JOURNAL OF ENGINEERING SCIENCES

Volume 10, Issue 1 (2023)

Prokopovych I. V., Kokhanov A. B., Khamitov V. M, Tikhenko V. M., Dašić P. (2023). Standardizing life cycle organization: A synergetic quality management approach. Journal of Engineering Sciences, Vol. 10(1), pp. B1-B7, doi: 10.21272/jes.2023.10(1).b1

Standardizing Life Cycle Organization: A Synergetic Quality Management Approach

Prokopovych I. V.[1*][0000-0002-8059-6507], Kokhanov A. B.[1][0000-0002-7197-6380], Khamitov V. M.[1][0009-0005-3494-8304], Tikhenko V. M.[1][0000-0003-1040-9160], Dašić P.[2][0000-0002-9242-274X]

[1] Odessa Polytechnic National University, 1, Shevchenko Ave., 65044 Odessa, Ukraine;
[2] High Technical Mechanical School of Professional Studies, 19, Radoja Krstića St., 37240 Trstenik, Serbia

Article info:

Submitted:	February 21, 2023
Received in revised form:	May 9, 2023
Accepted for publication:	May 19, 2023
Available online:	May 25, 2023

***Corresponding email:**
igor.prokopovich@gmail.com

Abstract. Standardization is essential for innovation (on the impacts on design, manufacturing, and operation processes) and its dissemination, both within a country and internationally. A phenomenological information model has been developed for the system of standards, which will be used as an information base for integrated quality management systems, environmental safety, and energy saving depending on the type of products, requirements of technical regulations, and conformity assessment procedures. Phase portraits of the life cycle system of complex products were constructed, and a general expression for the Lyapunov exponents characterizing the overall behavior of the dynamic system in phase space was obtained. The presence of particular areas to which, regardless of the initial conditions, all phase trajectories rapidly evolve has been established. The critical conditions for the control parameters were found. A diagram was constructed that determines the stability of the system states of the life cycle of complex products. It was found that the processes of the life cycle of complex products are carried out in two stages: in the first, there is a rapid evolution of components and parameters of technical and software tools, as well as energetic elements of functional subsystems, which is reflected in a specific attractive section of phase portraits, in the second, further slow development along it.

Keywords: additive manufacturing, industrial growth, production function, state parameter, synergetic order parameter.

1 Introduction

Energy efficiency and environmental impact of applied technologies are relevant for various industries and (to a large extent) related to the effectiveness of the use of technical and economic information in ensuring the quality of complex products (CP) [1, 2]. The ISO 9000 standards cover various aspects of quality management [3]. The standards provide guidance and tools for companies and organizations that want their products and services to meet customer requirements and consistently improve quality. This is especially true for products for industrial purposes (various production equipment) used to manufacture the final finished product. ISO has several quality management system standards developed from ISO 9001 and adapted to specific industrial sectors [4].

The growing awareness of the importance of the problem of environmental protection and the possible impacts associated with manufactured and consumed products has increased interest in developing methods to understand and study these impacts. One method being developed for this purpose is life cycle assessment (LCA). The standard ISO 14044 details the requirements for LCA [5]. The ISO man-agreement system helps organizations improve their performance by developing specific design, manufacturing, and operation steps that organizations will follow during their activities to achieve their goals and create an organizational culture.

Understanding and caring for mutually related processes at these stages as a system for judging the effectiveness and efficiency of the organization in the reach of planned results. Simulation is a recognized method for planning and optimizing production systems. Existing standards (e.g., ISO 14040/44), data sources, and software support LCA.

In paper [6], two approaches to the modeling of prospective resource reserves at the stages of the life cycle of the CP are distinguished, namely, predictive scenarios and ranges of scenarios both for the near term (current state of the life cycle) and for background modeling of the system (future state). The first approach depicts likely events with the status quo in mind. Technology learning curves can be used to build predictive scenarios [7]. The second approach includes extreme scenarios that can be obtained using stoichiometric ratios to analyze the best scenario [8]. These works propose including TRL and production readiness level (MRL) in assessing new technologies' life cycle to indicate technology maturity. The authors of these works define the problem of the functionality of the observed system. However, there is still no consistency in the perspective methodology of evaluating residential buildings.

