Restrictions on Application of Causal Modeling Methods in Forensic Mining and Technical Examination and Ways to their Overcoming

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Scientific issue of methodological gap between modern causal models of analysis of complex accidents and the procedural requirements of forensic mining and technical examination, within the limits of which forensic expert is obliged to rely only on the materials provided, his competence and substantiation procedures that are subject to verification is outlined. The research purpose is to substantiate the limits of application of modern foreign models of causal analysis in national forensic mining and technical examination and to develop phase-modular decomposition as a compensatory procedural and methodological mechanism for the reconstruction of complex

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accidents. The research methods include theoretical analysis of Ukrainian and foreign sources, normative and procedural interpretation of the role and boundaries of the competence of a forensic expert, logical and structural modeling of causal relationships, phase-modular decomposition of an accident and practical testing of the approach on two impersonal cases from real expert practice. It is shown that STAMP/CAST, SCM, causal graphs, counterfactual and other system models have significant heuristic value, however, their direct transfer to the field of forensic research is limited by the retrospective nature of forensic mining expertise, the scarcity of criminal proceedings materials, the requirements for the reproducibility of the conclusion and the prohibition to compensate for evidentiary gaps with probable assumptions. It is proven that phase-modular decomposition makes it possible to localize causality in technically homogeneous fragments of the event, establish an evidentiary basis for each module, procedurally correctly respond to the lack of initial data and form a logical, transparent expert conclusion. The suitability of the approach for analyzing events in open-pit and underground mining operations is confirmed by practical testing.

Keywords: *forensic mining and technical examination; causal relationship; causal analysis; phase-module decomposition; mining accident; expert conclusion; criminal proceedings.*

Research Problem Formulation

Forensic mining and technical examination (hereinafter referred to *as FMTE*) occupies a special place in the system of engineering and technical forensic examinations, since it combines a high level of industry specialization with increased requirements for the evidentiary strength of forensic expert conclusion. Its subject area encompasses events occurring in complex mining and underground environments where technical, organizational and natural factors form a multilevel causal chain. In such cases, the court and the pre-trial investigation body do not need a general description of the dangerous situation, but a clear written expert opinion on the technical causal relationship between specific actions or omissions and their consequences. This determines complexity and practical significance of expert research.

Theoretical aspect of this problem lies in the lack of a properly adapted model for explaining complex accident events for the needs of FMTE. In recent years, systemic and causal approaches to incident analysis have been actively developing in world science, in particular *Systems-Theoretic Accident Model and Processes* (*STAMP*) [1], *Causal Analysis based on STAMP (CAST)*,

1 Zhang Y., Dong Ch., Guo W., et al. Systems theoretic accident model and process (STAMP): A literature review. *Safety Science*. 2022. Vol. 152. DOI: 10.1016/J.SSCI.2021.105596 (date accessed: 20.03.2026) ; Hulme A., Stanton N. A., Walker G. H., et al. Are accident analysis methods fit for purpose? Testing the criterion-referenced concurrent validity of AcciMap, STAMP-CAST and AcciNet. *Ibid*. 2021. Vol. 144. DOI: 10.1016/j.ssci.2021.105454 (date accessed: 20.03.2026).

causal graphs, counterfactual models and structural causal models (*SCM*) [2]. These approaches have demonstrated high heuristic value in the study of complex socio-technical systems and process safety analysis, civil and marine engineering and assessment of system and accident stability. However, their direct borrowing for the needs of FMTE is problematic, since they were created mainly for safety engineering, risk management and preventive analysis, while forensic examination is retrospective in nature, carried out in accordance with requirements of criminal procedural law and ends with a written conclusion with a clearly defined subject of evidence. Therefore, there is a theoretical discrepancy between modern models of causal analysis of complex events and the real working conditions of a forensic mining expert.

Practical aspect of the issue is even more acute, since forensic expert does not carry out free research modeling, but a procedurally regulated expert study. He does not have the right to independently construct missing factual data, compensate for evidentiary gaps with probabilistic assumptions, or rely on opaque analytical procedures that cannot be properly verified within the limits of the trial. The expert's tools should correspond to the materials of the criminal proceedings, competence limits and requirements for conclusion content. In case of insufficiency of initial data, forensic expert submits a request for the provision of additional materials and in their lack, limits the conclusion to the actually established circumstances or formalizes the impossibility of resolving the relevant issue. That is why the direct borrowing of models that involve the use of probabilistic reconstructions, latent variables, or complex computing equipment to fill the deficit of evidentiary information is unacceptable for the FMTE. This is one of the main scientific and practical contradictions: the need for modern causal thinking is obvious, but the form of its implementation must remain procedurally compatible and methodologically suitable for practical application in real expert practice.

Connection of outlined issue with scientific and practical interests lies in the need to create such a model of expert analysis that would ensure adequate research of complex multifactorial mining accidents without taking forensic expert beyond the limits of his procedural role and approved methodological tools. Therefore, it is not a question of replacing national expert methods with foreign systemic models, but of developing an approach that would allow applying cognitive potential of the modern theory of causality in a form compatible with the practice of forensic examination. Such a statement of the question has scientific and applied significance, since it involves rethinking the limits of adapting modern causal concepts to forensic expert knowledge and creates a basis for increasing the accuracy, consistency and evidentiary value of conclusions in cases of accidents in the mining industry.

Scientific and practical task to which this study is directly related is to form the theoretical basis of a new FMTE methods capable of providing a structured ana-

2 Bongers S., Forré P., Peters J., Mooij J. M. Foundations of structural causal models with cycles and latent variables. *The Annals of Statistics*. 2021. Vol. 49. Is. 5. Pp. 2885–2915. DOI: 10.1214/21-AOS2064 (date accessed: 20.03.2026) ; Naser M. Z. Causality and causal inference for engineers: Beyond correlation, regression, prediction and artificial intelligence. *WIREs Data Mining and Knowledge Discovery*. 2024. Vol. 14. Is. 4. DOI: 10.1002/widm.1533 (date accessed: 20.03.2026).

lysis of causal relationships in complex emergency situations. Such a methodology should combine theoretical principles of research, algorithms of expert actions, tools for analyzing causal relationships, and practical approaches to solving expert tasks. Its main purpose is to increase the objectivity and reliability of expert conclusions and unify algorithms for investigating complex emergency events in mining. The article is aimed at developing a conceptual approach that can become the basis of the future official FMTE methods.

