *Insights into Imaging, 16 (1).* https://doi.org/10.1186/s13244-025-01970-2
21. Qutbi, M. (2024). Quantitative Performance Evaluation of Commonly Used Colormaps for Image Display in Myocardial Perfusion Imaging: Analysis based on Perceptual Metrics. *Molecular Imaging and Radionuclide Therapy, 33 (2),* 94–105. https://doi.org/10.4274/mirt.galenos.2024.34711
22. The Cancer Genome Atlas Program (TCGA). *Cancer.gov.* Available at: http://cancergenome.nih.gov/
23. Jain, R., Poisson, L., Narang, J., Gutman, D., Scarpace, L., Hwang, S. N. et al. (2013). Genomic Mapping and Survival Prediction in Glioblastoma: Molecular Subclassification Strengthened by Hemodynamic Imaging Biomarkers. *Radiology, 267 (1),* 212–220. https://doi.org/10.1148/radiol.12120846
24. Alkhimova, S., Krenevych, A. (2019). Brain tissues segmentation on mr perfusion images using CUSUM filter for boundary pixels. *International Journal of Computing, 18 (2),* 127–134. https://doi.org/10.47839/ijc.18.2.1411
25. Alkhimova, S. (2019). CUSUM Filter for Brain Segmentation on DSC Perfusion MR Head Scans with Abnormal Brain Anatomy. *Proceedings of the 2019 International Conference on Intelligent Medicine and Image Processing,* 43–47. https://doi.org/10.1145/3332340.3332357
26. Kudo, K., Sasaki, M., Yamada, K., Terae, S., Tha, K. K., Yoshida, Y., Miyasaka, K. (2006). Evaluation and minimization of the difference in MR perfusion maps among software. *Proceedings of the 14th Annual Meeting of ISMRM,* 3558. Available at: https://cds.ismrm.org/protected/06MProceedings/PDFfiles/03558.pdf
27. Kudo, K. (2005). *Acute Stroke Imaging Standardization Group Japan recommended standard LUT (a-LUT) for perfusion color maps.*
28. Schanda, J. (Ed.) (2007). *Colorimetry: understanding the CIE system.* John Wiley & Sons. https://doi.org/10.1002/9780470175637
29. Sara, U., Akter, M., Uddin, M. S. (2019). Image Quality Assessment through FSIM, SSIM, MSE and PSNR – A Comparative Study. *Journal of Computer and Communications, 7 (3),* 8–18. https://doi.org/10.4236/jcc.2019.73002
30. Sampat, M. P., Zhou Wang, Gupta, S., Bovik, A. C., Markey, M. K. (2009). Complex Wavelet Structural Similarity: A New Image Similarity Index. *IEEE Transactions on Image Processing, 18 (11),* 2385–2401. https://doi.org/10.1109/tip.2009.2025923
31. Lin Zhang, Lei Zhang, Xuanqin Mou, Zhang, D. (2011). FSIM: A Feature Similarity Index for Image Quality Assessment. *IEEE Transactions on Image Processing, 20 (8),* 2378–2386. https://doi.org/10.1109/tip.2011.2109730
32. Aljanabi, M. A., Hussain, Z. M., Shnain, N. A. A., Lu, S. F. (2019). Design of a hybrid measure for image similarity: a statistical, algebraic, and information-theoretic approach. *European Journal of Remote Sensing, 52,* 2–15. https://doi.org/10.1080/22797254.2019.1628617
33. Nordio, A., Chiasserini, C.-F., Viterbo, E. (2009). Signal Reconstruction Errors in Jittered Sampling. *IEEE Transactions on Signal Processing, 57 (12),* 4711–4718. https://doi.org/10.1109/tsp.2009.2027404
34. Yuhas, R. H., Goetz, A. F., Boardman, J. W. (1992). Discrimination among semi-arid landscape endmembers using the spectral angle mapper (SAM) algorithm. *JPL, Summaries of the Third Annual JPL Airborne Geoscience Workshop. Volume 1: AVIRIS Workshop.* Available at: https://ntrs.nasa.gov/citations/19940012193
35. Zhou Wang, Bovik, A. C. (2002). A universal image quality index. *IEEE Signal Processing Letters, 9 (3),* 81–84. https://doi.org/10.1109/97.995823

