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Integrated Estimation of a Cyber-Physical System's Sustainability

Elena Schislyaeva [1], Elena Balashova [2], Inna Krasovskaya [1], Olga Saychenko [1] and Elena Palkina [2,*]

[1] Department of International Economic Relations, State Marine Technical University, 190121 St. Petersburg, Russia; schislyaeva@corp.smtu.ru (E.S.); krasovskaya_inna@list.ru (I.K.); saychenko@corp.smtu.ru (O.S.)
[2] Department of Innovation Economics, State Marine Technical University, 190121 St. Petersburg, Russia; elenabalashova@mail.ru
* Correspondence: elena_palkina@hotmail.com; Tel.: +7-812-757-17-11

Abstract: Currently, in conditions of Industry 4.0, the use of cyber-physical systems in various fields is becoming widespread. This article is devoted to the problem of estimating CPS sustainability in the context of modern challenges faced by decision makers and IT developers in order to ensure effective proactive business process management using this innovative technology. The purpose of the research is to propose and substantiate a methodology for estimating CPS sustainability to ensure the reliability and strength of its elements, their interrelationships and interaction, as well as the effective functioning and development of this system in conditions of high dynamism and uncertainty of the external environment. In this study, we used methods of integral evaluation, synthesis, expert assessments, dynamic analysis, and systematic approach, and coined the term 'CPS sustainability'. Our study showed that negative risks, external and internal threats may have a significant adverse impact on CPS sustainability. The reliability of this system should be evaluated on the basis of integrated indicators. The key indicators, reflecting the reliability of maintaining the properties of the CPS in a normal state of its function and further development, were identified. We propose a methodology for estimating CPS sustainability. In general, the presented results form the basis for improving CPS management to increase the effectiveness and efficiency of its functioning and development.

Keywords: cyber-physical system; effectiveness; integrated estimation; key-point indicators; sustainability

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1. Introduction

At the present time, many countries all over the world in their competition for leadership in the global market are trying to implement new approaches to the organization of production, which are covered by the concept of Industry 4.0. The information and technological basis of modern manufacturing in the framework of the fourth industrial revolution includes cyber-physical systems, which are widely used in various fields of activity and play a significant role in the development of the digital economy. Undoubtedly, the main field of application of these technologies is industrial production. An innovative enterprise, such as a Smart Factory, is a digital ecosystem in which physical processes are integrated into a common unified information space, that is, product lifecycle management is automated; efficient use of big data is ensured; production processes are optimally built; computing systems are integrated into production processes; IoT technologies is implemented, and compatibility of automated equipment and software is ensured [1]. Practical application of the integrated technological solutions system allows the production of globally competitive new-generation products from the work piece to the finished product in the shortest possible time, the distinctive features of which are a high level of automation and robotization, eliminating the human factor and related errors that lead to loss of quality (unmanned production) [2,3]. Besides, cyber-physical systems are used in creation of such complex objects as Smart Cities (for example, Singapore, Masdar, Innopolis), Smart Grids (smart electric networks), autonomous automotive systems, medical monitoring, process control systems in agriculture and other industries, robotic systems, automatic pilot avionics and directions with smart components [4]. In [5], it is noted that it is also necessary to use distributed intelligent network management based on the CPS in conditions of increasing complexity of management situations and systems. By the way, we consider that speeding up decision-making is also an important factor in this phenomenon. In addition, digital technologies enable businesses to gain competitive advantage, improve their services and products and expand their markets [3]. According to this research, SME selling on-line and e-Commerce turnover have increased in 2020 compared to 2018. Obviously, the impact of new technologies, cyber-physical systems, which combine both virtual numerals and physical subsystems that can independently adapt to changes, on the transformation of global value chains in the digital economy will continue to grow.

At the same time, the widespread introduction of cyber-physical systems, providing new opportunities for socio-economic development, is associated with increased risks. This is mainly due to the fact that the process of digitalization of the economy is taking place simultaneously with the formation of the environment necessary for the development of platforms and technologies, and effective interaction of market entities and economic sectors (laws and regulations, information and communication, technological infrastructure, personnel training, information security and fuzzy systems.). According to the experts, in conditions of high levels of risk concerning information, energy, industrial, economic and other aspects of global security, cyber-physical systems may be vulnerable [6,7]. Approximately 60% of SMEs attacked by cybercriminals lose their business within 6 months [8]. According to this, and also taking into consideration that in time more and more facilities will be based on this technology, it is important to ensure CPS sustainability.