Research relevance is due to growing complexity of emergency events in the mining industry and the lack of a holistic model that would combine modern causal thinking with requirements of the criminal procedure, expert methods and the limits of competence of forensic expert. Under such conditions, judicial practice requires a logically transparent expert opinion suitable for proper procedural evaluation. It is this methodological gap that is a scientific problem consisting in inconsistency of modern approaches to the cause-and-effect analysis of complex man-made events with the capabilities of current methodological toolkit for the research of multiple accidents within criminal proceedings.

Analysis of Essential Researches and Publications

The issues to which this article is devoted are at the intersection of three research areas: the general theory of forensic examination, the criminal law and criminal procedure doctrine of causality, and modern interdisciplinary approaches to the analysis of complex accidents in socio-technical systems. That is why it is advisable to build a review of sources as a consistent identification of what has already been done in each of these areas and which link is missing for the needs of the FMTE. The national literature has sufficiently thoroughly developed general theoretical aspects of the subject of forensic examination, the status of the expert's conclusion and its evaluation in judicial proceedings. In particular, M. Shcherbakovskyi and A. Protsenko highlight the problems of conducting examinations in legal proceedings [3] and A. Muzyka and S. Bahirov: theoretical difficulties of determining causality in criminal law [4]. At the same time, the analysis of national publications indicates that they are focused mainly on general theoretical issues of forensic examination, criminal law aspects of causality or procedural issues of the evidentiary status of forensic expert conclusion. To date, no specialized methodological approach has been formed that would combine the theory of causality with the practice of the State Committee for the Protection of Natural Resources and Energy in cases of multi-factorial accidents. Thus, Ukrainian scientific thought has already developed appropriate provisions on the essence of causality, the place of an expert's conclusion in evidence, and general requirements for expert research, but has not yet proposed a full-fledged algorithm for establishing a technical causal relationship in complex mining incidents

3 Щербаковський М. Г., Проценко А. М. Експертизи в судовому провадженні : монографія. Харків, 2024. 280 с. URI: https://dspace.univd.edu.ua/handle/123456789/24257 (date accessed: 20.03.2026).

4 Музика А. А., Багіров С. Р. Каузальність і кримінальний закон в аспекті правового прагматизму : монографія. Київ, 2023. 143 с. URI: https://ekmair.ukma.edu.ua/handle/123456789/25290 (date accessed: 20.03.2026).

under procedural restrictions, incomplete materials, and complex interaction of causally significant factors. This aspect is a problematic field of research.

Foreign scientific literature is dominated by the intensive development of systems models of accident analysis and modern causal thinking in engineering. Separate works are devoted to empirical verification of the validity and reliability of such approaches. In particular, *A. Hulme* and co-authors showed that *AcciMap*, *STAMP-CAST* and *AcciNet* demonstrate only moderate validity indicators, and their ability to adequately reproduce the causal structure of accident events remains a subject of discussion [5]. In further work by these same authors, focused on assessing reliability, it was determined that all three approaches are characterized by weak or moderate positive consistency, and *STAMP-CAST* is distinguished by higher inter-expert reliability [6]. The study of *O. F. Hamim* and co-authors demonstrated the advantages of the combined use of systems methods for revealing multi-level causality [7]. Therefore, the significance of these works lies not only in the development of new analysis schemes, but also in empirical testing of their effectiveness and limits of application.

Second strong layer of literature is related to the development of the *STAMP* paradigm itself and its industry-specific modifications. In a literature review by *A. Zhang* et al., the evolution of *STAMP, STPA*, and *CAST* is systematized and it is shown that this group of approaches is increasingly integrated with the analysis of human and organizational factors, as well as with quantitative assessment procedures [8]. *B. O. Ceylan* et al. demonstrate which development of the STAMP approach in the direction of quantitative analysis of complex engineering systems, reflects the general trend towards formalization of causal interactions in modern accident research [9]. A similar trend is represented by *H. Ebrahimi* and co-authors, who combine *STAMP* with the fuzzy *DEMATEL* method to construct a quantitative map of causal influences, and *H. Sun, H. Wang, M. Yang* and *G. Reniers* a develop a *STAMP*-oriented approach to quantitatively assessing the stability of chemical process systems [10]. Together, these works

5 Hulme A., Stanton N. A., Walker G. H., et al. Are accident analysis methods fit for purpose? … . DOI: 10.1016/j.ssci.2021.105454 (date accessed: 20.03.2026).

6 Ibidem. Testing the reliability of accident analysis methods: A comparison of AcciMap, STAMP-CAST and AcciNet. *Ergonomics*. 2024. Vol. 67. Is. 5. Pp. 695–715. DOI: 10.1080/00140139.2023.2240048 (date accessed: 20.03.2026).

7 Hamim O. F., Hasanat-E-Rabbi Sh., Debnath M., et al. Taking a mixed-methods approach to collision investigation: AcciMap, STAMP-CAST and PCM. *Applied Ergonomics*. 2022. Apr: 100:103650. DOI: 10.1016/j.apergo.2021.103650 (date accessed: 20.03.2026).

8 Zhang Y., Dong C., Guo W., et al. Op. cit. DOI: 10.1016/j.ssci.2021.105596 (date accessed: 20.03.2026).

9 Ceylan B. O., Karatuğ Ç., Akyuz E., et al. A system theory (STAMP) based quantitative accident analysis model for complex engineering systems. *Safety Science*. 2023. Vol. 166. DOI: 10.1016/j.ssci.2023.106232 (date accessed: 20.03.2026).

10 Ebrahimi H., Zarei E., Ansari M., et al. A system theory based accident analysis model: STAMP-fuzzy DEMATEL. *Safety Science*. 2024. Vol. 173. DOI: 10.1016/j.ssci.2024.106445 (date accessed: 20.03.2026) ; Sun H., Wang H., Yang M., Reniers G. A STAMP-based approach to quantitative resilience assessment of chemical process systems. *Reliability Engineering & System Safety*. 2022. Vol. 222. DOI: 10.1016/j.ress.2022.108397 (date accessed: 20.03.2026).

indicate that the international school of systems accident analysis is consistently moving in the direction of increasingly deeper formalization of causal interactions. For safety engineering, this is a natural direction of development, but it is here that forensic expertise faces a fundamental question about the limits of adapting such models to the procedural form of an expert's conclusion.