DOI: 10.15587/2706-5448.2026.353012

DETERMINATION OF THE IMPACT OF TRAFFIC DELAYS AT SIGNALIZED INTERSECTIONS ON THE TRAVEL TIME OF A FIRE ENGINE TO THE PLACE OF A CALL

pages 93–98

Ivan Pasnak, *PhD, Associate Professor, Department of Operation of Vehicles and Fire-Rescue Equipment, Lviv State University of Life Safety, Lviv, Ukraine, e-mail: van-pas@ukr.net, ORCID: https://orcid.org/0000-0002-8405-4625*

The paper outlines the problem of the influence of various factors, in particular traffic delays at signalized intersections, on the movement of a fire engine to the place of a call. The object of research is the process of queue formation of vehicles at a signalized intersection, which leads to delays of a fire engine during its response. The conditions for queue formation at signalized intersections were identified, under which the queue may reach its maximum value or remain in a continuous growth mode. Thus, prerequisites for further research were established, and the maximum traffic flow intensity of 1000 passenger car units was selected. Using simulation modeling in the PTV Vissim environment, a model of a signalized intersection with a two-lane approach was developed. This model enables simulation of intersection crossing by varying traffic flow intensity, signal cycle length, and the proportion of green time within each cycle. Experimental studies of the maximum queue length were conducted using the full factorial experiment method. A relationship was obtained to determine the

ISSN-L 2664-9969; E-ISSN 2706-5448

maximum queue length at a signalized intersection as a function of traffic flow intensity, signal cycle length, and the proportion of green time in each cycle. The magnitude of the influence of each identified parameter on queue formation at the intersection was analyzed separately. It was established that increasing the proportion of the green signal from 0.20 to 0.50 reduces the queue length by approximately 35–40%. An increase in traffic intensity from 200 to 1000 passenger car units per hour leads to an approximately fourfold increase in queue length. The obtained relationships can be further used in the development of new or the improvement of existing models for determining optimal response routes of emergency vehicles to the place of a call, taking into account possible delays at signalized intersections.

Keywords: signalized intersection, travel route, traffic delay, fire, travel time, fire engine.