Further research in this area is needed to develop scaling schemes for new technologies. Thus, emphasis should be placed on uncertainty analysis. An assessment of the reliability of scaling methods can be established by analyzing assumptions and scaling models as the technology evolves. In this way, the quality of the scaling scheme can be assessed, evaluated, and verified. For example, due to the static nature of LCA data and standard data gaps, only averages from databases are often used in conjunction with generic black box models to define processes, materials, and resources.

Traditional LCAs cannot account for the dynamic effects of time-dependent variables. The number of input parameters and their uncertainties influence life cycle modeling, making it complex and challenging. As practice proves, the majority (55 %, according to [9]) of unsuccessful projects for the development and production of products is connected precisely with the lack of scientific approaches and appropriate regulatory and methodological support based on the use of system-wide evolutionary models. Such models should consider the large size and complexity of the data during the design, manufacture, and operation of the CP, depending on the dynamic change of the internal and external environment. As a result, there are significant unjustified costs of information, material, and energy resources when meeting the requirements of customers and other interested parties.

The purpose of this study is to develop, based on the principles of synergy, a phenomenological information model for improving the integrated system of quality management standards, environmental safety, and energy saving at the stages of the LCA of CP, depending on the requirements of technical regulations, conformity assessment procedures.

2 Literature Review

This paper analyzes the theoretical, methodological, and normative-methodical foundations of the formation and effective use of technical and economic information at the stages of the life cycle of complex products and objects of military equipment, taking into account the self-coordinated interaction of processes as an open system, the self-organization of which affects the achieved results in terms of satisfying customer requirements. In the work of [10], when assessing the sustainability of LC, economic aspects are combined with technical preparation of production (TPV), technological features, and environmental and social impacts.

A more detailed discussion of the various modes of operation of the LCA CP processes, including the future states of technical systems, is given in the results of the research works [12, 13], presents the results of studies of economic growth models based on production functions, which show realistic dynamic interdependencies associated with resource consumption, growth and structural changes at the LC stages. In models of economic growth [14], the production function describing the dependence of output on factors of production is usually assumed to be smooth everywhere. However, due to this limitation, the qualitative parameters affecting CP manufacturing cannot be included in the model.

The article [15] discusses the peculiar features of quality management in modern manufacturing and technological systems with consideration for risk-based thinking, which characterizes quality as a measurable and estimable factor, its indices, existing major categories of quality management, how and when they are applied, as well as their distinctive features.

In the article [16], the proposed approach emphasizes the relevance of the influence of dynamic effects in production systems at the life cycle stages of a complex product. This article introduces the concept of combining LCA and production system modeling, explains the types of models for each methodology, and provides an example of applying the combined methodology to analyze the case of integrating volatile energy sources into production control.

The research [17] addresses the problem of using machine learning methods to provide LCA solutions. The general hypothesis is this: LCA, backed up by machine learning and based on dynamic data, paves the way for a more accurate LCA, supporting decision-making throughout the Favi, C. [18] suggest including TRL and production readiness level (MRL) when evaluating the life cycle of new technologies as an indicator of technology maturity. The research works [19, 20] define the problem of the functionality of the observed system. Thus, the characteristic features of CP are the presence of emergent properties, inherent both to the elements of hierarchical structures of CP, which are diverse in their configurations, and to the processes that accompany them at the stages of CP; the need to take into account the influence of all factors of the external environment on the CP and the system of processes at the stages of the LC, which can change the composition, structure, and condition of the CP, cause deviations from the established requirements. In this regard, this research sets out the task of creating scientifically based bases for making decisions on ensuring compliance with the established requirements of CP in mechanical engineering based on life cycle (LC) management technologies and models of self-coordinated interaction of processes during design, manufacturing, and operation.

3 Research Methodology

Based on the main provisions of the theory of self-organization, the open system of the LC CP is represented by self-consistent nonlinear equations, which allows us to consider possible variants of phase transitions between modes of process implementation during design, manufacture, and operation. According to the synergistic approach, a self-organizing system is defined by self-consistent equations that relate the intensity of execution of the design processes $dF/d\tau$, manufacturing $dG/d\tau$ and operation $dQ/d\tau$ with the values of the functions F, G, Q, which can be considered as a control parameter, conjugate field and synergetic order parameter [21].