In modern scientific and specialized literature, much attention is paid to issues of the construction, device, implementation, functioning and development of CPS. So, CPS structure in the form of a semantic network has been presented [9]. A scheme of interaction between personnel and cyber-physical systems, as well as the functional scheme of the digital control system for cyber-physical equipment at Smart Factories has been presented [10]. Professor Zegzhda has considered the security indicators of the CPS [11]. Some scientific studies are devoted to the practical applications of CPS in various branches of economy; for example, in the field of industrial production [12,13], including automobile industry [14], on transport [15,16] and transportation systems [17,18], in the sphere of agriculture [19].

It should be noted that much attention has been paid to this innovative technology at the state level. For example, in Russia, a strategy for the development of the information society has being implemented, other relevant program documents have been approved (e.g., the Russian Federation Government Decree No. 317 dated 18 April 2016 "About the implementation of the National Technology Initiative", the Russian Federation Government Decree No. 1632-r dated 28 July 2017 "The program "Digital Economy of the Russian Federation"), and a series of state standards GOSTs have been implemented (e.g., GOST R "Internet of Things. Reference Architecture", GOST R "Big Data. Terms and Definitions", GOST R "Information technology. Smart city. Data interoperability" and oriented documents of this direction with the level of priority and review).

Generally, in the works mentioned above, it is noted that such a property of the CPS as its sustainability is very important, especially in conditions of high uncertainty and turbulence of the external environment. At the same time, as our literature analysis on this topic has shown, an insufficient number of works are devoted to methodological and methodical issues of assessing the CPS sustainability. As a result, this important and urgent problem, in our opinion, is currently insufficiently studied and needs further research and development. In connection with the above, the purpose of this study is to propose and substantiate the scientific points for assessing CPS sustainability to ensure the reliability and longevity of its elements, their interrelations and interaction, as well as the effective functioning and development of this system in conditions of high dynamism and uncertainty of external environment.

This determined the structure and content of our scientific work, which includes the study and development of the following issues: clarification of CPS definition, determination of CPS basic elements, main properties, characterization of CPS sustainability, foundation of the key performance indicators for assessing CPS sustainability, and working out relevant methodology for this task.

2. Materials and Methods

In the study of assessing CPS sustainability in conditions of digital economy development, the methods of information collection, document analysis, expert estimation, generalization, grouping, and brainstorming have been used.

In this study the authors used the methodology of CPS sustainability estimation, which consists of the following stages:

1. Substantiation of relevance of the problem based on the literature review.
2. Selection of the key indicators for assessment of CPS sustainability on the basis of considering the essence, structure, main properties of CPS, clarification of CPS sustainability, and requirements for key indicators.
3. Reviewing existing methods for assessing CPS sustainability.
4. Suggesting the most suitable approach to consider the variety of characteristics of CPS sustainability and the complexity of this term.
5. Identification of the advantages of the proposed algorithm for assessing CPS sustainability and discussion.

The concepts of stakeholders [20,21], Industry 4.0 [22,23], sustainable development [24], value-based management (VBM) [25], and a systematic approach to business process management (BPM) [26,27] formed the scientific basis of the research.

Thus, BPM is a management concept that links the strategy and goals of an organization with the expectations and needs of customers by appropriate organizing end-to-end processes [26]. As part of the issues considered concerning the functioning and development of cyber-physical systems, among the well-known basic BPM modules we examine continuous optimization as: (1) a long-term approach to improving the efficiency and productivity of specific processes based on a continuously functioning feedback control system, and (2) a self-supporting feedback management system aimed at improving the efficiency and effectiveness of processes.

Continuous improvement of business processes should become the basis for increasing the level of value created for various stakeholders due to CPS functioning and solving various tasks while ensuring the balance of interests of key stakeholders.

For the purposes of this study, we consider that sustainable development means economic growth based on using the innovative technologies, including cyber-physical systems that do not harm the environment and contribute to solving social problems, finding the balance between economic development, environmental protection and social responsibility.

In the study we used the following sources of information for identifying and summarizing key indicators, assessment and development of cyber-physical systems, works of different authors on this topic, official data and reports of the Russian Federation Government, statistics, the Digital Economy and Society Index (DESI) 2020 [3], and the foreign experience [28–31].

3. Results

During the research, we obtained the following scientific results: the CPS definition was clarified, the CPS basic elements and their main properties were determined, CPS sustainability was characterized, e key performance indicators for assessing CPS sustainability were suggested, and relevant methodology for this task was worked out.

3.1. Comprehension of CPS Sustainability

3.1.1. Definition of CPS

In 2006, Helen Gill, the Director of Embedded and Hybrid Systems at the US National Science Foundation, introduced the term "cyber-physical systems" to refer to complexes consisting of natural objects, artificial subsystems and controllers. The most important problem of production and economy modernization is closely connected with such systems.

There are many different definitions of the examined term. For example, CPS is represented by a holarchy of multiple holons [30], or CPS is a complex distributed system managed, controlled by computer algorithms, closely integrated with the Internet and its users [31]. The Internet of Things (IoT) forms its technological basis.