References

1. Hao, Z., Wang, Y., Yang, X. (2024). Every Second Counts: A Comprehensive Review of Route Optimization and Priority Control for Urban Emergency Vehicles. *Sustainability, 16 (7),* 2917. https://doi.org/10.3390/su16072917
2. Pasnak, I., Renkas, A. (2020). Optimization of the duration of emergency vehicle movement to the place of fire. *Transport Problems, 15 (4, Part 1),* 117–124. https://doi.org/10.21307/tp-2020-053
3. Hulida, E., Pasnak, I., Koval, O., Tryhuba, A. (2019). Determination of the Critical Time of Fire in the Building and Ensure Successful Evacuation of People. *Periodica Polytechnica Civil Engineering,* 63 *(1),* 308–316. https://doi.org/10.3311/ppci.12760
4. Behrooz, H., Ilbeigi, M. (2025). Adaptive emergency evacuation routing: a graph-based approach. *International Journal of Transportation Science and Technology, 20,* 178–192. https://doi.org/10.1016/j.ijtst.2024.11.010
5. Huliak, M., Marková, I. (2026). Analysis of access roads, boarding areas and arrival times of firefighting units to selected heritage wooden buildings. *Transportation Research Procedia, 93,* 1006–1012. https://doi.org/10.1016/j.trpro.2025.12.035
6. Wu, J., Kulcsár, B., Ahn, S., Qu, X. (2020). Emergency vehicle lane pre-clearing: From microscopic cooperation to routing decision making. *Transportation Research Part B: Methodological, 141,* 223–239. https://doi.org/10.1016/j.trb.2020.09.011
7. Musolino, G., Polimeni, A., Rindone, C., Vitetta, A. (2013). Travel Time Forecasting and Dynamic Routes Design for Emergency Vehicles. *Procedia – Social and Behavioral Sciences, 87,* 193–202. https://doi.org/10.1016/j.sbspro.2013.10.603
8. Humayun, M., Almufareh, M. F., Jhanjhi, N. Z. (2022). Autonomous Traffic System for Emergency Vehicles. *Electronics, 11 (4),* 510. https://doi.org/10.3390/electronics11040510
9. Huang, D., Wang, S., Liu, Z. (2021). A systematic review of prediction methods for emergency management. *International Journal of Disaster Risk Reduction, 62,* 102412. https://doi.org/10.1016/j.ijdrr.2021.102412
10. Wang, W., Wu, S., Wang, S., Zhen, L., Qu, X. (2021). Emergency facility location problems in logistics: Status and perspectives. *Transportation Research Part E: Logistics and Transportation Review, 154,* 102465. https://doi.org/10.1016/j.tre.2021.102465
11. Wu, J., Qu, X. (2022). Intersection control with connected and automated vehicles: a review. *Journal of Intelligent and Connected Vehicles, 5 (3),* 260–269. https://doi.org/10.1108/jicv-06-2022-0023
12. Li, Z., Wang, Q., Wang, J., He, Z. (2024). A Flexible Cooperative MARL Method for Efficient Passage of an Emergency CAV in Mixed Traffic. *IEEE Transactions on Intelligent Transportation Systems, 25 (8),* 8898–8912. https://doi.org/10.1109/tits.2024.3411487
13. Nahofti Kohneh, J., Murray-Tuite, P. (2025). Two-Level Routing Framework to Facilitate the Movement of Emergency Response Vehicles in a Transportation Network. *Transportation Research Record: Journal of the Transportation Research Board, 2679 (11),* 1143–1170. https://doi.org/10.1177/03611981251351873
14. Chen, Y., Wang, J., Lo, S., Sung, W. (2024). An emergency vehicle traffic signal preemption system considering queue spillbacks along routes and negative impacts on non-priority traffic. *IET Intelligent Transport Systems, 18 (8),* 1385–1395. Portico. https://doi.org/10.1049/itr2.12518
15. Pasnak, I., Prydatko, O., Gavrilyk, A. (2016). Development of algorithms for efficient management of fire rescue units. *Eastern-European Journal of Enterprise Technologies, 3 (3 (81)),* 22–28. https://doi.org/10.15587/1729-4061.2016.71604

DOI: 10.15587/2706-5448.2026.353068

SYMMETRIC APPROACH TO INDUSTRIAL SAFETY RISK ASSESSMENT BASED ON MUTUAL PROBABILITY CORRESPONDENCE

pages 99–112

Zakhar Matsuk, *PhD, Associate Professor, Department of Labor Protection, Civil and Technogenic Safety, Ukrainian State University of Science and Technology, SEI "Prydniprovska State Academy of Civil Engineering and Architecture", Dnipro, Ukraine, e-mail: matsuk.zachar@pdaba.edu.ua, ORCID: https://orcid.org/0000-0001-6114-9536*

Anatolii Bielikov, *Doctor of Technical Sciences, Professor, Department of Labor Protection, Civil and Technogenic Safety, Ukrainian State University of Science and Technology, SEI "Prydniprovska State Academy of Civil Engineering and Architecture", Dnipro, Ukraine, ORCID: https://orcid.org/0000-0001-5822-9682*

Ihor Maladyka, *PhD, Associate Professor, Head of Department of Geodesy, Land Management, Building Structures and Life Safety, Cherkasy State Technological University, Cherkasy, Ukraine, ORCID: https://orcid.org/0000-0001-8784-2814*

Oleksandr Tyshchenko, *Doctor of Technical Sciences, Professor, Department of Geodesy, Land Management, Building Structures and Life Safety, Cherkasy State Technological University, Cherkasy, Ukraine, ORCID: https://orcid.org/0000-0001-7303-6360*

Vadim Kharchenko, *Forensic Expert, Individual entrepreneur "Kharchenko V. V.", Kamianske, Ukraine, ORCID: https://orcid.org/0009-0003-0345-9116*