The analysis has been made in [22] demonstrations that in the process of the transition between low- and high-performance modes of realization of mutual interaction between the processes of design, manufacturing, and operation of CP for production and technical purpose, the characteristic time τ_Q of the production function change $Q(t)$ has a constant value. Inherently response of the system to the increase of Q can result in a scale increase of τ_Q, which can be represented using approximation [23]:

$$\tau_Q = \tau_0 \left(1 + \frac{k}{1 + \frac{Q^2}{Q_\tau^2}} \right)^{-1}, \tag{1}$$

which is characterized by positive constants of τ_0, k, and Q_τ.

The following expression can represent synergetic potential:

$$V = \frac{Q^2}{2} \left\{ 1 - \frac{F_e}{F_{c0}} \left(\frac{Q}{Q_m} \right)^{-2} \ln \left[1 + \left(\frac{Q}{Q_m} \right)^2 \right] \right\} + \\ + \frac{kQ_\tau^2}{2} \ln \left[1 + \left(\frac{Q}{Q_\tau} \right)^2 \right], \tag{2}$$

where $F_{c0} \equiv (a_Q a_G)^{-1}$.

According to Figure 1, for small values of F_e, the dependence $V(Q)$ has a monotone increasing form (curve 1) with its minimum in point $Q = 0$. This case corresponds to the low-performance realization of mutual interaction between design, manufacturing, and operation processes. In the following case, when the value of

$$F_c^0 = F_{c0} \left[1 + \frac{Q_\tau^2}{Q_m^2}(k-1) + 2\frac{Q_\tau}{Q_m} \sqrt{k \left(1 - \frac{Q_\tau^2}{Q_m^2} \right)} \right], \tag{3}$$

a plateau (curve 2) appears, which becomes transformed into a minimum.

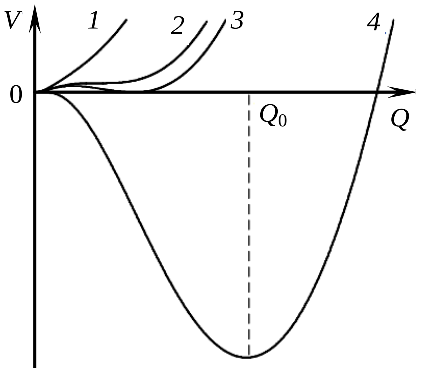

Figure 1 – Form of the dependence of synergetic potential upon the synergetic order parameter under different F_e values: 1 – $F_e < F_C^0$; 2 – $F_e = F_C^0$; 3 – $F_C^0 < F_e < F_C$; 4 – $F_e \geq F_C$

This case corresponds to the value of the production function $Q_0 \neq 0$ (high-performance mode) and maximum (unstable state), which separate minima $Q_0 = 0$, $Q_0 \neq 0$ (curve 3).

With further increasing of F_e level, the minimum high-performance mode of realization deepens, and the height of the barrier, which separates stationary states, drops and reaches zero under the following critical value:

$$F_c = F_{c0}(1+k). \tag{4}$$

If $F_e \geq F_c$ (Figure 1, curve 4), $V(Q)$ dependence has the same form as the analyzed above continuous transition. Stationary values of a production function Q here have the following form (Figure 2):

$$Q_0^{\mp} = Q_{00} \left\{ 1 \mp \left[1 + \left(\frac{Q_m Q_\tau}{Q_{00}^2} \right)^2 \frac{F_e - F_c}{F_{c0}} \right]^{1/2} \right\}^{1/2}, \tag{5}$$

$$Q_{00}^2 \equiv \frac{1}{2} \left[\left(\frac{F_e}{F_{c0}} - 1 \right) Q_m^2 - (1+k) Q_\tau^2 \right]. \tag{6}$$

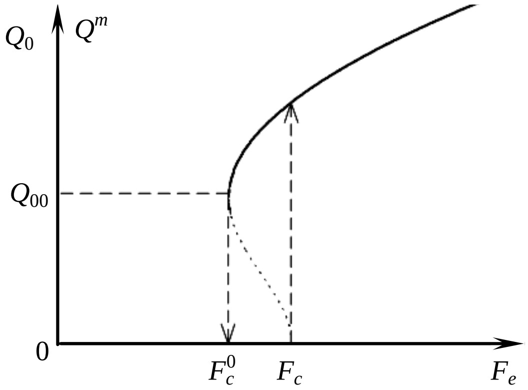

Figure 2 – Dependence of stationary values of the synergetic order parameters upon F_e rating parameter (solid curve corresponds to stable state Q_0, dotted – to unstable state Q_m)

The upper index corresponds to the unstable state Q^m, when synergetic potential reaches maximum, and lower one corresponds to stable state Q_0 in its minimum.