Third block of foreign works forms the theoretical basis of modern causal thinking in engineering. In the fundamental work of *S. Bongers* and co-authors, it is shown that in the case of cyclic dependencies and latent variables, many characteristics of classical acyclic causal models are not preserved automatically and require special solution conditions [11]. *J. P. Long* and co-authors investigate the assessment of causal effects under conditions of latent confounding using instrumental variables and environment invariance [12]. *M. Z. Naser* in the article *Causality and causal inference for engineers: Beyond correlation, regression, prediction and artificial intelligence* justifies the need for engineering thinking to go beyond correlation, regression, prediction and artificial intelligence towards more rigorous causal analysis; co-authored with *A. Teymori Gharah Tapeh*, he demonstrates the applicability of causal discovery, counterfactual analysis, and causal machine learning to civil engineering cases [13]. A concise but important overview of current trends in causal analysis is provided by *N. Mitra* and co-authors, while *M. Soohoo* and *O. A. Arah* show how time-varying uncontrolled confounding distorts the assessment of causal effects [14]. All of these works are of fundamental importance for the formation of the modern language of causal analysis, but at the same time they reveal the limits of their direct borrowing by forensics: most of them are designed to use statistical, computational, experimental, or quasi-experimental procedures that are not typical tools of a mining expert.

A separate group consists of research papers where system and causal approaches are adapted to specific industries and types of incidents. For example, *J. M. Fagundes* and co-authors combine CAST with TRACEr to analyze human errors in an industrial accident; *Sh. Zhong, J. Du* and *X. Jiang* apply *STAMP/STPA* to analyze a safety system in an energy laboratory; *A. J. Nakhal Akel* and co-authors

11 Bongers S., Forré P., Peters J., Mooij J. M. Op. cit. DOI: 10.1214/21-AOS2064 (date accessed: 20.03.2026).

12 Long J. P., Zhu H., Do K.-A., Ha M. J. Estimating causal effects with hidden confounding using instrumental variables and environments. *Electronic Journal of Statistics*. 2023. Vol. 17. Is. 2. Pp. 2849–2879. DOI: 10.1214/23-EJS2160 (date accessed: 20.03.2026).

13 Naser M. Z. Causality and causal inference for engineers … . DOI: 10.1002/widm.1533 (date accessed: 20.03.2026) ; Naser M. Z., Teymori Gharah Tapeh A. Causality, causal discovery, causal inference and counterfactuals in Civil Engineering: Causal machine learning and case studies for knowledge discovery. *Computers and Concrete*. 2023. Vol. 31. No. 4. Pp. 277–292. DOI: 10.12989/cac.2023.31.4.277 (date accessed: 20.03.2026).

14 Mitra N., Roy J., Small D. The Future of Causal Inference. *American Journal of Epidemiology*. 2022. Art. 191(10):1671-1676. DOI: 10.1093/aje/kwac108 (date accessed: 20.03.2026) ; Soohoo M., Arah O. A. Investigation of the structure and magnitude of time-varying uncontrolled confounding in simulated cohort data analyzed using g-computation. *International Journal of Epidemiology*. 2023. Art. 52(6):1907-1913. DOI: 10.1093/ije/dyad150 (date accessed: 20.03.2026).

build a *STAMP*-oriented model for safety analysis in industrial facilities [15]. At the same time, *F. Zhang* and colleagues integrate *STPA* with multi-level flow modeling to detect cyber-physical hazards in the process industry, and *J. Ge* and co-authors develop a systems-theoretical concept of accident causality and the SAAMWS method for complex production systems [16]. Of particular importance for the topic of this article is the work of *J. Dong* and co-authors, in which *STAMP* is directly applied to the analysis of the mechanism of accidents in coal mines [17]. This industry layer is organically supplemented by a review study by *L. Cruz-Ausejo* and co-authors, who summarize the results of research on occupational injuries among mining workers over the past thirteen years and outline typical organizational, production and individual factors that are also relevant for expert reconstruction of mining events [18]. The above works allow us to draw two conclusions: first, systemic causal thinking has long gone beyond the boundaries of abstract theory and is actively used in applied sectors; second, even in industries closest to the topic of this article, it is mainly focused on safety management, preventive diagnostics or system improvement, and not on the formation of a written expert opinion that is procedurally suitable for a court.

Thus, analysis of recent research and publications allows us to identify several stable trends. Ukrainian science has convincingly developed the general issues of the subject of forensic examination, evidentiary value of forensic expert conclusion and criminal-legal nature of the causal relationship, but has not proposed a full-fledged industry model for the study of multifactorial mining accidents. Foreign science, on the contrary, has formed a developed arsenal of systemic and causal models of complex incident analysis, but these models were created mainly for safety engineering, systemic risk analysis, system stability assessment and post-accident organizational train-

15 Fagundes J. M., Gaya de Figueiredo M. A., Alberton A. L., et al. Analysis of accidents through combination of CAST and TRACEr techniques: A case study. *Journal of Loss Prevention in the Process Industries*. 2022. Vol. 74. Art. 104639. DOI: 10.1016/j.jlp.2021.104639 (date accessed: 20.03.2026) ; Zhong Sh., Du J., Jiang X. Analysis of Energy Laboratory Safety Management in China Based on the System-Theoretic Accident Model and Processes/System Theoretic Process Analysis STAMP/STPA Model. *Sustainability*. 2023. Vol. 15. No. 15. DOI: 10.3390/su151511505 (date accessed: 20.03.2026) ; Nakhal Akel A. J., Patriarca R., Tronci M., et al. A STAMP Model for Safety Analysis in Industrial Plants. *Chemical Engineering Transactions*. 2022. Vol. 91. Pp. 403–408. DOI: 10.3303/CET2291068 (date accessed: 20.03.2026).

16 Zhang F., Chen L., Zhang B., et al. An integrated system theoretic process analysis with multilevel flow modeling for the identification of cyber-physical hazards in a process industry. *Process Safety Progress*. 2024. Vol. 43. Is. 3. Pp. 587—596. DOI: 10.1002/prs.12604 (date accessed: 20.03.2026) ; Ge J., Zhang Yu., Xu K., et al. A new accident causation theory based on systems thinking and its systemic accident analysis method of work systems. *Process Safety and Environmental Protection*. 2022. Vol. 158. Pp. 644–660. DOI: 10.1016/j.psep.2021.12.036 (date accessed: 20.03.2026).