The object of research is the process of assessing the level of safety of complex technical systems of critical infrastructure under conditions of uncertainty. The problem of the limitations and asymmetry of risk assessment methods was investigated. Risk assessment processes were studied based on IAEA data, using a combination of theoretical and computational modeling methods. The theoretical basis was based on factor risk analysis. Dynamic and temporal dependencies were taken into account using a synthesized modular scalable dynamic Bayesian network (MSDBN), which integrated local components and their interaction into hierarchical models. Probabilistic assessments were performed using Monte Carlo simulation, as well as structural and hybrid learning algorithms for Bayesian networks. The limitations, asymmetry, and dependence on expert opinion of traditional risk assessment methods were shown. It was shown that the synthesis of Bayesian networks and the Monte Carlo method as basic approaches meets the criteria for symmetry in risk event modeling. It was established that the maximum adequacy of risk event prediction is achieved when using a modular Bayesian architecture with a multi-criteria approach through assessing the compliance of production system elements with regulatory requirements, historical analogies and/or modeling results. MSDBN improves the quality and validity of management decisions, is integrated into automated control systems, serves as a tool for digital twins, can be used in the educational process, is symmetric and suitable for assessing the effectiveness of security measures. The proposed approach is useful for state, defense and industrial systems, including under conditions of uncertainty.

Keywords: probabilistic risk assessment, industrial safety, industrial safety, dynamic Bayesian modeling, Monte Carlo modeling, symmetric probabilistic modeling.

