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Investigation of the impact of force majeure circumstances as a market instability factor on the flexibility and sustainability of engineering SMEs

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Abstract

INTRODUCTION: Modern manufacturing operates under complex natural, economic, and political conditions. Small and medium-sized enterprises (SMEs), as the most flexible representatives of the engineering industry, must account for potential stress factors in their current and future development. Research indicates that enterprises must respond rapidly to such stressors to maintain competitiveness and stability in domestic and international markets. Management decisions to ensure SME resilience should adopt a comprehensive approach, considering economic indicators such as productivity, product quality, logistics, and cost, as well as social aspects like employee safety, workplace conditions, and resource-efficient technologies.

This study develops and analyzes a mathematical model describing the impact of various stress factors on the stability of SMEs in the engineering sector under force majeure conditions. The research identifies key stressors, formulates a mathematical model to assess their influence on enterprise resilience, and evaluates the model's effectiveness over time. The integral flexibility functional serves as the foundation for this model, incorporating market fluctuations, production costs, and force majeure impacts, including quarantine restrictions and enterprise relocation.

To optimize this functional, the study employs the automated planning method PPLAN, which is rooted in artificial intelligence. This approach enables the generation of adaptive strategies to mitigate stress factors affecting SME stability. The findings reveal that relocation due to force majeure is the most detrimental factor, leaving minimal time for recovery actions, while demand fluctuations exert a more cyclical influence. The proposed methodology provides a structured framework for enhancing SME resilience in dynamic and unpredictable environments

OBJECTIVES: The objective of this paper is to develop a mathematical model that quantifies the impact of stress factors on the stability of small and medium-sized enterprises (SMEs) in the engineering sector under force majeure conditions. The study aims to identify key external and internal stressors, construct a functional model based on the integral flexibility approach, and optimize enterprise resilience strategies using artificial intelligence-based automated planning. By analyzing the model's effectiveness over time, the research provides a structured framework for enhancing SME adaptability and sustainability in dynamic and unpredictable environments.

METHODS: The research employs techniques derived from social network analysis to model and analyze the stability of small and medium-sized enterprises (SMEs) in the machine engineering industry under stress and force majeure conditions. Specifically, the study uses a mathematical model that integrates stress factors like market demand and supply fluctuations, relocation, and quarantine restrictions. The optimization of this model is achieved through automatic planning methods based on the PPLAN approach, which enables the consideration of various anti-stress measures and their impacts on the stability of SMEs over time. Additionally, 3D technologies are identified as critical tools for enhancing the flexibility and adaptability of production processes during external stresses.

RESULTS: The main results of this paper include the development of a mathematical model for analyzing the impact of stress factors on the stability of SMEs in the machine engineering sector. Additionally, optimizing the model using the PPLAN method demonstrated the effectiveness of 3D technologies in enhancing the adaptability and resilience of SMEs under force majeure conditions.

CONCLUSION: This paper concludes that integrating 3D technologies and using the PPLAN optimization method can significantly improve the stability and adaptability of SMEs in the machine engineering sector during stress and force majeure events.

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Keywords: enterprise stability, stress factors, integral flexibility functional, automatic planning, PPLAN (planning based on preferences method), digital transformation

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1. Introduction

Modern manufacturing operates in complex natural, economic, and political conditions, requiring enterprises, especially small and medium-sized enterprises (SMEs), to be highly flexible and adapt quickly to various stress situations. In machine engineering, where SMEs play a central role, it is crucial to consider short-term and long-term risks that may affect the company's stability. As research shows, the response to stress factors must be rapid; otherwise, it threatens not only the competitiveness in domestic and international markets but also the overall stability of the enterprise [1-3]. To ensure the sustainability of SMEs, management decisions must be based on a comprehensive approach to managing stress factors that directly impact key economic indicators: productivity, product quality, logistics costs, and cost of goods sold. However, in addition to economic aspects, it is also important to consider social factors, such as employee safety, comfortable working conditions, and the implementation of progressive resource-saving technologies [4, 5]. In this context, particular attention should be given to modeling the management behavior of company leadership in the face of continuously changing stress situations, which defines the relevance of this study.