17 Dong J., Gao Z., Liu T., et al. Analysis of the Causative Mechanism of Coal Mine Safety Accidents Based on STAMP Model. *Journal of Mining Engineering and Safety Technology*. 2022. Vol. 1. Is. 1. DOI: 10.23977/jmest.2022.020101 (date accessed: 20.03.2026).

18 Cruz-Ausejo L., Cama-Ttito N. A., Solano P. F., et al. Occupational accidents in mining workers: Scoping review of studies published in the last 13 years. *BMJ Open*. 2024. Vol. 14. Is. 10. DOI: 10.1136/bmjopen-2023-080572 (date accessed: 20.03.2026).

ing, and not for procedurally regulated forensic research. Thus, there is a methodological discrepancy between the Ukrainian procedural-expert tradition and the international systemic-causal school. Its overcoming does not consist in mechanically transferring *STAMP/CAST, SCM* or *DAG* into the practice of FMTE, but in developing an approach that would allow applying their logical potential in a procedurally compatible form. This is precisely where the need for phase-modular decomposition arises as the theoretical basis of the new FMTE methods.

Article Purpose

Theoretically substantiate the limits of application of modern foreign models of causal analysis in the national FMTE and develop a compensatory procedural and methodological mechanism: phase-modular decomposition of a complex emergency event.

Systematic and causal approaches formed within the framework of security engineering can be applied in FMTE only after their logical adaptation to the retrospective nature of forensic research, requirements of criminal procedural legislation of Ukraine, limits of the competence of a forensic expert and mandatory reliance on case files of criminal proceedings and current methods. Unlike previous researches, the article focuses not on general characteristics of the causal relationship or the description of system models as such, but on the formation of a specialized forensic approach, within which the concepts of procedurally compatible causal analysis, phase-modular decomposition and event module as the basic elements of the FMTE methods are defined.

Research Methods

For achieving this goal and solve the outlined scientific and practical problems, a set of general scientific and special methods corresponding to the research topic was applied. The system-structural approach contributed to critical analysis of modern causality models and identification of limits of their cognitive and practical applicability in forensic mining expertise. The method of normative and procedural analysis helped to determine the limits of competence of forensic expert and the requirements for the evidentiary basis and the form of forensic expert conclusion in accordance with the current criminal procedural legislation of Ukraine. The basis for development of the phase-modular decomposition algorithm were the methods of logical modeling and deductive reasoning that made possible to structure multifactorial accidents. For verify practical applicability and procedural compatibility of the proposed approach, method of approbation was applied on the materials of two impersonal expert proceedings from real practice: regarding a production event in open-pit mining and a group incident in underground conditions. These methods provided a comprehensive justification for the proposed theoretical and methodological tools.

Main Content Presentation

The approach proposed in the article is not limited to either criticism of modern causal models or their review comparison. Its content is to solve a specific scientific and practical task: how to preserve the cognitive value of modern causal thinking, without going beyond forensic expert competence, case files of criminal proceedings and procedural requirements for the form

and content of the conclusion. At the center of the research is not mathematical or programmatic aspect of modern causality models, but possibility of transforming their logical core into a tool for retrospective reconstruction of the event, suitable for forensic practice.

Within the framework of the proposed approach, several basic concepts need to be clarified. *Procedurally compatible causal analysis* in this article is a way of reconstructing an event that is based only on the materials of criminal proceedings, does not replace evidence gaps with probabilistic constructs and ends with a written expert opinion suitable for procedural evaluation. *Phase-modular decomposition* is a way of dividing a complex emergency event into fragments that are relatively isolated in time, space and mechanism of the event development. *Event module: a* causally completed node of the emergency process, within which a local technical causal relationship can be determined without loss of procedural certainty.

Practical suitability of the outlined provisions depends on their compatibility with the real conditions of forensic research. Thereby, further it is necessary to determine the procedural and methodological limitations of the direct transfer of modern causal models to the FMTE field.

Causal modeling in modern scientific discourse forms a language for describing causality through causal schemes, counterfactual constructs, and rules for distinguishing causality from ordinary association. However, FMTE belongs to a different class of tasks than engineering investigations of safety profile: it is carried out within the framework of a procedurally regulated research, limited to the case files of criminal proceedings and directed to retrospective establishment of a technical cause and technical causal relationship between actions or inaction and their consequences.

Procedural form of an expert opinion is one of the primary barriers to the direct adoption of modern causal models in Criminal Procedural Code of Ukraine, forensic expert conclusion should include, in particular, description of the obtained content, detailed description of performed research, applied methods, obtained results and their expert assessment, as well as substantiated answers to each asked question [19]. Under such conditions, the method should be not only scientifically sound but procedurally reproducible: it should be possible to trace which materials were used, what investigative actions were performed, what results were obtained, and how the expert evaluated them. This raises the bar for argumentation and limits the inclusion in the conclusion of constructions not transparently linked to the materials of the criminal proceedings.

Second barrier is associated with the strict binding of forensic research to the case files of criminal proceedings and the procedural algorithm of actions in case of their insufficiency. According to Part 3 of Article 69 of the Criminal Procedure Code of Ukraine, the expert has the right to file a petition for the provision of additional materials and samples, as well as for the performance of other actions related to the conduct of the examination [20]. In the event of a lack of critically important information, appropriate response is not to compensate for evidentiary gaps with assumptions, but to apply the procedural mechanism of requiring additional materials. If they are not

19 Кримінальний процесуальний кодекс України від 13.04.2012 р. № 4651-VI (зі змін. та допов.). URL: https://zakon.rada.gov.ua/laws/show/4651-17#Text (date accessed: 20.03.2026).
20 Там само.

provided, forensic expert limits the conclusion to the actually established circumstances or notes impossibility of resolving the relevant issue within the limits of provided evidentiary base.

Third barrier is related to functional purpose incompatibility of some foreign system approaches with FMTE tasks. In foreign scientific literature, *STAMP/CAST, AcciMap, AcciNet* and their modifications are positioned as system methods for analyzing accidents in complex socio-technical systems; a significant part of their applied purpose is related to the development of safety measures, the detection of control failures at different levels of the system and, in a broader context, support of safety management [21]. For forensic examination, such a formulation is methodologically useful only partially: it contributes to structuring of multi-level causes and interactions, but goes beyond the subject of judicial review where the retrospective determination of the technical cause is replaced by the logic of system improvement or the construction of a causal picture focused on management practices beyond proof limits. As a result, direct borrowing of system models without special adaptation creates discrepancies between the subject of expert research and the analytical horizon of the model itself: instead of an answer to the question of the initiator of forensic examination, multi-level description of factors arises that can be meaningful, but procedurally redundant or insufficiently correlated with asked questions.

