Management of enterprise cyberphysical systems sustainable development while undergoing a digital transformation

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Abstract. The paper considers the sustainability of the digital and industrial technologies interaction. Based on the analysis of existing studies on the introduction of innovative digital technologies and cyber-physical systems, it was realized that in the conditions of intelligent technologies joint implementation unstable states of the system are inevitable, and continuously monitoring of the system sustainability is essential. The expediency of applying the laws of the theory of open systems proposed by L. von Bertalanffy, A. Hall, and others to substantiate the managing sustainability appropriateness of the enterprise cyber-physical system is given. The quantitative estimates based on the information approach of A.A. Denisov are proposed, which allow to assess the degree of system’s integrity. System’s integrity degree ensures sustainability of a system, on the other hand, freedom of system’s elements ensures the system development. The proposed estimates can be used for accessing the influence of digital technologies on the implementation enterprise strategy, ensuring the effectiveness of its development and increasing competitiveness based on the digitalization of production and management while maintaining stable functioning.

1. Introduction
The purpose of the work is to develop a method for sustainability assessment of the cyberphysical system (CPS) in the implementation of digital technologies in industrial enterprise. In this paper the CPS is understood as a combination of control system and techniques of a new generation, that help enterprises to create advanced modern products with the use of the information technologies’ possibilities.

The subject of the study is the methods for sustainability assessment of the enterprise in the introduction of digital technologies.

In accordance with Industry 4.0 conception a large-scale introduction of CPSs into factory processes is planned. CPSs imply a completely synergistic integration of computing and control with physical devices and processes [1]. Moreover, the introduction of a CSP into the enterprise’s automated systems will help to combine automated process control, automated production and enterprise management in general, and will help to create a manageable system, from order to implementation.

According to the ideologist of the Fourth industrial revolution, K. Schwab, “Technologies will help find a solution to many of the problems that we face today, but they will exacerbate some of these
problems” [2]. K. Schwab predicts that initially innovative digital technologies can be used separately, but “there will soon come a turning point when they begin to develop, overlapping and reinforcing each other, representing the technologies interweaving from the world of physics, biology and digital realities” [3].

Under these conditions, the technical and industrial complexes behavior becomes similar to the behavior of open systems with active elements, which, in accordance with the concept of L. von Bertalanffy [4], seek to be in a mobile equilibrium state.

Therefore, it becomes important to propose methods for studying the state of modern technical systems as open systems with active elements and to develop methods and techniques for controlling the industrial complexes’ state. Moreover, it is necessary to develop a sustainability theory and controllability of such systems.

In the automatic control theory sustainability criteria for “closed” technical systems have been developed. In this paper it is proposed to supplement these criteria with new ones. That could be done on the basis of the sustainability theory principles, on the basis of the theory of open systems laws, which allows us to refine the open systems sustainability assessment in the state of “mobile equilibrium” (dynamic equilibrium) (according to L. von Bertalanffy [4, 15]) or fundamental nonequilibrium (according to E. Bauer [16]). To characterize this state, the “sustainable development” concept was introduced.

2. Materials and methods

2.1. Methods of the automatic control theory and the possibility of using them in the field of technologies’ management

At the first stage of the work the methods proposed in the theory of automatic control and their capabilities were studied.

2.1.1. The ideas the Lyapunov’s stability theory of dynamical systems

The foundations of a rigorous dynamical systems’ stability theory were developed by Aleksandr M. Lyapunov.

The solution $x^*(t)$ of the system of differential equations $\dot{x} = Ax + Bu$ with the initial conditions $x(0) = x_0$ is Lyapunov stable if for any $\epsilon > 0$ there exists $\delta = \delta(\epsilon) > 0$ such that if $||x(t_0) - x^*(t_0)|| < \delta$, then $||x(t) - x^*(t)|| < \epsilon$ for all $t \geq 0$.