2. Objective and Research Tasks

This study aims to develop and analyze a mathematical model that describes the impact of various factors on the stability of SMEs in the machine engineering industry under stressful and force majeure circumstances.

To achieve this goal, the following tasks must be accomplished:

- identify the main stress factors affecting the stability of SMEs in the machine engineering sector;
- discover the dependencies and formulate a mathematical model of the influence of these factors on the stability of the enterprise;
- analyze the developed mathematical model to determine the level of impact of these factors on the stability of SMEs in the machine engineering industry over time.

3. Research Tasks

One of the most discussed issues in modern scientific literature is ensuring the stability of enterprise development under the Industry 4.0 paradigm and the speed of changes in supply-demand dynamics on the market [5-7]. This is particularly relevant for SMEs. Market instability is a multifactorial phenomenon encompassing macroeconomic, political, technological, and social aspects. It directly affects the technological sustainability of SMEs, as resource constraints complicate the implementation of cutting-edge technologies. At the same time, fluctuations in raw material supply and market conditions create additional risks. SMEs, an essential component of economies contributing to job creation and innovation, often face competitive pressure from larger companies and international players, creating additional challenges in fluctuating market conditions [8]. Intense competition may force SMEs to adapt through the adoption of new technologies and organizational innovations as globalization and technological progress present new challenges [9, 10]. Furthermore, as studies show, process innovations are essential for maintaining SMEs' competitiveness during market fluctuations and improving operational efficiency in response to evolving external condition**s** [11, 12]. At the same time, market instability can reduce profit margins as competition becomes more aggressive and demanding, thus increasing the need for SMEs to focus on innovative strategies [13].

In work [14], the existing problems of relocating high-tech enterprises (including those due to military actions) are analyzed, and a model for selecting a new location for the enterprise is proposed, taking into account conflicting indicators (long logistics chains, economic losses, alignment with component manufacturers, etc.). The model includes a multi-criteria optimization of supplier selection based on assessing the emergence of threats and the consequences of their actions related to disruptions in the enterprise's logistics, which allows scientifically substantiated requirements to be formed for relocating a high-tech enterprise to a new location.

In article [15], it is noted that many contemporary studies lack a clearly defined approach to forecasting enterprise productivity in relation to time and technological preparation of production. To address this gap, the paper analyzes time-based system models aimed at improving technological preparation of production and enhancing enterprise sustainability. However, these models remain disconnected from actual market dynamics.

The work [16] is dedicated to improving the competitiveness of Ukrainian enterprises, exploring ways to ensure market advantages for the enterprise amid new challenges in the global economy: globalization, the need for new knowledge and skills among staff, automation, and computerization of production processes, etc. Some steps to increase the competitiveness of Ukrainian business entities are proposed. However, these studies focus solely on working with enterprise personnel and do not consider other factors necessary to ensure sustainable development, especially under force majeure circumstances.

In work [17], an information software system is proposed, implementing a hierarchical model for solving dispatching and planning tasks in small-scale production. This system formulates a procedure for decision-makers and optimizes the potential order portfolio and execution deadlines. Despite the effectiveness of such planning, the system does not allow for quick and timely responses to force majeure situations and market changes. A more modern proposal is made in the work [18], where the authors use the relocation of the enterprise as a strategic decision affecting long-term profitability, thus requiring a benchmark model for its relocation as a basis for decision-making. In the study [18], a model for organizing the relocation of factories in global manufacturing enterprises is proposed, including phases for analyzing industrial conditions, planning the relocation, and implementation, as well as evaluating effectiveness. However, these studies, on the one hand, do not allow responding to market changes and force majeure situations, and on the other hand, the proposed model is only suitable for large enterprises without considering the specific features of SMEs.

In work [19], the focus is on the relationships between the relocation of value chain modules and the competitive position of the company undergoing relocation. Both positive impacts of relocation on competitiveness (competitiveness of resources, improving competitive position, etc.) and negative ones are considered.