Fourth barrier is related to the requirement of reliability and reproducibility of the description of causal factors in an environment where forensic expert conclusion has procedural meaning. Even in the field of safety sciences, the need for empirical verification of the characteristics of accident analysis methods is emphasized. In particular, it is determined that systemic methods of accident analysis require special verification of validity and reliability; in some comparative researches, results have been obtained that indicate limited validity of such methods compared to the reference expert analysis, as well as the need for further studies of their reliability [22]. For forensic science, this circumstance is of particular importance, since reproducibility and internal consistency of the conclusion are prerequisites for trust in it and its resistance to professional criticism.

Fifth barrier relates to the methodological complexity of modern framework of causality that is not a flaw in itself but requires careful consideration during application. Theory of structural causal models is evolving to account for cyclical interactions and latent variables, which makes causal structures more realistic for complex technical systems, but at the same time increases the demands on conditions of correctness, initial assumptions, and interpretation of results [23]. For

21 Zhang Y., Dong C., Guo W., et al. Op. cit. DOI: 10.1016/j.ssci.2021.105596 (date accessed: 20.03.2026) ; Hamim O. F., Hasanat-E-Rabbi Sh., Debnath M., et al. Op. cit. DOI: 10.1016/j.apergo.2021.10365 (date accessed: 20.03.2026).

22 Hulme A., Stanton N. A., Walker G. H., et al. Are accident analysis methods fit for purpose? ... . DOI: 10.1016/j.ssci.2021.105454 (date accessed: 20.03.2026) ; Ibidem. Testing the reliability of accident analysis methods ... . DOI: 10.1080/00140139.2023.2240048 (date accessed: 20.03.2026).

23 Bongers S., Forré P., Peters J., Mooij J. M. Op. cit. DOI: 10.1214/21-AOS2064 (date accessed: 20.03.2026).

FMTE, this means that directly transferring the entire theoretical framework into expert practice is not only impractical but also potentially risky, since, given insufficient source materials, it can create the illusion of analytical depth or replace evidential logic with procedurally unsound constructs.

Sixth barrier relates to the scope of a forensic expert's competence and the permissible limits of expert testimony. The expert operates within the scope of their specialized knowledge and the materials provided, which determines the permissible level of generalization. Pursuant to Article 102 of the Criminal Procedural Code of Ukraine, forensic expert conclusion must contain substantiated answers to the questions posed, and Article 69 of Criminal Procedural Code of Ukraine provides for the right to file a motion requesting additional materials [24]. Thereby in the event of a shortage of materials, it is procedurally correct to file a motion for additional materials, to limit the opinion to the facts actually established, or to report the impossibility of providing an opinion. This approach ensures compliance with the limits of forensic expert's competence and preserves the evidentiary value of the substantiated parts of the conclusion.

Thus, procedural barriers do not deny the value of modern theories of causality. They only determine that FMTE requires a compensatory mechanism that, firstly, does not go beyond the special knowledge and materials of criminal proceedings; secondly, ensures the reproducibility and transparency of expert logic; thirdly, turns a complex multivariate event into a sequence of technical causal fragments available for procedural verification; and, finally, makes possible to form reasonable answers or motivated limits of the conclusion in the event of a data shortage. It is the combination of these requirements that necessitates a procedurally compatible approach to causal analysis.

Outlined procedural and methodological limitations do not deny cognitive value of modern causal models, but indicate the need for their special adaptation to FMTE needs. Thereby the next step is to substantiate such procedurally compatible tools that would make it possible to apply the logic of multilevel causal analysis without going beyond the limits of special knowledge, materials of criminal proceedings and the subject of evidence. Within the framework of this article, such a toolkit is the phase-modular decomposition of a complex emergency event.

Phase-modular decomposition is proposed as an applied procedural and methodological toolkit that makes it possible to adapt the logical framework of systems-based approaches to the requirements of judicial proof without exceeding the scope of competence and without substituting a retrospective determination of the technical cause with a description of risk profiles or organizational improvements. Underlying idea is that a multifactorial incident in the mining industry should be viewed not as a single event, but as a set of technically diverse episodes, each of which has its own causal mechanism, temporal boundaries, spatial localization, and documentary record. Systematic methods of accident analysis in global practice emphasize the advantages of a multi-level examination of causes and the combination of analytical

24 Кримінальний процесуальний кодекс України … . URL: https://zakon.rada.gov.ua/laws/show/4651-17#Text (date accessed: 20.03.2026).

boundaries [25]; however, in FMTE such a multi-level approach should be adapted to a form suitable for providing substantiated answers to the questions posed in accordance with Article 102 of Criminal Procedural Code of Ukraine [26].

In procedural terms, a phase is a time interval in development of an event during which technical mechanism remains relatively consistent (specifically, the transition from normal operation to an emergency state, the formation of a hazardous condition, its escalation, and the occurrence of the consequence). A module is likewise a minimally sufficient technical fragment of an event that can be isolated in time and space, has a defined factual basis in the materials of criminal proceeding and allows for the application of current and established expert approaches to identify technical cause and causal relationship within the scope of a specific issue. This structure does not contradict systems thinking; on the contrary, it creates a disciplined method of controlled simplification that reduces the risk of mixing causes at different levels: technical, organizational, and human one into a single unclear causal chain.

Phase-modular decomposition performs at least three interrelated functions in FMTE. The first of them is the procedurally correct localization of causality. In complex incidents, causal relationships often become networked. At the same time, questions posed to forensic expert require a specific answer regarding the technical cause and the causal relationship between actions (inaction) and consequences. Phase-modular decomposition makes possible to transform such a network configuration into a sequence of modules, each of which can be investigated as a linear causal fragment while maintaining the integration logic of the event.

Second function is to respond to a lack of materials in a procedurally correct manner. If critically necessary documents or information are missing within a particular module, the forensic expert has the right to file a motion requesting additional materials in accordance with Article 69 of the Criminal Procedural Code of Ukraine [27]. If such a motion is denied or the necessary materials are missing, decomposition algorithm allows the conclusion to be limited to the scope of the relevant module with a reasoned explanation of the grounds, without undermining the evidentiary value of other modules where the factual basis is sufficient. This strategy is consistent with the requirements for the content of an expert opinion, particularly regarding the reflection of the materials used, the methods applied, obtained results and their evaluation and upholds the principle of the reasonableness of responses, as enshrined in Article 102 of Criminal Procedural Code of Ukraine [28].