The control parameter

$$F_0 = \frac{(1+Q_{00}^2) - \sqrt{(1+Q_{00}^2)^2 - (1-Q_\tau^2)\dfrac{F_e}{F_{c0}}}}{1-Q_\tau^2} \qquad (7)$$

fall freely with increasing the value

$$F_{c0} = 1 + Q_\tau \sqrt{\frac{k}{1-Q_\tau^2}}\,, \qquad (8)$$

that corresponds to $F_e = F_c^0$ up to F_c under $F_e \to \infty$.

From Figure 2, under free scientific and technological development in point $F_e = F_c$ a sudden change of the stationary value of production function Q_0 from zero up to $\sqrt{2} \cdot Q_{00}$ occurs, and then its value increases freely according to the law (5).

In the inverse case, when F_e decreases, the stationary value of production function Q_0 decreases freely according to the dependence (5) up to the point $F_e = F_c^0$, $Q_0 = Q_{00}$. Then it reaches zero value by sudden change.

The stationary value of the production function F_0 coincides with the level of engineering and design information F_e only within interval $0 < F_e < F_c^0$.

In case when the level of scientific and technological development $F_e > F_c^0$, the production function F_0 becomes double-valued, following the descending curve, which decreases freely from the value F_{c0} (8) under $F_e = F_c^0$condition up to F_c under $F_e \to \infty$ condition.

In case of a free increase of the level of scientific and technological development F_e from 0 up to F_c, the stationary value of the production function F increases linearly within the same interval. After a sudden drop in $F_e = F_c$ The value of F_0 decreases freely according to the dependence (7). In the inverse case, when the level of scientific and technological information F_e decreases, the stationary value of production function F_0 suddenly increases in F_c^0 the point from F_{c0} value up to F_c^0 value.

Thus, we observe hysteresis, which is conditioned by the availability of the barrier for the effective potential (2) and is revealed under $Q_\tau/Q_m < 1$ condition when changing Q and F production functions. The hysteresis loop gets narrow as the rate of non-equilibrium parameter change increases.

4 Results

Measuring Q, G, and F values in such units of measurement $Q_m = (a_G a_F)^{-1/2}$, $G_m \equiv (a_Q^2 a_G a_F)^{-1/2}$, and $F_c \equiv (a_Q a_G)^{-1}$, we are to analyze different boundary relations of the characteristic times τ_0, τ_G, τ_F, as we have already analyzed them for continuous phase transition. Here, the characteristic time τ_Q of the production function change is set by the equation (1). The carried-out investigation shows that Lorentz's combined equations (9)-(11) allow representing principal features of phase transitions between modes of realization of simultaneous functioning of the design, manufacturing, and operation processes (Figure 3).