References

1. Borys, O. P. (2017). History of development of state fire protection and its role in formation of the system of civil protection of Ukraine. *Derzhavne upravlinnia: udoskonalennia ta rozvytok, 1,* 28–36. Available at: http://www.dy.nayka.com.ua/?op=1&z=1330 Last accessed: 25.12.2025
2. *ISO 31000:2018. Risk management – Guidelines* (2018). Geneva: International Organization for Standardization, 16.
3. *ISO 31010:2019. Risk management – Risk assessment techniques* (2019). Geneva: International Organization for Standardization, 92.
4. Blanco, C. C., Caro, F., Corbett, C. J. (2019). Managing Safety-Related Disruptions: Evidence from the U.S. Nuclear Power Industry. *Risk Analysis, 39 (10),* 2197–2213. Portico. https://doi.org/10.1111/risa.13307
5. Zhang, J., Yin, X., Xing, J., An, X. (2023). Dynamic risk assessment for train brake system considering time-dependent components and human factors. *Computers & Industrial Engineering, 185,* 109687. https://doi.org/10.1016/j.cie.2023.109687
6. Zarei, E., Khakzad, N., Cozzani, V., Reniers, G. (2019). Safety analysis of process systems using Fuzzy Bayesian Network (FBN). *Journal of Loss Prevention in the Process Industries, 57,* 7–16. https://doi.org/10.1016/j.jlp.2018.10.011
7. Bazaluk, O., Tsopa, V., Cheberiachko, S., Deryugin, O., Radchuk, D., Borovytskyi, O., Lozynskyi, V. (2023). Ergonomic risk management process for safety and health at work. *Frontiers in Public Health, 11.* https://doi.org/10.3389/fpubh.2023.1253141
8. Mandal, M. K., Mandal, A. (2023). Human Reliability: Cognitive Bias in People–System Interface. *Human Reliability Programs in Industries of National Importance for Safety and Security.* Springer, 127–138. https://doi.org/10.1007/978-981-99-5005-8_13
9. Hollcroft, B., Lyon, B. K., Popov, G. (2022). *Risk assessment: A practical guide to assessing operational risks.* Wiley, 380. Available at: https://www.wiley.com/en-us/Risk+Assessment%3A+A+Practical+Guide+to+Assessing+Operational+Risks%2C+2nd+Edition-p-9781119755920
10. Purkait, P., Mondal, S., Changmai, S., Volli, V., Shu, C. (2024). *Hazards and safety in process industries: Case studies.* Routledge. Available at: https://www.routledge.com/Hazards-and-Safety-in-Process-Industries-Case-Studies/Purkait-Mondal-Changmai-Volli-Shu/p/book/9780367516512
11. Environment of peace: Security in a new era of risks (2022). *Stockholm International Peace Research Institute (SIPRI).* Available at: https://www.sipri.org/publications/2022/policy-reports/environment-peace-security-new-era-risk
12. Matsuk, Z. M. (2021). Concept of security and energy efficiency of the oil and gas industry of Ukraine. *Ukrainian Journal of Civil Engineering and Architecture, 4,* 46–57. https://doi.org/10.30838/j.bpsacea.2312.310821.46.789
13. Matsuk, Z., Belykov, A., Cheberiachko, Y., Nesterova, O. (2026). Methodology of Safety Risk: Assessment of Adequacy of Measures. *International Conference: Challenges of Ensuring Ukraine's Mineral Resources in the Context of Post-War Reconstruction (CEUMR), 172,* 327–334. https://doi.org/10.4028/p-qviuu5
14. Chernobyl accident: Updating of INSAG-1 (INSAG-7) (1992). *International Atomic Energy Agency.* Available at: https://www-pub.iaea.org/MTCD/Publications/PDF/Pub913e_web.pdf
15. Amano, Y. (Ed.) (2015). The Fukushima Daiichi accident: Report by the Director General. *International Atomic Energy Agency.* Available at: https://www.iaea.org/publications/10962/the-fukushima-daiichi-accident
16. The Fukushima Daiichi Nuclear Accident Independent Investigation Commission: The official report (2012). *International Atomic Energy Agency.* Available at: https://warp.ndl.go.jp/en/web/20121025090656/naiic.go.jp/en/report/
17. Kelman, M., Ortynsky, V. (2021). Chernobyl disaster – a tragic lesson for all humanities: 35th anniversary of the Chernobyl accident. *Visnyk Natsionalnoho Universytetu "Lvivska Politehnika". Seria: Yurydychni Nauky, 8 (2 (30)),* 1–7. Available at: https://science.lpnu.ua/law/all-volumes-and-issues/volume-8-number-230-2021/chernobyl-disaster-tragic-lesson-all-humanities
18. Grabowska, S., Saniuk, S. (2022). Business Models in the Industry 4.0 Environment – Results of Web of Science Bibliometric Analysis. *Journal of Open Innovation: Technology, Market, and Complexity, 8 (1),* 19. https://doi.org/10.3390/joitmc8010019
19. Gajdzik, B., Grabowska, S., Saniuk, S., Wieczorek, T. (2020). Sustainable Development and Industry 4.0: A Bibliometric Analysis Identifying Key Scientific Problems of the Sustainable Industry 4.0. *Energies, 13 (16),* 4254. https://doi.org/10.3390/en13164254
20. Liao, Y., Deschamps, F., Loures, E. de F. R., Ramos, L. F. P. (2017). Past, present and future of Industry 4.0 – a systematic literature review and research agenda proposal. *International Journal of Production Research, 55 (12),* 3609–3629. https://doi.org/10.1080/00207543.2017.1308576
21. Friedman, N., Koller, D. (2003). Being Bayesian About Network Structure. A Bayesian Approach to Structure Discovery in Bayesian Networks. *Machine Learning, 50 (1-2),* 95–125. https://doi.org/10.1023/a:1020249912095
22. Hari Krishna, S. M., Sharma, R. (2024). Comparative Study of Orchestration using gRPC API and REST API in Server Creation Time: An Openstack Case. *International Journal of Computer Networks & Communications, 16 (1),* 87–104. https://doi.org/10.5121/ijcnc.2024.16106
23. xAI. (2025). *Grok (Version 4.1) [Computer software].* Available at: https://x.ai/grok

MATHEMATICAL MODELING

DOI: 10.15587/2706-5448.2026.352493

INCLUSION AND HOLES DETECTION IN 3D OBJECTS USING NUMERICAL MODELING AND NEURAL NETWORKS

pages 113–122

Roman Havdulskyi, *PhD Student, Department of Software, Lviv Polytechnic National University, Lviv, Ukraine, e-mail: roman.i.havdulskyi@lpnu.ua, ORCID: https://orcid.org/0009-0004-6737-6018*

Liubov Zhuravchak, *Doctor of Technical Sciences, Senior Researcher, Professor, Department of Software, Lviv Polytechnic National University, Lviv, Ukraine, ORCID: https://orcid.org/0000-0002-1444-5882*

The object of research is a stationary heat-conduction process in three-dimensional heterogeneous media which components are in ideal thermal contact.