Another problem in optimizing such complex integral functionalities is that traditional mathematical models are not maximally effective for solving decision-making tasks in stressful and force majeure situations, where a wide range of fuzzy parameters must be taken into account [20]. The most promising solution for optimizing such functionality seems to be the method of automatic planning, a branch of artificial intelligence, which works based on a preference system (known as PPLAN planning) [20,21]. The development of automatic planners based on hierarchical task networks (HTN) has been widely discussed [20,21,22]. In such automatic planners, expressing time constraints becomes possible through the use of simple temporal networks (STN). The value of such planners is that it allows for consistency checking of a simple temporal network and provides a convincing solution regarding the fulfillment of time constraints in the plan.

Work [3] examines the factors that enhance the adaptability of SMEs in response to dynamic market demands. It considers the optimization of the integral functionality of SME flexibility using the PPLAN-based planning approach. This approach allows for the optimization of resource allocation, reduction of execution timelines, maintenance of productivity, and product quality, thereby ensuring the enterprise's sustainability. A unique flexibility approach to decomposition is presented, enabling SMEs to manage demand-supply fluctuations and stress challenges strategically. However, the operation of SMEs in conditions of demand and supply fluctuations in the market, as well as the impact of force majeure circumstances on the planning system, requires more detailed attention.

4. Materials and methods

As noted in [3], in general, the mathematical process of ensuring the stability of an enterprise can be represented as an integral functional of flexibility^

$$F_{st}(\tau_0) = \int_0^{T_o} \sum \sigma_i \cdot W_i(t;\ \tau_0)\, dt \to \min; \qquad (1)$$
$$PC(t) < PC(t)_{mrkt}$$

where $W_i(t)$ is a multifactorial function that describes the relevant factors influencing various aspects of the production process and the enterprise's ability to respond to current market changes; σ_i are the weighting coefficients that reflect the degree of influence of the corresponding function on the analyzed functional; $PC(t)$ and $PC(t)_{mrkt}$ refer to the cost price and market price of the produced goods, respectively, τ_0 – the initial state of the system.

Changes in the main characteristics of the production process over time, triggered by shifts in external factors, were discussed in [3].

Let's consider stress factors affecting the sustainability of small and medium-sized enterprises (SMEs). Two groups can be identified: economic factors (such as changes in demand and supply of goods in the market) and factors related to force majeure, unforeseen circumstances (such as quarantine, military actions, and natural disasters requiring suspension of production or even the relocation of the enterprise to another region or country). While the first group of economic factors can be forecasted to some extent, the second group typically occurs suddenly and unexpectedly. In this case, the mathematical impact of these factors on the integral functional of flexibility can be considered a combination of individual integral functionals.

Considering these stress factors, such as rapid changes in demand ($\Delta D_{mn}(t)$) and supply ($\Delta Sup(t)$) in the market ($s_1(\Delta D_{mn}(t), \Delta Sup(t)) = \xi_1(\Delta D_{mn}(t) + \Delta Sup(t))$), as well as enterprise relocation and quarantine restrictions ($s_2(\Delta Rlc(t), \Delta LckD(t)) = \xi_2 \cdot (\Delta Rlc(t) + \Delta LckD(t))$), the stability of SMEs, which depends on its flexibility, will require additional analysis of these parameters. Thus, the integral functional of flexibility will have the form:

$$F_{total}(\tau_0) = F_{st}(\tau_0) + \int_0^{T_o} [\,\xi_1(\Delta D_{mn}(t) + \Delta Sup(t)) + \xi_2 \cdot (\Delta Rlc(t) + \Delta LckD(t))]\, dt \to \min, \quad (2)$$

where $\Delta Rlc(t)$ - changes in costs and supply chain connections due to relocation; $\Delta LckD(t)$ indicates changes in costs associated with quarantine at the enterprise or in the country; ξ_1 and ξ_2 are coefficients that show the impact of force majeure circumstances on the flexibility of SMEs and can be defined as constants that quantitatively assess the influence of various force majeure conditions on the overall flexibility level of the enterprise.