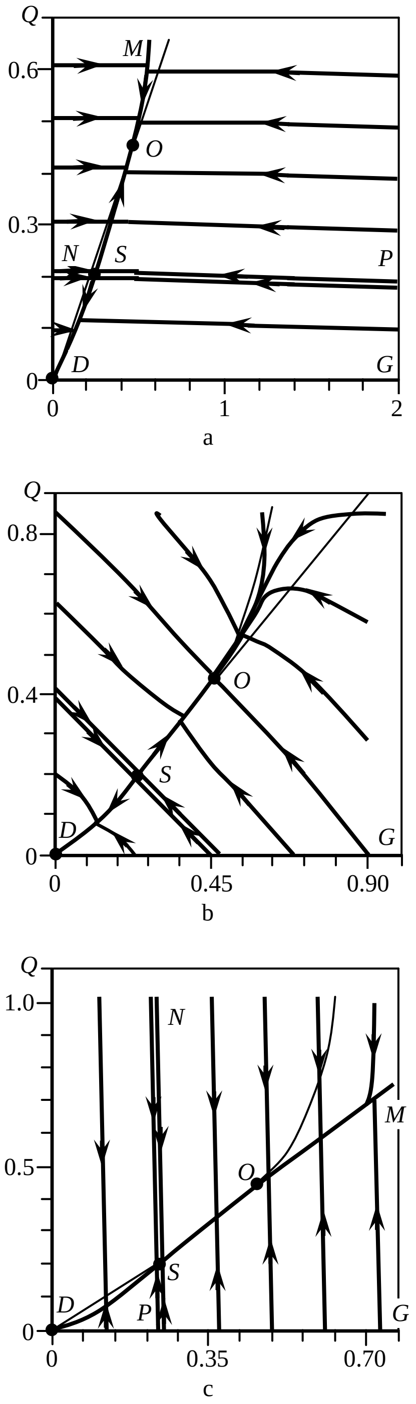

Figure 3 – Phase portraits of discontinuous transition (k = 1, $Q_\tau = 0.1Q_c$, $F_e = 1.25F_c$): a – $\tau_F << \tau_0 = 100\tau_G$; b – $\tau_F << \tau_0 = \tau_G$; c – $\tau_F << \tau_G = 10^2\tau_0$

According to phase portraits of discontinuous transition (Figure 3), at $F_e = F_c^0$ bifurcation takes place, and there appears a saddle S corresponding to the energy barrier on $V(Q)$ dependence and attracting vertex/focus O, which characterizes the high-performance mode of realization because of bifurcation. At that, attracting vertex D, which again corresponds to low-performance mode, remains changeless. With increasing of control parameter within the interval (F_c^0, F_c), a saddle S shifts to vertex D assimilating it in point F_c, and vertex/focus O

shifts towards increasing synergetic order parameter and conjugate field. The type of singular point *O*, which corresponds to a high-performance mode of the system of joint functioning of the design, manufacturing, and operation processes, depends upon the relation of characteristic times τ_Q, τ_G, and τ_F.

We consider the time of change τ_0, which belongs to dependence (1), as the value of change of production function of operation functional subsystem τ_Q for discontinuous transition [7]. If values τ_Q, τ_G, and τ_F are not equal, we can distinguish six specific modes [8]:

$$\begin{aligned} &a)\, t_G << t_F << t_Q; \quad d)\, t_F << t_Q << t_G; \\ &b)\, t_Q << t_F << t_G; \quad e)\, t_G << t_Q << t_F; \\ &c)\, t_F << t_G << t_Q; \quad f)\, t_Q << t_G << t_F . \end{aligned} \tag{9}$$

As the carried-out analysis shows, in cases (9 a-d), point *O* is an attractive vertex. In a short time, the trajectory of the system of joint functioning of the design, manufacturing, and operation processes exits onto a universal area ("stream of a big river"), which location is determined by external conditions (by the value of F_e). The availability of such an area causes the universal character of the system's evolution. In the given phase portraits "stream of a big river" is represented in parametric space *Q*, *G*, and *F* in such a way that when projecting onto planes *F-Q*, *F-G*, it has a form of monotonously falling curve of *MOD-type* [9] or *MOS-type* (discontinuous transition).

Projection onto plane *G-Q* is close to bisectrix (Figure 3a). Universal area *NSP*, which corresponds to the system's transition over the energy barrier, occurs in case of discontinuous transition (Figure 3). The presented phase portraits let us see that for the modes (9 a-d), exit to universal area occurs along almost linear paths, practically parallel to axes, corresponding to minimum relaxation time. Thus, in mode (9 a), the point moves rapidly in the beginning along the straight line parallel to the *G*-axis, then it shifts onto the segment parallel to the *F*-axis and moves along it with speed τ_F/τ_G times less than before, but τ_Q/τ_F times higher than the speed of further moving within the universal area. After this, the shift onto the "stream of a big river" occurs.

For relations of relaxation times, which characterize cases (9 e-f), the system gets decaying oscillations within the plane corresponding to two maximum values of these times. For both cases, the characteristic time of change of the control parameter (F) has the most significant value. Critical increasing of times τ_Q, τ_G in compliance with relations of the type $\tau_Q/(F_e - F_c)$, $\tau_G/(F_e - F_c)$ is a cause of oscillation origination. Near to critical point F_c, it secures parity of values $\tau_Q|F_e - F_c|^{-1}$ and τ_F (in case (9 e)), as well as $\tau_G|F_e - F_c|^{-1}$ and τ_F (in case (9 f)), in consequence of that relation between respective values *Q*, *F* and *G*, *F* gets resonance character. As to evolution along *G* and *Q* axes, which correspond to minimum times in cases (9 e-f), it preserves the same character, as for transition to universal mode: the system with speed τ_F/τ_G and τ_F/τ_Q times higher than oscillation frequency, (cases (9 e) and (9 f), respectively), shifts to the corresponding plane along the perpendicular axis.