The addressed problem is the difficulties in detecting, localizing, and classifying inclusions in 3D objects. Most methods rely on employing active thermography which produces data as time-dependent sequences. Both capturing and processing it is quite costly and resource required.

The paper proposes a hybrid approach that relies on steady-heat thermograms, which are significantly easier and cheaper to capture. The developed approach uses one of the variants of the indirect near-boundary element method (INBEM), SOTA detectors (YOLO 11n and 12n), and a custom depth head based on ConvNeXt V2. Additionally, the paper showed that attention-centric architecture is promising for processing steady heat images.

INBEM with near-boundary elements in the form of families of points achieves an execution time of approximately 50 seconds per sample, with a general maximum error of approximately 0.08. This enabled the creation of a large dataset, comprising approximately 130K samples. Additionally, a testing dataset with a size of 7K and slightly different variance is obtained. Both YOLO 11n and 12n showed mAP50:95 metric results on the testing dataset of 85.2% and 89.4%, respectively. The precision/recall for both models are the following: 92.0/92.8 and 92.3/96.3. The depth head showed a MAPE of about 2%.

The proposed method focuses on detecting inclusions and holes using steady heat images, so it is suitable for relatively low-cost analysis, as obtaining

ISSN-L 2664-9969; E-ISSN 2706-5448

such data is easier and quicker than collecting time-dependent data. It may be useful to screen slab-like structures, such as photovoltaic panels. Wall diagnostics is one possible future application area, as the work can be extended to semi-infinite objects. Thus, the results may serve as a basis for a low-cost inspection tool.

Keywords: YOLO, steady-heat thermography, non-destructive testing, synthetic data generation, numerical modeling.