In this article, we consider a CPS as a complex system of computational and physical elements that constantly receives data from the environment and uses such data to further optimize management processes [14].

The comprehension of CPS is closely connected with the concepts of robotics and sensor networks with the intelligent mechanisms of computing intelligence systems.

Industry 4.0 is characterized by implementation of CPS into production processes. It is assumed that these systems will be combined into a common network, communicate with each other in real time, self-tune and self-learn new behavior models. Such networks will be able to execute a process with the least number of errors, interact with the goods produced and, if necessary, adapt to the new necessary requirements of consumers. For example, a product in the process of release will be able to determine the equipment itself that can produce it. All this is completely offline without human intervention.

3.1.2. Basic Elements of CPS

Analysis of special literature [31–37] has allowed us to identify the following main elements of the CPS:

- Support technologies, which include: the Internet of Things (IoT), which provides "machine-human", "machine-machine" communications, ubiquitous computing, embedded systems, cloud technologies, special network exchange technologies and fuzzy logic.
- Components of the physical environment, in particular, identification, measurement, data transmission, data processing tools, different interfaces, server equipment, diagnostic equipment, production equipment, including automation elements: sensors, control devices, actuators, robots, machine tools and intelligent systems.
- Components of the information environment such as Product Lifecycle Management System (PLM), Product Data Management System (PDM), Enterprise Resource Planning System (ERP), Manufacturing Execution System (MES), Supervisory Control and Data Acquisition (SCADA), Programmable Logic Controller (PLC), and OpenStack (a software package that implements the cloud platform functions).

It is important to note that the CPS physical and information components are closely interrelated due to the use of different support technologies. Each component operates in different spatial and temporal scales, demonstrates lots of various behavioral models and interacts with others in many ways. As a whole, the abovementioned elements form the basis for construction of multiple CPS conceptual and component models.

3.1.3. Main Properties of CPS

Analysis of [23,33–40] on the topic under consideration allowed us to summarize the fundamental properties of cyber-physical systems that should be taken into account while designing the functioning of cyber-physical systems. There main ones are sustainability, self-programming, adaptability, autonomy, efficiency, functionality, seamlessness, reliability, ability to self-study, usability, transparency, friendliness to human environment, fast speed of functioning and adaptation to environmental changes, complexity (number of incoming components), high power consumption, creation product value, and economic value-added.

In addition, the specific peculiarities of CPS from the safety point of view are presented in [11]. These are: modularity, heterogeneity, decentralization, and interoperability.

It is important to note, in our opinion, that sustainability is the main property of cyber-physical systems, which determines their competitiveness and demand in the market. We consider this aspect in the next section.

3.1.4. Sustainability of CPS

The CPS functioning is subject (constantly or periodically) to various influences: on control subsystems, on human-machine interface, on devices that are part of it, on interaction protocols, network equipment and standards. In the fall of 2016, a smart system for monitoring water temperature and pressure in heating batteries in Lappeenranta (Finland) was damaged by a powerful DDoS attack. As a result, residents of multistory houses spent a week without heating and hot water [11]. Besides, approximately 10% of all enterprises in the EU reported that the most frequent problem was the unavailability of ICT services, followed by the destruction or corruption of data and the disclosure of confidential data [3]. That is why most of EU enterprises pay attention to ICT security issues by implementing various relevant activities. In all, 99% of large EU enterprises and 92% of SMEs deploy some ICT security measures [3]. At the same time, according to experts, less than 5% of those attacked report incidents in the field of security violations of cyber-physical systems in order to avoid damage to their reputation, a decrease in market value of company shares and other negative consequences [11].

In this article, we consider CPS sustainability as the ability of a CPS to save continuity of management processes in conditions of destabilizing influences, constancy of an internal state through coordination of its components to maintain a dynamic equilibrium, to restore lost balance, and to overcome the effects of external and internal environmental factors. On the whole, sustainability reflects the strength and reliability of CPS elements, vertical, horizontal and other connections within the system, ability to withstand internal and external loads, and restoration of the established normal state after its sudden damage by any external or internal factor.

At the same time, it is important to emphasize the dynamic aspect of CPS sustainability. Maintaining CPS development is interpreted as preservation of non-decreasing growth rate in efficiency, not only at present but also in the future. CPS sustainable development is the creation of new and more effective cyber-physical systems. This dynamic development is characterized by certain proportions in the CPS structure before and after changes. Disturbance of proportions and connections between different CPS components leads to destabilization and is a signal of a transition from a safe to a dangerous state. The more sustainable the CPS development, the less the probability of threats and damage to the activities of its users.