An automatic planning method was used to optimize the proposed integral functional, a branch of artificial intelligence that operates based on the planning method based on preferences - PPLAN planning. This method allows the optimization of SMEs' overall integral flexibility functional, considering the variability of solutions, to mitigate the impacts of stress factors on the enterprise's stability over time. A set of atomic tasks is generated upon completion of the planning process, representing a structured plan to ensure the SME's sustainable operation under uncertain conditions. These tasks typically include the reallocation of production resources between technological nodes, the dynamic reconfiguration of supply chains through the selection of alternative suppliers or logistical routes, the updating of digital production models (digital twins), the adaptation of process parameters to altered environmental or material conditions, the initiation of staff retraining procedures to match updated operational requirements, as well as the implementation of temporary technological or logistical support mechanisms. The systematization and sequential execution of such atomic tasks contribute to the formation of an adaptive scenario that increases the resilience of SMEs in the face of abrupt changes in demand and/or supply, forced partial or full relocation of production facilities, or other force majeure circumstances.

Figure 1 presents the result of applying this method for the normalized analysis of SME behavior under external stress caused by market changes: demand fluctuations, supply instability, forced enterprise relocation, and quarantine restrictions, which serve as destabilizing triggers for the enterprise's stability. In this context, «normalized» refers to transforming raw input data into dimensionless values using a min-max normalization technique. This approach scales the data within a predefined range (usually between 0 and 1), consistently comparing various stress factors. The normalization process allows for the relative evaluation of the impact of different stressors on SME stability, making it easier to interpret the enterprise's dynamic response to these external challenges.

Each curve in Figure 1 reflects the magnitude and direction of variation of a specific external parameter within a normalized range from –1 to 1. These values characterize the time-dependent dynamics of the stressors rather than their direct impact on enterprise stability. The purpose of this graph is to enable a comparative assessment of the timing, intensity, and frequency of changes in external conditions. This visualization serves as the foundation for evaluating the influence of these stressors within the overall integral flexibility functional, allowing further computational modeling of the SME's adaptive behavior under stress.

Based on the fact that time is a key control parameter in the stability and flexibility of small and medium-sized enterprises (SMEs), the task was set to determine the impact of the time component in ranking stress factors on SME stability. It was identified that stress caused by the relocation of an enterprise due to force majeure circumstances (such as military actions) is the most harmful and fleeting and does not leave a «relatively adequate» time frame for anti-stress measures to restore the enterprise's stability and competitiveness in the market. Stress caused by quarantine restrictions also affects the stability of the enterprise fairly quickly; however, the damage caused by them is somewhat less and can be resolved more quickly. In this case, everything depends on the duration of quarantine restrictions and the ability of the state to regulate the situation.

Unlike stress related to force majeure circumstances, stress caused by a reduction in the enterprise's ability to generate supply or respond to demand is cyclical and requires more time to take anti-stress actions to restore the enterprise's stability.

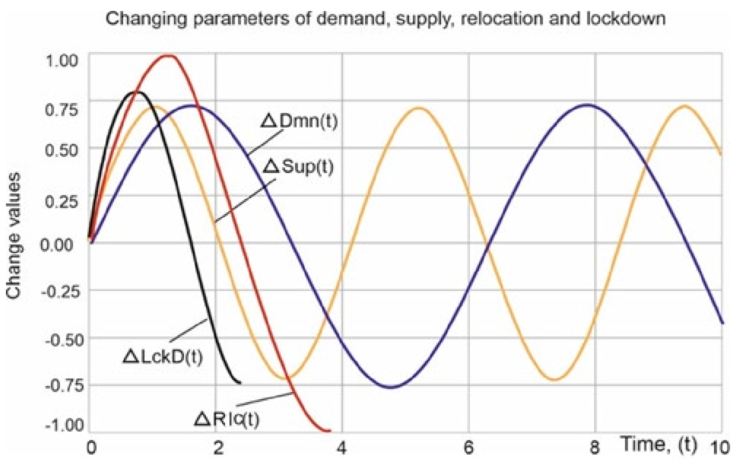

Figure 1. Analysis of the Impact of Stress Factors on the Overall Flexibility Functional Over Time (measured in weeks)