References

1. Rezayiye, R. K., Ibarra-Castanedo, C., Maldague, X. (2024). Methods for Corrosion Detection in Pipes Using Thermography: A Case Study on Synthetic Datasets. *Algorithms, 17 (10),* 439. https://doi.org/10.3390/a17100439
2. Salah, M., Werghi, N., Svetinovic, D., Abdulrahman, Y. (2025). *Multi-Modal Attention Networks for Enhanced Segmentation and Depth Estimation of Subsurface Defects in Pulse Thermography*. ArXiv. https://doi.org/10.48550/arxiv.2501.09994
3. Sels, S., Bogaerts, B., Verspeek, S., Ribbens, B., Steenackers, G., Penne, R. et al. (2020). 3D Defect detection using weighted principal component thermography. *Optics and Lasers in Engineering, 128,* 106039. https://doi.org/10.1016/j.optlaseng.2020.106039
4. Dudzik, S. (2015). Two-stage neural algorithm for defect detection and characterization uses an active thermography. *Infrared Physics & Technology, 71,* 187–197. https://doi.org/10.1016/j.infrared.2015.03.003
5. Szymanik, B., Psuj, G., Hashemi, M., Lopato, P. (2021). Detection and Identification of Defects in 3D-Printed Dielectric Structures via Thermographic Inspection and Deep Neural Networks. *Materials, 14 (15),* 4168. https://doi.org/10.3390/ma14154168
6. Kumar, R., Puranik, V. E., Gupta, R. (2024). Unveiling the Potential of Infrared Thermography in Quantitative Investigation of Potential-Induced Degradation in Crystalline Silicon PV Module. *Solar Energy Advances, 4,* 100049. https://doi.org/10.1016/j.seja.2023.100049
7. Spajić, M., Talajić, M., Mršić, L. (2024). Using CNNs for Photovoltaic Panel Defect Detection via Infrared Thermography to Support Industry 4.0. *Business Systems Research Journal, 15 (1),* 45–66. https://doi.org/10.2478/bsrj-2024-0003
8. Di Tommaso, A., Betti, A., Fontanelli, G., Michelozzi, B. (2022). A multi-stage model based on YOLOv3 for defect detection in PV panels based on IR and visible imaging by unmanned aerial vehicle. *Renewable Energy, 193,* 941–962. https://doi.org/10.1016/j.renene.2022.04.046
9. Ta, Q. T., Mac, V. H., Huh, J., Yim, H. J., Lee, G. (2025). Automatic detection of subsurface defects in concrete structures using state-of-the-art deep learning-based object detectors on the infrared dataset. *Engineering Structures, 329,* 119829. https://doi.org/10.1016/j.engstruct.2025.119829
10. Jeon, M., Yoo, S., Kim, S.-W. (2022). A Contactless PCBA Defect Detection Method: Convolutional Neural Networks With Thermographic Images. *IEEE Transactions on Components, Packaging and Manufacturing Technology, 12 (3),* 489–501. https://doi.org/10.1109/tcpmt.2022.3147319
11. Liu, J., Long, X., Jiang, C., Liao, W. (2024). Multi-feature vision transformer for automatic defect detection and quantification in composites using thermography. *NDT & E International,* 143, 103033. https://doi.org/10.1016/j.ndteint.2023.103033
12. Wu, Z., Chen, S., Feng, F., Qi, J., Feng, L., Tao, N. et al. (2023). Automatic defect detection and three-dimensional reconstruction from pulsed thermography images based on a bidirectional long-short term memory network. *Engineering Applications of Artificial Intelligence, 124,* 106574. https://doi.org/10.1016/j.engappai.2023.106574
13. Resendiz-Ochoa, E., Trejo-Chavez, O., Saucedo-Dorantes, J. J., Morales-Hernandez, L. A., Cruz-Albarran, I. A. (2024). Application of Thermography and Convolutional Neural Network to Diagnose Mechanical Faults in Induction Motors and Gearbox Wear. *Applied System Innovation, 7 (6),* 123. https://doi.org/10.3390/asi7060123
14. Era, I. Z., Zhou, F., Raihan, A. S., Ahmed, I., Abul-Haj, A., Craig, J. et al. (2024). *In-Situ Melt Pool Characterization via Thermal Imaging for Defect Detection in Directed Energy Deposition Using Vision Transformers*. ArXiv. https://doi.org/10.48550/arxiv.2411.12028
15. Zheng, S., Zhang, J., Zu, R., Li, Y. (2024). Vision transformer-enhanced thermal anomaly detection in building facades through fusion of thermal and visible imagery. *Journal of Asian Architecture and Building Engineering, 24 (4),* 2854–2868. https://doi.org/10.1080/13467581.2024.2379866
16. Campione, I., Lucchi, F., Santopuoli, N., Seccia, L. (2020). 3D Thermal Imaging System with Decoupled Acquisition for Industrial and Cultural Heritage Applications. *Applied Sciences, 10 (3),* 828. https://doi.org/10.3390/app10030828
17. Sabathiel, S., Sanchis-Alepuz, H., Wilson, A. S., Reynvaan, J., Stipsitz, M. (2024). Neural network-based reconstruction of steady-state temperature systems with unknown material composition. *Scientific Reports, 14 (1).* https://doi.org/10.1038/s41598-024-73380-1
18. Zhuravchak, L. M., Zabrods'ka, N. V. (2010). Nonstationary thermal fields in inhomogeneous materials with nonlinear behavior of the components. *Materials Science, 46 (1),* 36–46. https://doi.org/10.1007/s11003-010-9261-9
19. Zhuravchak, L., Kruk, O. (2015). Consideration of the nonlinear behavior of environmental material and a three-dimensional internal heat sources in mathematical modeling of heat conduction. *Mathematical Modeling and Computing, 2 (1),* 107–113. https://doi.org/10.23939/mmc2015.01.107
20. Zhuravchak, L. (2019). Computation of pressure change in piecewise-homogeneous reservoir for elastic regime by indirect near-boundary element method. *2019 IEEE 14th International Conference on Computer Sciences and Information Technologies (CSIT),* 141–144. https://doi.org/10.1109/stc-csit.2019.8929820
21. Zhuravchak, L.; Shakhovska, N., Medykovskyy, M. O. (Eds.) (2019). Mathematical Modelling of Non-stationary Processes in the Piecewise-Homogeneous Domains by Near-Boundary Element Method. *Advances in Intelligent Systems and Computing IV*. Cham: Springer, 64–77. https://doi.org/10.1007/978-3-030-33695-0_6
22. Havdulskyi, R., Zhuravchak, L. (2025). Recognition of inclusion characteristics using neural network methods in stationary process modeling. *Visnyk Natsionalnoho universytetu "Lvivska politekhnika". Seriia Informatsiini systemy ta merezhi, 17,* 75–92. https://doi.org/10.23939/sisn2025.17.075
23. Havdulskyi, R., Zhuravchak, L., Yakovyna, V.; Hovorushchenko, T., Savenko, O., Popov, P. T., Lysenko, S. (Eds.) (2025). Inclusion parameters estimation using INBEM and CNNs with gradient-based feature extraction. *2nd International Workshop on Intelligent & CyberPhysical Systems (ICyberPhyS 2025). CEUR Workshop Proceedings,* 4013. Available at: https://ceur-ws.org/Vol-4013/paper2.pdf
24. Khanam, R., Hussain, M. (2024). *YOLOv11: An Overview of the Key Architectural Enhancements*. ArXiv. https://doi.org/10.48550/arxiv.2410.17725
25. Tian, Y., Ye, Q., Doermann, D. (2025). *YOLOv12: Attention-Centric Real-Time Object Detectors*. ArXiv. https://doi.org/10.48550/arxiv.2502.12524
26. Sharma, A., Kumar, V., Longchamps, L. (2024). Comparative performance of YOLOv8, YOLOv9, YOLOv10, YOLOv11 and Faster R-CNN models for detection of multiple weed species. *Smart Agricultural Technology, 9,* 100648. https://doi.org/10.1016/j.atech.2024.100648
27. Jaeger, B. E., Schmid, S., Grosse, C. U., Gögelein, A., Elischberger, F. (2022). Infrared Thermal Imaging-Based Turbine Blade Crack Classification Using Deep Learning. *Journal of Nondestructive Evaluation, 41 (4).* https://doi.org/10.1007/s10921-022-00907-9
28. Zhuravchak, L. M., Zabrodska, N. V. (2020). Using of partly-boundary elements as a version of the indirect near-boundary element method for potential field modeling. *Mathematical Modeling and Computing, 8 (1),* 1–10. https://doi.org/10.23939/mmc2021.01.001
29. Zhuravchak, L. M. (2024). Potential field modeling by combination of near-boundary and contact elements with non-classical finite differences in a heterogeneous medium. *Mathematical Modeling and Computing, 11 (2),* 373–384. https://doi.org/10.23939/mmc2024.02.373