The solution $x^*(t)$ of the system $\dot{x} = Ax + Bu$ is asymptotically stable if it is Lyapunov stable and the condition:

$$\lim_{t \to \infty} ||x(t) - x^*(t)|| = 0$$

under the condition $||x(0) - x^*(0)|| < \delta$.

In this case, all solutions close enough to $x^*(0)$ at the initial instant of time gradually converge to $x^*(t)$ with increasing $t$.

If the solution $x^*(t)$ is asymptotically stable and, moreover, from the condition $||x(0) - x^*(0)|| < \delta$ implies that $||x(t) - x^*(t)|| \leq \alpha ||x(0) - x^*(0)|| e^{-\beta t}$ for all $t \geq 0$, then the solution $x^*(t)$ is exponentially stable. In this case, all solutions close to $x^*(0)$ at the initial moment converge to $x^*(t)$ with a speed (greater than or equal to), which is determined by an exponential function with parameters $\alpha, \beta$ [5].

The Lyapunov condition for stability of systems is formulated as follows: “in a stable system, the free component of the solution of the dynamics equation written in deviations should tend to zero, that is, decay” [6]. This implies the stability condition for linear dynamical systems: a linear system will be stable if all real roots and all real parts of the complex roots of the characteristic equation corresponding to the original differential equation of free system motion are negative, which gives exponentially decaying solutions [7].
2.1.2. The criteria of Routh and Hurwitz

The necessary and sufficient conditions for stability are given by the algebraic criteria of Routh and Hurwitz, which are a mathematical expression of the necessary and sufficient conditions for the negativity of the real parts of the equation roots of the nth degree with constant real coefficients [8]:

\[ D(\lambda) = a_0 \lambda^n + a_1 \lambda^{n-1} \ldots + a_{n-1} + a_n = 0. \] (1)

According to Routh, first the coefficients \( a_i \) are written in the form of a table:

\[
\begin{array}{cccc}
\lambda^n & a_n & a_{n-2} & a_{n-4} & a_{n-8} & \ldots \\
\lambda^{n-1} & a_{n-1} & a_{n-3} & a_{n-5} & a_{n-7} \\
\lambda^{n-2} & b_1 & b_2 & b_3 \\
\lambda^{n-3} & c_1 & c_2 & c_3 \\
\lambda^{n-4} & d_1 & d_2 \\
\end{array}
\]

Coefficients \( b_i, c_i, \) etc. the following lines are determined through the coefficients of the two previous ones:

\[
\begin{align*}
 b_1 &= (a_{n-1}a_{n-2} - a_0a_{n-3})/a_{n-1}, \\
 b_2 &= (a_{n-1}a_{n-4} - a_0a_{n-5})/a_{n-1}, \\
 c_1 &= (b_1a_{n-3} - a_{n-1}b_2)/b_1, \\
 d_1 &= (c_1b_2 - b_1c_3)/c_1.
\end{align*}
\]

New rows are added to the table in the same way up to \( n+1 \) rows. When the table is fully defined, the number of zeros \( D(\lambda) \) with positive real parts is determined by the number of changes in the signs of the coefficients in the first column of the table.

For polynomials of the third and fourth orders, the stability requirements are as follows. For a cubic equation of the form \( a_3 \lambda^3 + a_2 \lambda^2 + a_1 \lambda + a_0 = 0 \), the requirement that there are no roots in the right half-plane are as follows [9]:

1) All coefficients are of the same sign and are not equal to zero;
2) \( a_1a_2 - a_0a_3 > 0 \).

For equations of the fourth degree of the form \( a_4 \lambda^4 + a_3 \lambda^3 + a_2 \lambda^2 + a_1 \lambda + a_0 = 0 \), the roots in the right half-plane will be absent when:

1) All coefficients have the same sign and are not equal to zero;
2) \( a_1(a_3a_2 - a_0a_4) - a_3^2a_0 > 0 \).