It should be noted that these graphs are of a general nature, and the coefficients used in the modeling were based on the average statistics for the mechanical engineering sector SMEs [23], as well as on available data regarding the duration of quarantine restrictions during the COVID-19 epidemic [24] and the relocation of production caused by the military aggression of the Russian Federation [25]. Depending on the actual production conditions, the type of products, and other factors, the amplitude of the curves may vary, and consequently, the impact on the final result may differ. In this case, the proposed analysis should be considered a research methodology.

The analysis of the behavior of the factors in question allows us to hypothesize that 3D technologies may become a key element in overcoming stress for enterprises due to their ability to ensure the flexibility of the production process after relocation [26-31], support the functioning of some divisions through remote access, rapidly adapt to new market conditions, and stabilize supply in a new market through the restructuring of production with the availability of modern digital models and technologies.

Thus, with a surge in demand, when an enterprise needs to adapt to market requirements quickly, 3D tools for information representation create the opportunity for rapid stress alleviation. For example, when resources are reduced, technological and production processes can be adapted using 3D technologies, particularly through digital twins and 3D modeling of production components and systems. These tools allow for rapid reconfiguration of manufacturing workflows, optimization of resource use, and even virtualization of testing and prototyping stages, thereby mitigating supply-related stress. Additive manufacturing also makes it possible to produce critical components in-house, bypassing disrupted supply chains. Such applications of 3D technologies in supply chain adaptation and resilience have been discussed in recent studies [26-29]. Finally, in the case of relocation, the enterprise will need resources that can be quickly adapted to new conditions. In these conditions, 3D technologies will allow for the reproduction of production processes [30-31] at a new location without significant delays.

In this case, when 3D technologies are used for adapting to force majeure circumstances, the integral flexibility functional, considering force majeure circumstances, will have the following form (Figure 2).

From Figure 2, it is evident that the initial flexibility functional of the SME rapidly increases, but later fluctuations begin, indicating the internal instability of the enterprise caused by the accumulation of internal and external barriers that affect SME development over time. The impact of market conditions $(\Delta D_{mn}(t) + \Delta Sup(t))$ was modeled based on market fluctuation scenarios, such as changes in demand or supply instability, and measured by their effect on key production parameters, such as resource allocation, costs, and production capabilities. These changes were incorporated into the integral flexibility functional, resulting in the red line (Figure 2), illustrating the dynamics of SME adaptation to market pressure over time. The changes in market conditions were simulated by varying $\Delta D_{mn}(t)$ and $\Delta Sup(t)$ values, and the corresponding effect on the functional was computed. Subsequently, after the adoption of anti-stress measures, this pressure gradually decreases.