Third function is to unify and ensure reproducibility of forensic research. Phase-modular decomposition creates a standardized analytical framework that can be described as a sequence of operations relatively independent of the expert's individual style. The issue of reproducibility

25 Zhang Y., Dong C., Guo W., et al. Op. cit. DOI: 10.1016/j.ssci.2021.105596 (date accessed: 20.03.2026) ; Hamim O. F., Hasanat-E-Rabbi Sh., Debnath M., et al. Op. cit. DOI: 10.1016/j.apergo.2021.103650 (date accessed: 20.03.2026).

26 Кримінальний процесуальний кодекс України … . URL: https://zakon.rada.gov.ua/laws/show/4651-17#Text (date accessed: 20.03.2026).

27 Там само.

28 Там само.

is of fundamental importance, given that even in security sciences, the validity and reliability of systematic methods for analyzing accidents require separate empirical verification [29]. For FMTE, unification does not imply mechanical rigidity; it implies availability of procedure that ensures a repeatable and logically transparent path from the materials of the criminal proceedings, through forensic expert's investigative actions, to the result obtained and its evaluation by forensic expert.

Procedurally, phase-modular decomposition can be presented as algorithm for retrospective reconstruction of an emergency event, covering several consecutive stages.

At the first stage, formal procedural boundary of the research is formed: the questions asked by the initiator of the examination are recorded, their technical content is established without expanding research topic and the range of provided objects and materials is determined that can be used as the initial basis.

At the second stage, initial reconstruction of the event chronology is carried out: sequence of events and states is structured with reference to the relevant sources (information available in the case files of criminal proceedings is arranged); no new data is created.

At the third stage, according to the chronology, development phases of the event are created, namely: time intervals within which comparable constancy of technical mechanism is maintained (for example, normal mode, formation of a dangerous state, escalation and implementation of the consequence). Boundaries of the phases need to be argued by references to the materials of the proceedings and technical signs of a change in the event development mechanism.

In the fourth stage, modules are formed as technically homogeneous fragments of the event within each phase. Such modules can be, for example, fragments related to the state of attachment, the mode of work or control and supervision in a specific time interval. Each module should be described by its temporal and spatial boundaries, list of necessary materials of criminal proceedings, as well as the expected result of the research; definition of a technical cause, causal relationship or technical feasibility or impossibility of certain actions in a particular situation within the framework of the asked question.

At the fifth stage, sufficiency of materials for the research on each module is checked. If the available factual basis is not sufficient for a reasoned response, the examiner shall submit a request for additional materials.

In the sixth stage, within each module, established and certified expert methodologies suitable for performing the relevant task are applied. The investigation result should remain procedurally admissible, that is, it must contain a description of the materials used, the actions taken, and the methods applied, as well as the results obtained, their evaluation, and a reasoned answer to the question posed, in accordance with Article 102 of Criminal Procedural Code of Ukraine [30]. Within the

29 Hulme A., Stanton N. A., Walker G. H., et al. Are accident analysis methods fit for purpose? … . DOI: 10.1016/j.ssci.2021.105454 (date accessed: 20.03.2026) ; Ibidem. Testing the reliability of accident analysis methods … . DOI: 10.1080/00140139.2023.2240048 (date accessed: 20.03.2026).

30 Кримінальний процесуальний кодекс України … . URL: https://zakon.rada.gov.ua/laws/show/4651-17#Text (date accessed: 20.03.2026).

module, only analytical tools based on the case materials, forensic expert specific expertise and certified methods can be used.

In the seventh stage, module-specific results are integrated into a single causal conclusion by logically combining the established findings. If a particular module cannot be established due to insufficient data, this is indicated as a conclusion limitation.

Thus, phase-modular decomposition is a compensatory mechanism that makes possible to apply the heuristic potential of modern systemic and causal concepts, in particular, the structured delimitation of multilevel causes, identification of critical nodes and the prevention of mixing of causes of different levels without going beyond the procedural requirements and without replacing retrospective task of forensic examination with the goals of a security investigation. In practice, the described approach forms theoretical and methodological basis for future official FMTE methods, since it sets a reproducible, documented and procedurally suitable algorithm for forensic expert's actions during the research of complex multiple emergency events.

It is advisable to test the practical applicability of the proposed approach using materials from actual forensic practice. To this end, we utilized two anonymized case studies from previously performed forensic examinations that differ as in the type of object under investigation as in nature of causal configuration. The first case concerns industrial incident at an open-pit mine involving a conveyor system and a rotary complex. Second case relates to a group incident in underground conditions, characterized by a multi-chain mechanism of event development. It is precisely comparison of these two situations that demonstrates that a procedurally compatible causal analysis using phase-modular decomposition is suitable for both relatively localized industrial incidents and complex accident scenarios with a branched structure of causal relationship.

Applied part of the research is presented in a form compatible with professional thinking and real tools of forensic mining expert: initial basis is only case files of criminal proceedings and the documents provided, and if there is a lack of critical information, procedurally correct limit of the response is fixed by filing a petition for the provision of additional materials or indicating inability to resolve the issue in the relevant part.

The first case concerns an incident at an open-pit mining site involving operation of conveyor systems and rotary complex equipment. The incident occurred during production operations within operational area of this equipment, resulting in fatal injury of a worker while performing his duties. Forensic examination content included a set of documentary sources typical for mining practice, covering organization of work, occupational safety, equipment operation and a special investigation of the incident. At the same time, some of the raised questions could not be resolved due to the lack of certain design-technical and technical materials, that clearly highlighted one of fundamental limitations of forensic examination: procedurally correct documentation of the incompleteness of the initial factual basis.

Under this approach, an event is broken down into phases and modules, each of which has its own temporal and spatial boundaries is based on materials from criminal proceedings, addresses a technical issue and concludes with a definitive conclusion or a clearly defined limit to its formulation.