In the general case, the kinetic pattern of transition from a low-performance state of the system of joint functioning of the design, manufacturing, and operation processes to a high-performance one is defined by a set of three synergetic and kinetic parameters. The key role in the first group belongs to the external factor (level of engineering and design provision) F_e, which relates to critical value F_c defines the type of the system state (Figure 3).

Two other synergetic parameters (k and $Q_1 \equiv Q_\tau/Q_c$), which values are set by law (1) of dispersion of change time of production function *Q*, define the area of discontinuous transition. It is limited by minimum value $k = Q_1^2/(1 - Q_1^2)$, moving away from, which increases this area. Characteristic of discontinuous transition lies in the fact that separatrix appears in phase portrait, and the availability of separatrix results in the critical dependence of the system evolution upon the choice of its initial state.

Characteristic times τ_0, τ_G, τ_F of changes of functions *Q*, *G*, and *F* in independent modes are kinetic parameters that define the system behavior. The carried-out investigations show that the universal representation of the evolution of the system of joint functioning of the design, manufacturing, and operation processes realizes if the last of the abovementioned times get the minimum value. At that, the system for a short time τ_F exits onto universal area *MOS* (Figure 3), which position depends only upon synergetic parameters but not upon the relation of scales τ_0, τ_G, τ_F. Such a situation is realized for the high-performance mode of realization of the system of joint functioning of the design, manufacturing, and operation processes. Under the anomalous increasing of times of change of function *F*, twisting of phase portraits takes place near the high-performance mode of realization, obtained through a series of drops and jumps.

Moreover, under $\tau_G \sim \tau_Q << \tau_F$ condition, when the level of scientific and technical development gets overcritical value $(F_e - F_c) \sim \tau_Q/\tau_F \sim \tau_G/\tau_F << 1$ the system of joint functioning of the design, manufacturing, and operation processes shifts to the mode of strange attractor, where evolution becomes unpredictable. This is evidence of the extreme risk of regulation of the level of engineering and design provision under the conditions of self-consistent development of the system of joint functioning of the design, manufacturing, and operation processes.

5 Discussion

The large-scale behavior of the life cycle and CP depends on a specific case, and a lower impact on the environment at the advanced technological stage cannot be taken for granted. In addition, the consequences of a scaled life cycle system are not often compared with the consequences of a mature alternative technology. In addition, there is still no formal and strict definition of a complex or large technical system. Based on the content analysis results, we identified the following four challenges: comparability, scaling issues, data availability, and uncertainty. However, we included the scaling issue in the data call because scaling is required to create inventory data for a scaled product system.

6 Conclusions

Based on models of production functions, a method of evaluating the effectiveness of the compatible interaction of functional subsystems (design, manufacturing, and operation) is proposed, each of which can have an independent nature of applying its results in the life cycle stages. Application of a choice model of effective modes of realization of mutual interaction between functional subsystems allows estimation of each variant of CP design from the point of view of expenditures for its design, manufacturing, and operation.

One can choose the most optimal from the market standpoint by analyzing the advantages and disadvantages of these variants. The joint functioning of the design, manufacturing, and operation processes can be represented as an open interaction system between corresponding functional subsystems. Each of them can have an independent pattern of use of the results.

Integration into the general system provides a new qualitative sense, combination of characteristics and degree of utility of machine-building products, and improves technical and economic indices when designing and manufacturing.

Modes of the system realization are defined by a combination of conditions and means of many economic, technical, and social processes, which are unequally influenced by the external environment and have various persistence levels.

7 Acknowledgments

The research presented in this paper was supported by the international grant project Jean Monnet Actions under ERASMUS+ Programme ERASMUS-JMO-2021-HEI-TCH-RSCH EUGreeCon – 101047527.