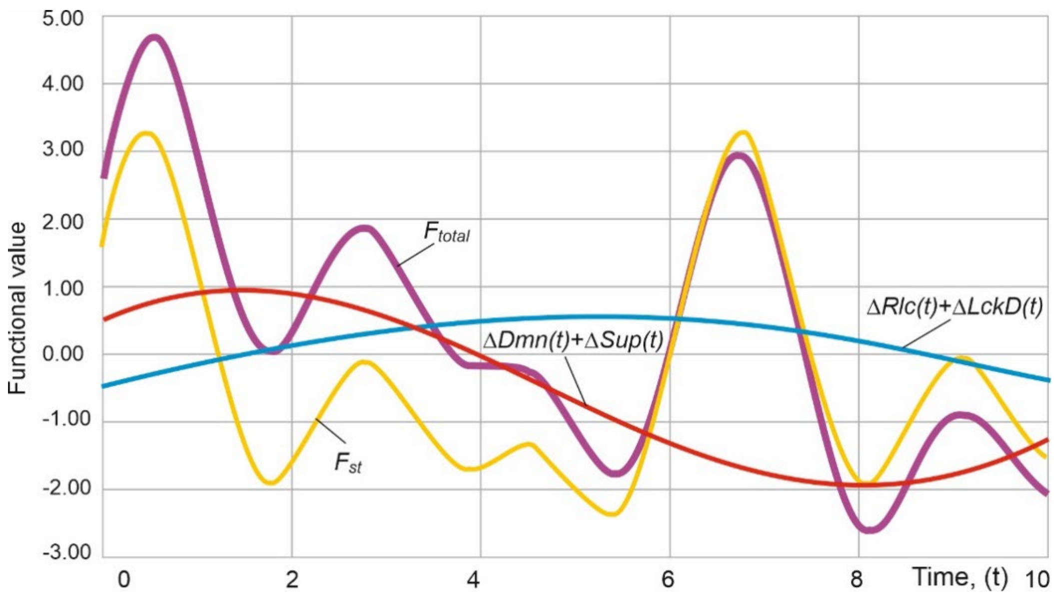

Figure 2. Integral Flexibility Functional Considering Force Majeure Circumstances (measured in weeks)

In general, the market has a relatively stable influence on the sustainability of SMEs, provided that the enterprise is flexible in accordance with changes in consumer preferences or reduced demand for goods. The impact of forced relocations of enterprises or quarantine restrictions ($\Delta Rlc(t) + \Delta LckD(t)$) on the stability of SMEs over time gradually increases, which is a reflection of the accumulation of negative consequences from partial or full relocation of production capacities: the loss of key suppliers, resources, personnel, distance from established markets, increased logistics costs, additional expenses for ensuring worker protection and safety, etc. This also requires mitigation through thoughtful crisis management actions.

And finally, the overall flexibility functional of SMEs, F_{total}, initially demonstrates a certain level of enterprise stability, which over time transitions to a state of increased instability due to the combined effects of external stress factors. This behavior of the overall flexibility functional can be explained by the constant stress conditions in the market, which are exacerbated during force majeure situations, when SMEs demonstrate greater vulnerability to market fluctuations, in contrast to large manufacturing companies (provided they are not subject to relocation, as the relocation of large enterprises is more complex and costly). This is why the ability of small enterprises to respond quickly to changes in demand and supply, as well as to manage production during a crisis or force majeure situation effectively, is a key factor in maintaining their stability.

The maximum peaks on the graph indicate that the enterprise can still adapt to market changes and force majeure conditions, but this adaptation can only be achieved through the implementation of well-founded crisis management measures, which are necessary to restore stability during periods of extreme stress, as reflected in the peaks on the graph**.** In the current era of rapid automation, the digitalization of the enterprise and the use of 3D technologies at all stages of production preparation and implementation represent the most effective means of ensuring enterprise stability. While the figure does not explicitly illustrate the use of 3D technologies, the functional analysis results, supported by the preference-based planning method, demonstrate how digital tools, such as digital twins and 3D modeling, can enhance the enterprise's ability to respond to stress factors and improve its adaptability and stability.

5. Conclusions

It has been demonstrated that for a more detailed analysis of the integral flexibility functional of SMEs, which allows for the examination of various aspects of the production flexibility of a machine-building enterprise and its ability to adapt to current changes over time, it is necessary to supplement the analysis with factors related to force majeure and unpredictable circumstances. This allowed for the expansion of the mathematical model of the integral flexibility functional of SMEs with additional components of stress factors such as: rapid changes in demand and supply in the market, as well as changes in enterprise activities due to relocation or quarantine restrictions, either within the enterprise or the country.

Based on the optimization of the overall integral flexibility functional of SMEs using the automatic planning method based on preferences (PPLAN planning), it has been established that it is possible to account for the variability of anti-stress decisions capable of neutralizing the impact of stress factors on the stability of the enterprise over time. This can be achieved by utilizing 3D technologies at various levels of information representation for production objects, which allows for the rapid stabilization of SME stability by compensating for the weakened characteristics of other functional components, including those caused by force majeure circumstances.