The first phase can be defined as the phase of preconditions for a hazardous situation id est, organizational and technical context of the event when the employee has not yet come into direct contact with hazardous factor, but conditions for the incident subsequent development have already been established. Within this phase, at least two distinct modules are identified. The first module covers the organization of work and authorization to perform the relevant operations. In this module, the status of the work being performed as high-risk work is examined, along with the existence and content of the written work order, compliance with authorization procedures, conduct of briefings and the exercise of control by engineering and technical staff. It is the results of analysis of this module that provide the factual basis for answering the question of whether organization of work and the procedure for authorizing employees complied with requirements of regulatory and technical documents and local regulations in effect in production setting.

Second module in this phase focuses on the technical condition of the equipment and availability of engineering safety barriers, including guardrails and interlocks. Here, they verify whether physical restrictions on access to hazardous zones of moving existed parts, whether guardrails were properly secured, whether signs of malfunction or incompleteness of protective structures were identified and whether responsible personnel monitored their condition as part of their job duties. In this module, it is fundamentally important to demonstrate that improper condition or lack of a guardrail should be viewed not as an abstract systemic deficiency, but as a specific technical condition that created possibility of employee entering a hazardous area and, accordingly, became one of causally significant factors in subsequent incident development.

Second phase is formation of danger, that is, transition of the event to a critical state. Within the boundaries of this phase, module is distinguished, associated with the dangerous approach of the worker to the moving equipment parts. From the materials of forensic examination, it is known that dangerous situation arose as a result of the person being in the zone of action of the moving parts of the conveyor. It is this module that has an important causal significance, since within its boundaries organizational and technical prerequisites are transformed into a specific mechanism of traumatic action of a dangerous production factor.

Next phase is associated with implementation of the consequence, id est, with the direct mechanism of injury. Within the limits of this phase, the module in which the injury mechanism is considered as a sequential technical chain becomes crucial. The content of forensic expert conclusion indicates that actions or inaction of event participants and responsible officials related to the admission or non-admission of the employee to the dangerous zone of the moving parts of the conveyor, the failure to provide proper fences and technical barriers, improper control of workplaces and technical equipment condition, as well as the failure to stop operation of equipment or its corresponding section until the danger is eliminated are causally significant in this part. In this context, specified circumstances are important not as a basis for formulating preventive recommendations, but as elements of a retrospective technical analysis, that make possible to establish which actions or inactions created conditions for injury mechanism implementation.

Practical result of applying proposed approach in the first case is primarily to streamline the causal structure of the event by isolating modules available for technical verification related to organization and admission to work, existence of engineering barriers, presence of the employee in the danger zone, injury mechanism, as well as control and supervision. Such decomposition makes possible to avoid a mixed explanation, in which the technical mechanism, organizational background and job responsibilities merge into a single, undivided explanatory structure. At the same time, it makes possible to isolate direct technical node of causality, within the limits of which the presence of the employee in the danger zone of moving parts of the conveyor and the absence or improper condition of barrier elements are considered as a specific causally significant link that connects technical prerequisites with the consequence.

An important result is the procedural correctness of determining the limits of the conclusion. Those event components that cannot be established due to the lack of necessary technical materials are not compensated by assumptions, but are recorded as a reasonably delineated response limit. This approach preserves the evidentiary value of the established fragments of the causal chain without going beyond the provided factual basis and expert's specific expertise.

Second case concerns a group incident that occurred underground during work in a mine. The incident resulted in injuries to a group of workers due to development of an explosive process. Forensic expert conclusion indicates that causality in this case is reconstructed not as a single linear chain, but as a combination of several parallel and sequential causal chains, within which each link is simultaneously consequence of the previous one and the cause of the next. Within the structure of this analysis, modules are identified related to the gas factor, condition of collective protection and control equipment, workflow management o in the hazardous zone, as well as compliance or non-compliance with specific safety requirements for the relevant type of work. At the same time, conclusion notes that lack or failure to provide some of the materials requested by forensic experts limits the ability to detail individual causal components, which once again confirms a fundamental limitation of forensic analysis: analysis of causes cannot go beyond the factual basis provided for the investigation.

It is precisely the existence of multiple causal chains in this incident that allows us to clearly demonstrate the advantages of phase-modular decomposition in situations where the causal structure of an event cannot be adequately reconstructed using a single linear explanation.

Within the phase-modular decomposition of this incident, the first phase should be defined as the phase of accumulation of hazardous conditions. Within its structure, the module associated with the gas factor and ventilation id est, with the formation of an explosive atmosphere is identified first. Within this module, it is established that the emergence of the hazard is linked to gas accumulation processes, specifically the accumulation of gas in the face or backfill area, as well as to the technological and organizational conditions of ventilation. This module is of decisive importance, as it creates the physical conditions for the development of an explosive event. The second module within this same phase concerns the condition and use of collective protection and control measures. Forensic expert conclusion indicates availability of disconnected or malfunctioning

components of such measures, particularly automatic functions related to ensuring safe operation when maximum permissible concentrations are exceeded. In terms of causation, this creates a sequence in which the hazardous condition was not stopped, limited, or localized in a timely manner, thereby creating conditions for a further increase in concentration.

A separate stage in the event development is associated with the launch of its mechanism. Within its framework, a module related to the source of initiation and further development of the event as a sequential chain of interactions becomes important. In this case, causality is described using several interconnected chains with multiple links that makes possible to decompose a multivariate event into logically ordered components and determine not the overall *cause of the explosion*, but the sequence of technical conditions, actions or inaction that led to the consequence.

Final phase is associated with human casualties and reflects the immediate injury mechanism. Within this phase, the factor related to the presence of employees in the restricted area takes on decisive importance, and is considered a separate technical link in the chain of causality. Forensic expert conclusion indicates that the injury was caused not only by the development of an explosive process but by the presence of people within a zone where their presence was impermissible under the specific production conditions. Furthermore, the reason for such presence was identified as non-compliance with special safety rules for the relevant type of work, specifically lack, inconsistency, or failure to implement properly executed documents regulating the boundaries of the hazardous zone, procedure for informing employees and restrictions on access to. From a methodological standpoint, this framework allows for a clear distinction between the physical possibility of the incident, determined by gas factors and ventilation conditions; technical realization of the incident through its initiation and progression; and the actual injury linked to the area where people were present and the lack of access barriers.