The Routh method is complicated enough to remember and use. The Hurwitz criterion was presented in a more convenient form for practitioners.

The Hurwitz theorem is formulated as follows: in order for all the roots of the characteristic equation to have negative real parts, it is necessary and sufficient that the condition for the non-negativity of diagonal minors is satisfied [10]: \( \Delta_k > 0, \ k = (1, n) \).

\[
M = \begin{bmatrix}
\alpha_1 & \alpha_0 & 0 & \ldots & 0 \\
\alpha_3 & \alpha_2 & \alpha_1 & \ldots & 0 \\
\alpha_5 & \alpha_4 & \alpha_3 & \ldots & 0 \\
\ldots & \ldots & \ldots & \ldots & \ldots \\
0 & 0 & 0 & \ldots & \alpha_n
\end{bmatrix}, \quad \Delta_1 = \alpha_1, \quad \Delta_2 = \begin{bmatrix}
\alpha_1 & \alpha_0 \\
\alpha_3 & \alpha_2
\end{bmatrix}, \\
\Delta_3 = \begin{bmatrix}
\alpha_1 & \alpha_0 \\
\alpha_3 & \alpha_2
\end{bmatrix} \quad \ldots \quad \Delta_n = a_n \Delta_{n-1} = |M|.
\] (2)
The determinant $\Delta_i$ is constructed so that its first element is always $a_i$, the indices in each row successively increase by “2”, and in each column decrease by “1”, and $a_k$ is assumed to be zero if $k > 0$ or $k > n$.

Hurwitz conditions for high order determinants involve a large number of calculations. Therefore, various rules were proposed that simplified the application of this criterion - the Stodola condition, the Lienard-Shipar criteria, and others.

At present, it is customary to talk about the considered conditions as algebraic Routh – Hurwitz criteria. The Hurwitz criterion is conveniently applied to equations of no higher than 4th degree. With the use of computer technology, the possibilities of using this criterion are expanded. However, when using computers, the algorithmic form of the Routh criterion is considered more economical.

2.1.3. Analysing possibility of using the classical automatic control theory methods in the field of modern technology management

However, when the order of the characteristic equation is high, the algebraic stability criteria do not make it possible to establish the influence degree of individual parameters on stability and to receive recommendations on the choice of these parameters.

In this regard, in the thirties of the 20th century the more suitable for engineering research criteria were developed. These criteria are based on graph-analytical methods using frequency characteristics, and namely these are criteria of G. Nyquist [11] and A.V. Mikhailov [12].

Nevertheless, all the discussed methods and criteria are insufficient to manage complex technical systems, such as CPSs, and communication networks. Therefore, there is a need to develop new approaches and methods for estimating sustainability technical systems. These methods should take into account the fact that any complex technical system demonstrates the open system qualities. In particular, the methods should allow accessing the influence of digital technologies on the implementation enterprise strategy.

2.2. Features of the cyberphysical system as an open system

To create a CPS, it is necessary to select and implement digital technologies. However, the innovations are introduced not one at a time, but together with other technologies, because of that processes “layering” of technologies occurs (in other words the cumulative effect of technology implementation is lost). On the other hand, the combination of technologies leads to an “emergent effect”, and modern technologies in foreign works are often called “emergent technologies”.

Since parts of a CPS continuously exchange information with computing platforms, sensors, network structure, and operators, such system is considered to be an “open system”. Thus, the functioning of CPSs becomes even closer to living, open systems with active elements [4, 15], and there is a need to develop a theory of sustainable development of such systems.

A study of L. von Bertalanffy showed that an open system, in contrast to a closed (isolated) system, under certain conditions reaches a state of “mobile equilibrium”, in which its structure remains constant. But unlike ordinary equilibrium, this constancy is maintained in the process of continuous exchange and movement of matter [15].