References

1. Zaloga, V., Dyadyura, K., Rybalka, I., Pandova, I. (2019). Implementation of integrated management system in order to enhance equipment efficiency. *Management Systems in Production Engineering*, Vol. 27(4), pp. 221-226.
2. Zaloga, V., Dyadyura, K., Rybalka, I., Pandova, I., Zaborowski, T. (2020). Enhancing efficiency by implementation of integrated management system in order to align organisational culture and daily practice. *Management Systems in Production Engineering*, Vol. 28(4), pp. 304-311.
3. ISO 9001:2015 Quality Management Systems – Requirements.
4. ISO/TS 9002:2016 Quality Management Systems – Guidelines for the Application of ISO 9001:2015.
5. ISO 14044:2006 Environmental Management – Life Cycle Assessment – Requirements and Guidelines.
6. Krenicky, T., Hrebenyk, L., Chernobrovchenko, V. (2022). Application of concepts of the analytic hierarchy process in decision-making. *Management Systems in Production Engineering*, Vol. 30(4), pp. 304-310.
7. Dyadyura, K., Hovorun, T.P., Pylypenko, O.V., Hovorun, M.V., Pererva, V.I. (2017). Influence of roughness of the substrate on the structure and mechanical properties of TiAlN nanocoating condensed by DCMS. *Proceedings of the 2017 IEEE 7th International Conference on Nanomaterials: Applications and Properties, NAP 2017*, 01FNC10.
8. Sukhodub, L.F., Dyadyura, K. (2018). Design and fabrication of polymer-ceramic nanocomposites materials for bone tissue engineering. *Journal of Nano- and Electronic Physics*, Vol. 10(6), 06003.
9. Blind, K., Von Laer, M. (2022). Paving the path: Drivers of standardization participation at ISO. *J Technol Transf*, Vol. 47, pp. 1115-1134.
10. Jemghili, R., Ait Taleb, A. Mansouri, K. (2023). A collaborative multidisciplinary design methodology for additive manufacturing with a left-handed mouse as a case study. *Int J Adv Manuf Technol*, Vol. 125, pp. 4925-4951).
11. Santolaya, J.L., Lacasa, E., Biedermann, A. et al. (2019). A practical methodology to project the design of more sustainable products in the production stage. *Res Eng Design*, Vol. 30, pp. 539-558.
12. Ghoroghi, A., Rezgui, Y., Petri, I. et al. Advances in application of machine learning to life cycle assessment: A literature review. *Int J Life Cycle Assess*, Vol. 27, pp. 433-456.
13. França, W.T., Barros, M.V., Salvador, R. et al. (2021). Integrating life cycle assessment and life cycle cost: A review of environmental-economic studies. *Int J Life Cycle Assess*, Vol. 26, pp. 244-274.
14. King, C.W. (2022). Interdependence of growth, structure, size and resource consumption during an economic growth cycle. *Biophys Econ Sust*., Vol. 7, 1.
15. Malik, A.I., Kim, B.S. (2021). Coordination supply chain management under flexible cleaner production system and stochastic conditions. *Ann Oper Res*, Vol. 21, https://doi.org/10.1007/s10479-021-04303-w
16. Sadler, H. (2020). ER^{2}C SDMLC: Enterprise release risk-centric systems development and maintenance life cycle. *Software Qual J.*, Vol. 28, pp. 1755-1787.

17. Priarone, P.C., Catalano, A.R. Settineri, L. (2023). Additive manufacturing for the automotive industry: On the life-cycle environmental implications of material substitution and light-weighting through re-design. *Prog Addit Manuf*, https://doi.org/10.1007/s40964-023-00395-x
18. Favi, C., Campi, F. Germani, M. (2019). Comparative life cycle assessment of metal arc welding technologies by using engineering design documentation. *Int J Life Cycle Assess.*, Vol. 24, pp. 2140-2172.
19. Yanıkoğlu, İ., Albey, E., Okçuoğlu, S. (2022). Robust parameter design and optimization for quality engineering. *Oper. Res. Forum*, Vol. 3, 8 (2022).
20. Siran, K.C., Dipendra, G. (2021). Progress in sustainable structural engineering: a review. *Innov. Infra-struct. Solut*., Vol. 6, 68.
21. Dyadyura, K., Hrebenyk, L., Krenicky, T., Zaborowski, T. (2021). Modeling of the manufacturing systems state in the conditions of the lean production. *MM Science Journal*, Vol. 2021(June), pp. 4408-4413.
22. Cao, Y., Liu, Y., Ye, X. et al. (2020). Software-physical synergetic design methodology of mechatronic systems based on formal functional models. *Res Eng Design*, Vol. 31, pp. 235-255.
23. Zhang, X., Dong, S. (2019). Analysis on supply-demand system of automotive manufacturer-supplier with synergetics. *Cluster Comput*., Vol. 22(3), pp. 6817-6826.