Practical application of the proposed approach in the second case study lies primarily in addressing the problem of an event's multi-link causal structure. Rather than searching for a single *root cause*, phase-modular decomposition allows for the formal and structured identification of causality modules, while maintaining certainty of conclusions regarding each technically defined link. An equally important result is the translation of a systemic event into a process-driven format: even with a significant volume of input materials and a large number of asked questions, conclusion can be constructed as a sequence of interrelated modular answers, rather than as a general description of the event. At the same time, the case materials demonstrate a fundamentally important result: formalization of the limits of detail. Limitation on detail recorded in the conclusion, resulting from the non-disclosure of some materials at the experts' request, confirms that a correct method does not compensate for missing data with assumptions but rather establishes the limits of a possible conclusion.

Summarizing the results of practical approbation gives grounds to assert that the proposed approach is not a declarative theoretical construct, it can be reproducibly applied to real materials of forensic examinations by isolating phases and modules, localizing the technical node of causality and procedurally correct response to incompleteness of materials.

Such an applied model does not require tools that go beyond competence of a forensic mining expert: the research is carried out by analyzing documents, retrospective reconstruction of the event and comparing actual situation with the statutory requirements with the formation of a written answer to the questions posed and a clear delineation of the limits of the conclusion in case of data deficiency.

Conclusions

Currently, the main scientific challenge facing modern FMTE lies in the mismatch between the increasing complexity of multifactorial accident scenarios and the limited capabilities of traditional linear analysis frameworks for determining technical causes and causal relationships in the context of criminal proceedings. Modern systemic and causal models developed in foreign engineering science have significant heuristic potential; however, they cannot be directly transferred to national forensic practice without special methodological adaptation. The obstacle lies not in the scientific value of these models, but in the fact that a significant portion of their applied tools is oriented toward preventive analysis, systemic improvement, probabilistic reconstructions and analytical procedures that are incompatible with the procedurally defined order of forensic research.

Academic novelty of the research lies in the substantiation of the fact that procedurally compatible causal analysis in FMTE should be built not on the direct borrowing of *SCM, DAG, STAMP/CAST* and related models in their original form, but on the transformation of their logical core into a tool for retrospective reconstruction of the event. The idea of using modern causal thinking not as a mathematical-computational or software apparatus, but as a way of organizing forensic research in accordance with the requirements of criminal procedural legislation, has been further developed. In this context, phase-modular decomposition is justified as a compensatory procedural-methodological mechanism that allows combining analytical advantages of modern theories of causality with reproducibility requirements, documentation and procedural suitability of forensic expert conclusion.

Theoretical significance of the results obtained lies in the clarification of conceptual apparatus and logic of constructing an expert investigation in cases of complex accidents in the mining industry. The content of procedurally compatible causal analysis is specified as a method of reconstructing an event, in which the expert acts only within the limits of the provided content, does not compensate for deficiency of the factual basis with assumptions, and, if necessary, uses the procedural mechanisms provided for by law for requesting additional materials or formalizes the limits of a possible answer. At the same time, phase-modular decomposition is revealed not as a descriptive metaphor, but as a research algorithm that includes event localization, separation of phases of its development, the formation of modules, checking sufficiency of materials, application of current certified methods within the limits of each module, and integration of module results into a single causal conclusion. It is this logic that creates the theoretical and methodological basis for the new FMTE methodology.

Practical significance of the research was confirmed by testing proposed approach on depersonalized cases from real expert practice. The analysis of a production event in open-pit mining operations associated with conveyor transport and a rotor complex demonstrated that phase-modular

decomposition allows us to clearly delimit the block of work organization and admission to their execution, the block of the technical condition of protective barriers, dangerous situation formation phase and the injury mechanism without mixing different causal levels in one generalized explanation. The analysis of a group incident in underground conditions indicated that the same approach allows us to decompose the multichain mechanism of the event into separate causal modules and maintain the certainty of local conclusions even with the incompleteness of individual materials. Thus, it is proven that phase-modular decomposition is not only a theoretical construct, but applied tool for a forensic expert to work with case files of criminal proceedings.

In general, the research result give grounds to believe that the promising direction of the FMTE development is not the mechanical borrowing of ready-made foreign models, but the construction of its own methodology based on procedurally adapted causal analysis. The approach proposed in the article creates a proper basis for this, since it combines scientific validity, procedural compatibility and applied suitability. Thereby, phase-modular decomposition can be considered as the basic design of the future official FMTE methods, focused on increasing objectivity, reproducibility and evidentiary value of forensic expert conclusions.

Обмеження застосування методів каузального моделювання в судовій гірничотехнічній експертизі та шляхи їх подолання

Іван Пугач, Юрій Чеберячко, Вадим Харченко, Інна Пугач

Окреслено наукову проблему методичного розриву між сучасними каузальними моделями аналізу складних аварійних подій і процесуальними вимогами судової гірничотехнічної експертизи, у межах якої експерт зобов'язаний спиратися лише на надані матеріали, свою компетенцію та процедури обґрунтування, що піддаються перевірці. Мета дослідження — обґрунтувати межі застосування сучасних іноземних моделей каузального аналізу в національній судовій гірничотехнічній експертизі й розробити фазово-модульну декомпозицію як компенсаторний процесуально-методичний механізм реконструкції складних аварій. Методи дослідження охоплюють теоретичний аналіз українських та іноземних джерел, нормативно-процесуальне тлумачення ролі та меж компетенції судового експерта, логіко-структурне моделювання причинних зв'язків, фазово-модульну декомпозицію аварійної події та практичну апробацію підходу на двох знеособлених кейсах із реальної експертної практики. Показано, що STAMP/CAST, SCM, каузальні графи, контрфактуальні й інші системні моделі мають значну евристичну цінність, проте їх пряме перенесення у сферу судово-експертного дослідження обмежено ретроспективним характером судової гірничотехнічної експертизи, дефіцитом матеріалів кримінального провадження, вимогами до відтворюваності висновку та забороною компенсувати доказові прогалини ймовірними припущеннями. Доведено, що фазово-модульна декомпозиція дає змогу локалізувати причинність у технічно однорідних фрагментах події, установлювати доказову основу для кожного модуля, процесуально коректно реагувати на нестачу вихідних даних і формувати логічний, прозорий висновок експерта. Підтверджено придатність підходу для аналізу подій на відкритих і підземних гірничих роботах за допомогою практичної апробації.

Ключові слова: *судова гірничотехнічна експертиза; причинно-наслідковий зв'язок; каузальний аналіз; фазово-модульна*

декомпозиція; гірнича аварія; висновок експерта; кримінальне провадження.

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Declaration of Competing Interest

Author declares no conflict of interest.

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