At the same time, when studying the differences between living, developing objects and non-living ones, the biologist Erwin Bauer hypothesized that living is fundamentally in an unstable, nonequilibrium state and, moreover, a living system uses its energy to maintain itself in a nonequilibrium state (which is life itself). In this case, problems of maintaining the sustainability of the system arise [16].

Consequently, the approach to the CPSs management proposed in this paper is based on the theory of open systems developed by L. von Bertalanffy and its development in the works of several authors [4, 13, 14].
2.3. The development of the sustainability theory methods on the basis of the open systems’ laws functioning and the A.A. Denisov information approach

Based on his research, L. von Bertalanffy actually proposed a new law, which in open systems with active elements contradicts the second law of thermodynamics, which is extended by physicists to all systems.

The ability to withstand entropy (destroying the system) tendencies and manifest non-entropic tendencies is due to the presence of active elements that stimulate the exchange of material, energy and information products with the environment and display their own “initiatives”, an active principle. Owing to this, in such systems the law of increasing entropy is violated (analogous to the second law of thermodynamics, which operates in closed systems, the so-called “second law”), and non-entropic tendencies appear.

When studying entropy-non-entropy processes, it is important to take into account the laws of system theory, which allow one to evaluate the degree of manifestation of entropy and non-entropy tendencies in the system.

On the one hand, non-entropic tendencies realized in the form of innovations are the basis of development, but at the same time they destabilize the system and introduce instability, that is, disorder. And the entropy trends, considered as a manifestation of disorder, on the contrary, stabilize the state of the system, since the minimum energy state to which the entropy processes lead is the most stable.

Studies conducted in the field of innovation theory have shown that any innovation disrupts the normal functioning of enterprises and organizations, creates a situation of “creative destruction” (according to J. Schumpeter [13] and V. Zombart [14]) or “breakthrough innovations” according to K. Christensen [17].

Research of the features and patterns of open systems helps to understand these contradictions.

Studies of the properties of open systems with active elements, conducted by philosophers, psychologists, and specialists in system theory, have shown [18] that such systems have the ability to adapt to changing environmental conditions; they are characterized by a fundamental disequilibrium, the ability to withstand entropy (destroying the system) tendencies and manifest non-entropy tendencies; the ability to develop behaviors and change their structure, uniqueness. However, these useful properties that bring them closer to living organisms at the same time lead to instability and unpredictability of the behavior of the system in specific conditions, etc.

The laws of system theory help to understand these contradictions, allow us to assess the degree of manifestation of entropy and non-entropy trends in the system.

Thus, the regularity of integrity (emergence) leads to the appearance in the system of new properties that the elements did not have [18], while the properties of the system are not a simple sum of the properties of its constituent elements (parts) $q_i$:

$$Q_s \neq \sum_{i=1}^{n} q_i;$$  \hspace{1cm} (3)

At the same time, the elements integrated into the system lose some of their properties that are inherent to them outside the system, that is, the system seems to suppress a number of element properties; but, on the other hand, elements that fall into the system can acquire new properties.

If $a_i \in S \Rightarrow q_i \downarrow$ and $q_i' \uparrow$.

Regularity of additivity or sustainability characterizes the decay of the system into parts, i.e.

$$Q_s = \sum_{i=1}^{n} q_i.$$  \hspace{1cm} (4)

The regularity of hierarchical or hierarchical ordering leads to an intensification of the process of emergence of new, including unpredictable and uncontrollable properties of any system, society.

A higher hierarchical level exerts a guiding effect on the underlying level subordinate to it, and this effect is manifested in the fact that subordinate members of the hierarchy acquire new properties that they did not have in an isolated state (confirmation of the position on the influence of the whole on the
elements given above), and in as a result of the appearance of these properties, a new, different “appearance of the whole” is formed (the influence of the properties of elements on the whole). The new whole that has arisen in this way acquires the ability to carry out new functions, which is the goal of the formation of hierarchies.