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References

[1] Basova Y, et al. Increasing SME supply chain resilience in the face of rapidly changing demand with 3D model visualisation. Int J Mechatronics Appl Mech. 2023; 2023 (14) : 35-47. https://doi.org/10.17683/ijomam/issue14.5.

[2] Yakovenko IE, Linnik OI, Permyakov OA, Basova EV. Technological innovations as a means of ensuring competitive advantage for micro, small, and medium-sized machine-building enterprises. Bulletin of the National Technical University "KhPI". Series: Techniques in a Machine Industry. Kharkiv: NTU "KhPI"; 2024. p. 74-87. https://doi.org/10.20998/2079-004X.2024.2(10).08

[3] Basova EV, Dobrotvorsky SS, Yakovenko IE. Modeling changes in production flexibility over time for small and medium machine-building enterprises under sharp market fluctuations. Visnyk of the National Technical University "KhPI". Series: Machine Engineering and CAD Systems. Kharkiv: NTU "KhPI"; 2024. p. 6-13. https://doi.org/10.20998/2079-0775.2024.2.01

[4] Dobrotvorskiy S, Balog M, Ruzmetov A, Basova Y, Hrdzelidze S, Dobrovolska L. Increasing the sustainability of manufacturing processes in the conditions of SMEs enterprises by predicting their information intensity. In: Balog M, Iakovets A, Hrehova S, editors. *EAI International* Conference on Automation and Control in Theory and Practice. EAI ARTEP 2023. Cham: Springer; 2023. p. 207-219. doi: 10.1007/978-3-031-31967-9_16.

[5] Iakovets A, Balog M, Židek K. The use of mobile applications for sustainable development of SMEs in the context of Industry 4.0. *Appl Sci*. 2023;13(1):429. doi: 10.3390/app13010429.