30. Zhuravchak, L., Zabrodska, N. (2024). Algorithm for determining inclusion parameters in solving inverse problems of geoelectrical exploration using the profiling method. *Geodynamics, 1 (36),* 98–107. https://doi.org/10.23939/jgd2024.01.098

31. Russakovsky, O., Deng, J., Su, H., Krause, J., Sanjeev Satheesh, Ma, S. et al. (2014). *ImageNet Large Scale Visual Recognition Challenge.* ArXiv. https://doi.org/10.48550/arxiv.1409.0575

32. Woo, S., Debnath, S., Hu, R., Chen, X., Liu, Z., Kweon, I. S. et al. (2023). *ConvNeXt V2: Co-designing and Scaling ConvNets with Masked Autoencoders.* ArXiv. https://doi.org/10.48550/arxiv.2301.00808

33. Shazeer, N. (2020). *GLU Variants Improve Transformer.* ArXiv. https://doi.org/10.48550/arXiv.2002.05202

34. Arora, I. (2024). Improving Performance of Data Science Applications in Python. *Indian Journal Of Science And Technology, 17 (24),* 2499–2507. https://doi.org/10.17485/ijst/v17i24.914

35. Zhuravchak, L. (2023). Computational Aspects of the Use of Different Types of Near-boundary elements in Modeling the Non-stationary Heat Conduction Process. *2023 IEEE 18th International Conference on Computer Science and Information Technologies (CSIT).* Lviv: IEEE, 1–5. https://doi.org/10.1109/csit61576.2023.10324216

36. Sapkota, R., Harsha, C. R., Sharda, A., Karkee, M. (2025). *YOLO26: Key Architectural Enhancements and Performance Benchmarking for Real-Time Object Detection.* ArXiv. https://doi.org/10.48550/arxiv.2509.25164