Hall and D. Fagin [19], studying the processes in the “Bell telephone lines” company, realized that no real complex system (including a technical one) can exist as absolutely integral and stable and is in a certain state called L. von Bertalanffy, a state of mobile equilibrium. A. Hall proposed the qualitative characteristics of this state, which he called progressive factorization – the desire of the system for a state with increasingly independent elements, and progressive systematization – the desire of the system to reduce the independence of the elements, i.e. to greater integrity.

Based on the research of A. Hall and the information approach of A.A. Denisov introduced comparative quantitative estimates of the degree of integrity α and the coefficient of utilization of the properties of elements as a whole, i.e. freedom of elements β in the manifestation of their properties [20],

\[ \alpha = -C_m/C_i \]
\[ \beta = C_s/C_i \]

where \( C_s, C_i \) and \( C_m \) are systemic, internal and mutual informational complexity:

\[ C_s = C_i + C_m; \]
\[ C = J \cap H, \]

where \( J \) is perception information; \( H \) – informational entity (potential); \( J \) and \( H \) can be measured probabilistically and deterministically [20].

A.A. Denisov showed that any developing system is, as a rule, between the state of absolute integrity and absolute additivity, and the distinguished state of the system (its “slice”) can be characterized by the degree of manifestation of one of these properties or the tendency to increase or decrease. Moreover, integrity ensures sustainability, and increasing the integrity of the system should increase the efficiency of the existence and sustainability of the system.

\[ \alpha + \beta = 1. \] (6)

Studies of the processes of part and the whole interaction in the system showed that the effectiveness of the functioning of the system first increases with the degree of regulation (degree of integrity), and when excessive regulation begins to decrease, initiatives (negentropic trends) that contribute to the development of the system are suppressed, and this negatively affects the efficiency growth of the system, reduces the safety of its functioning and in the future may lead to the death of the system.

Based on the study of entropy-non-entropy processes, A. Hall showed that factorization can be of two types:

1) the destruction of the system (wear, aging);
2) development of a system based on the delineation of functions based on the introduction of new technologies and the formation of new subsystems.

For example, there is a system of equations:

\[ a_1 x_1 + a_2 x_2 = c_1 \]
\[ b_1 x_1 + b_2 x_2 = c_2. \] (7)

The reciprocal or “portable” terms \( a_1 \) and \( b_1 \) are assumed to be functions of time. If these terms decrease, tending to zero, that is, \( a_2 \to 0 \) and \( b_1 \to 0 \), then in the end we get two independent systems represented by the above equations, and the surrounding system consisting of two Equations (7) will become “factorized”.

Based on the information approach of A.A. Denisov and by the analogy with Equations (7), we can propose the following criterion for assessing the preservation of the integrity of the technical system.
3. Results

In this paper a method for assessment CPS sustainability was proposed. For implementing this method CPSs were considered as open systems with active elements.

Firstly, the methods proposed in the theory of automatic control and their capabilities were analyzed and it was shown that the algebraic stability criteria of A. M. Lyapunov, Routh and Hurwitz do not make it possible to establish the influence degree of individual parameters on stability. The criteria proposed by G. Nyquist and A.V. Mikhailov also are insufficient in complex technical systems’ management.

On the next stage a new approach was developed. This approach to estimating technical systems’ sustainability takes into account the fact that a complex technical system demonstrates the open system qualities. Therefore, the proposed approach is passed on the sustainability theory principles, on the theory of open systems law and on the information approach of A.A. Denisov.

The use of Denisov’s information approach allows to form different types of models for estimating technical systems’ sustainability. These models use the concept of ”information potential” ($H_i$), and the most simplest type of model has a form:

$$H_i = - q_i \log (1 - p'_i),$$  \hspace{1cm} (8)

where $H_i$ is information potential of the $i$-th criterion (the $i$-th element of a system, etc.), bit; $p'_i$ is probability of achieving the goal when using the $i$-th criterion (the $i$-th element), $0 \leq p'_i < 1$; $q_i$ – probability of using the $i$-th criterion (the $i$-th element) to achieve the appropriate goal (the enterprise management goal), $0 \leq q_i \leq 1$. In accordance with the Denisov’s informational approach, for each criterion experts evaluate the degree of satisfaction (i.e. the probability of achieving the goal – $p'_i$) and the probability of using the criterion ($q_i$). With these two probabilities the information potential (i.e. significance) of the criterion can be calculated [20].