[6] Garcia-Muiña FE, González-Sánchez R, Ferrari AM, Settembre-Blundo D. The paradigms of Industry 4.0 and circular economy as enabling drivers for the competitiveness of businesses and territories: The case of an Italian ceramic tiles manufacturing company. Soc Sci. 2018;7(12):255. doi: 10.3390/socsci7120255.
[7] Dvorsky J, Kubalek J, Barinova D, Androniceanu A, Khan KA. Selected factors influencing the social and environmental aspects of sustainability of SMEs. Transform Bus Econ. 2024;23:200-218.
[8] Amoah J, Jibril AB, Egala SB, Keelson SA. Online brand community and consumer brand trust: Analysis from Czech millennials. Cogent Business & Management. 2022; 9 : 2149152.
[9] Ocloo CE, Akaba S, Worwui-Brown DK. Globalization and competitiveness: Challenges of small and medium enterprises (SMEs) in Accra, Ghana. *Int J Business Soc Sci*. 2014;5:287-296.
[10] Fedorovych O, et al. Modeling of the relocation of high-tech enterprises for the release of innovative products. Radioelectronic and Computer Systems. 2023;2:180-192. https://doi.org/10.32620/reks.2023.2.15
[11] Liñán F, Paul J, Fayolle A. SMEs and entrepreneurship in the era of globalization: Advances and theoretical approaches. *Small Bus Econ*. 2020;55:695-703.
[12] Muharam H, Andria F, Tosida ET. Effect of process innovation and market innovation on financial performance with moderating role of disruptive technology. *Syst Rev Pharm*. 2020;11:223.
[13] Daradkeh M, Mansoor W. The impact of network orientation and entrepreneurial orientation on startup innovation and performance in emerging economies: The moderating role of strategic flexibility. *J Open Innov Technol Mark Complexity*. 2023;9:100004.
[14] Gamage NG, Kumara SK, Ekanayake EMS, Abeyrathne GAKNJ, Prasanna RPIR, Jayasundara JMSB, Rajapakshe PSK. A review of global challenges and survival strategies of small and medium enterprises (SMEs). *Economies*. 2020;8:79.
[15] Hiller T, Deipenwisch L, Nyhuis P. Systemising data-driven methods for predicting throughput time within production planning & control. In: IEEE, editor. 2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM); 2022 Dec 5-8; Kuala Lumpur, Malaysia. IEEE; 2022. p. 716-721. https://doi.org/10.1109/IEEM55944.2022.9989885
[16] Zelinska H, et al. Innovative development of Ukraine: competitiveness of enterprise staff in the context of globalization changes. J Hygienic Eng Design. 2022;40:294-303.
[17] Zgurovsky MZ, Pavlov AA. Algorithms and Software of the Four-Level Model of Planning and Decision Making. In: Combinatorial Optimization Problems in Planning and Decision Making. Cham: Springer; 2019. p. 153-167. https://doi.org/10.1007/978-3-319-98977-8_9
[18] Leu JD, Yu-Tsung H. Factory relocation of global manufacturing enterprises: A case study. Int J Ind Eng: Theory Appl Pract. 2011;18(10):524-535.
[19] Dzikowska M. The importance of relocation for the competitive position of an enterprise: The perspective of companies from the clothing and automotive industries located in Poland. Argumenta Oeconomica. 2014;32(1):141-176.
[20] Qi C, Wang HW. HTN planning based emergency response action plan development. In: Proceedings of ISCRAM ASIA; 2012 May 21-24; Beijing, China. p. 430-436.
[21] Li M, Wang H, Qi C, Zhou C. Handling temporal constraints with preferences in HTN planning for emergency decision-making. J Intell Fuzzy Syst. 2016;30(4):1881-1891. doi:10.3233/IFS-151899.
[22] Hiller T, Deipenwisch L, Nyhuis P. Systemising data-driven methods for predicting throughput time within production planning & control. In: IEEE, editor. 2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM); 2022 Dec 5-8; Kuala Lumpur, Malaysia. IEEE; 2022. p. 716-721. https://doi.org/10.1109/IEEM55944.2022.9989885
[23] Statista. Number of small and medium-sized enterprises (SMEs) in the manufacturing sector in the EU from 2008 to 2022. Statista Research Department. 2023. Available from: https://www.statista.com/statistics/1234892/smes-in-manufacturing-sector-eu/.
[24] World Health Organization. Contact tracing and quarantine in the context of the COVID-19 pandemic: interim guidance. WHO guidelines. 2022;6 July 2022:1–12.
[25] Ministry of Economy of Ukraine. Relocation program for Ukrainian enterprises: official website. Relocation.gov.ua. 2023. Available from: https://relocation.gov.ua/en
[26] Tabassum T, Mir AA. A review of 3D printing technology – the future of sustainable construction. Mater Today Proc. 2023;93(3):408–414. https://doi.org/10.1016/j.matpr.2023.08.013
[27] Delic M, Eyers DR. The effect of additive manufacturing adoption on supply chain flexibility and performance: An empirical analysis from the automotive industry. Int J Prod Econ. 2020; 228:107689. https://doi.org/10.1016/j.ijpe.2020.107689
[28] Liu W, Liu X, Liu Y, Wang J, Evans S, Yang M. Unpacking additive manufacturing challenges and opportunities in moving towards sustainability: An exploratory study. Sustainability. 2023;15(4):3827. https://doi.org/10.3390/su15043827
[29] Alogla AA, Baumers M, Tuck C, Elmadih W. The impact of additive manufacturing on the flexibility of a manufacturing supply chain. Appl Sci. 2021;11(8):3707. https://doi.org/10.3390/app11083707
[30] Balletti C, Ballarin M. An application of integrated 3D technologies for replicas in cultural heritage. ISPRS Int J Geo-Inf. 2019;8(6):285. https://doi.org/10.3390/ijgi8060285
[31] Gress DR, Kalafsky RV. Geographies of production in 3D: Theoretical and research implications stemming from additive manufacturing. Geoforum. 2015;60:43–52. https://doi.org/10.1016/j.geoforum.2015.01.003