For evaluating the CPSs components influence on each other was proposed another model based on the Denisov’s approach. In that model the composition of the system and the interaction of its components is displayed using the following system of equations:

$$H_1 = f(H_{11}, H_{12}, H_{13}, ..., H_{1j});$$
$$H_2 = f(H_{21}, H_{22}, H_{23}, ..., H_{2j});$$
$$H_3 = f(H_{31}, H_{32}, H_{33}, ..., H_{3j});$$
$$...;$$
$$H_i = f(H_{ii}, ..., H_{ij}),$$

where $H_{ij}$ is the value of $i$-th technology component for the CPS development; $H_{ij}$ is the value of the relations between the $i$-th technology component and $j$-th technology component (mutual influence); $i = 1, ..., n$, $j = 1, ..., n$.

The set of Equations (9) reflects the interconnectedness and interdependence of all elements of the information model.

To assess the sustainability of the system, it is enough to imagine the mutual influence of technologies in the form of a matrix:

$$
egin{bmatrix}
H_{11}, H_{12}, ..., H_{ij}, ..., H_{in} \\
H_{21}, H_{22}, ..., H_{ij}, ..., H_{in} \\
... \\
H_{n1}, H_{n2}, ..., H_{ij}, ..., H_{nn}
\end{bmatrix},
$$

(10)

where $i = 1, ..., n$, $j = 1, ..., n$,

in general, this matrix can be represented as

$$
\Delta_i = \begin{bmatrix} H_{ii} & H_{ij} \\ \end{bmatrix}
$$
If $H_0$ increases, then there is a tendency to gradual systematization, i.e. striving for greater integrity, and, consequently, sustainability of the system. And if $H_0$ decreases, then there is a tendency of progressive factorization, i.e. to system instability.

In the particular case, Equations (9) can be replaced by linear equations similar to Equation (10):

$$H_1 = H_{11} + H_{12} + H_{13} + ...;$$
$$H_2 = H_{21} + H_{22} + H_{23} + ...;$$
$$H_3 = H_{31} + H_{32} + H_{33} + ....$$

(11)

Relations (11) can be used as the means of interviewing experts or to obtain estimates of $H$ using some characteristics introduced for specific situations.

In this case, it is possible to quantify the changes in the significance of the CPS components when interacting with others.

4. Discussion
Following the above-mentioned statements, it can be concluded that when managing enterprises’ CPSs, it is advisable to complement the methods developed in the theory of automatic control with the methods for ensuring sustainability.

The methods proposed in the paper are based on the laws of open systems proposed by L. von Bertalanffy [4, 5], A. Hall [19], quantitative estimates based on the information approach of A.A. Denisov [20], which make it possible to evaluate the degree of integrity, which ensures the system sustainability, and the freedom of its elements, ensuring the system development.

A criterion for assessing the desire of the system for progressive factorization or progressive systematization, i.e. to decay or integrity, which is a definite contribution to the existing theory of sustainability.

These results should be taken into account when developing models for managing the sustainable development of systems, which is especially important when introducing digital technologies and CPSs developing (for example, [21–24]).

In the future, it is planned to study the components of the system from the point of view of their activity and interaction with the environment, which introduces significant instability in enterprises functioning when introducing the digital technologies.

5. Conclusion
In the paper methods based on the laws of open systems and the information approach are proposed. The developed methods allow ensuring the effectiveness of enterprise management and increasing enterprise competitiveness while undergoing a digital transformation.

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