The main reasons for CPS vulnerability are using outdated hardware and software, unreliable algorithms, weak authorization and authentication tools, lack of encryption in industrial transport protocols, undeveloped audit and event registration tools, the human factor, as well as significant difficulties in the case of necessity to make operationally significant changes in the system, a high-level risk of system auto-blocking when updating operating systems, applications, implementing security tools and other technology.

It is important to note that the main vulnerable area for CPS includes information and energy security. Generally, CPS sustainability determines its competitiveness and the stability, functioning and development of economic entities that use them.

3.2. Key Performance Indicators for Assessing CPS Sustainability

3.2.1. Requirements for Key CPS Sustainability Indicators

When forming a system of CPS sustainability indicators, it is recommended to select indicators according to the following main criteria:

- Representativeness, for displaying the main characteristics of CPS sustainability.
- Measurability of the indicator.

- A limited number of indicators (the recommended number is not less than six and not more than twenty-five).
- Implementation of evaluation indicators for both information and physical components of the CPS.
- Setting indicators that characterize the CPS state as a whole, such a system-wide indicators reflecting the emergent properties of the system, that is, the CPS properties as a whole that are not inherent in its individual elements.
- Profitability—the costs of collecting information and evaluating CPS indicators should not exceed the possible effects of their use for management purposes.
- Complexity, which provides an opportunity to influence the determinants of the CPS sustainability indicators in real time.

Effectiveness and performance of CPS sustainability management depend on how optimally the set of indicators for assessing CPS sustainability is selected, because certain corrective measures are developed on the basis of the evaluation indicators designed to ensure CPS sustainable development.

The general CPS orientation to increase its sustainability can be described by formulating certain target settings. Consciously designing and controlling the indicators' dynamics, it is possible not only to determine the direction of CPS development, but also to manage this process to achieve the set goals.

3.2.2. Main CPS Sustainability Indicators

A review of modern literature has allowed us to identify a representative set of indicators that characterize various properties of CPS from the standpoint of ensuring its objective function, based on the definition above in Section 3.1.1 [3,6–9]. At the same time, the analysis showed the issues of forming a system of evaluation indicators for purposes of monitoring and managing CPS sustainability have not been investigated enough and require additional study.

When designing the indicative frame of a CPS, we suggest consideration of the main issues of CPS sustainability that were mentioned above in Section 3.1.4. As a result, we offer a set of indicators, which allow us to estimate each significant attribute of CPS sustainability (Table 1). This includes:

- Number of possible failures (units)
- Number of cyber-attacks (units)
- The CPS energy efficiency ratio (index)
- Speed of CPS operations (flops)
- Fixed high-capacity network coverage (% of facilities)
- Digital skills (% of employees)
- Protection from Internet attacks (index)
- Spotting vulnerabilities of information and physical components (index)
- System manageability ratio (index)
- Economic value-added (monetary unit).

It is important to note that the proposed indicator of economic value-added (EVA) not only determines the amount of increase in company's market value as a result of CPS using but also reflects the interests of all key stakeholders of an organization, as shown in [34].

In terms of their content, the indicators presented above represent a reflection of the actions implemented in the CPS determined during the process of making managerial decisions. Any newly made management decision and, accordingly, a change in the set of implemented actions, is reflected in the dynamics of the CPS state and determines the degree of its sustainability.

It is necessary to determine the target value for each estimated indicator of CPS sustainability that will need to be achieved as a result of CPS dynamic development. It should be noted that the list of indicators may change periodically depending on the adjustment of strategic goals and ways to achieve them.

Using the proposed evaluation indicators, reflecting target settings will increase the degree of sustainability of CPS functioning in achieving strategic goals of an organization.

Table 1. Set of indicators for assessment CPS sustainability.

Main Issues of CPS Sustainability	Key Indicators of CPS Sustainability
Continuity of management processes in conditions of destabilizing influences	- Speed of CPS operations (flops) - System manageability ratio (index) - economic value added (monetary unit)
Constancy of internal state through coordination of its components in order to maintain dynamic equilibrium	- Fixed high-capacity network coverage (% of facilities) - Digital skills (% of employees)
Restoring the lost balance	- Spotting vulnerabilities of information and physical components (index) - Number of possible failures (units)
Overcoming the effects of external and internal environmental factors	- CPS energy efficiency ratio (index) - Number of cyber-attacks (units) - Protection from Internet attacks (index)

3.3. Methodology for Estimating CPS Sustainability

3.3.1. Review of Existing Methods for Assessing CPS Sustainability

Analysis of the existing special literature on this issue [11,18,21–23] allows us to state the lack of a unified approach and methods for assessing CPS sustainability. The authors mainly consider the issues of estimating of CPS safety. Thus, in [11] "Approaches to Estimation of the Security of Cyber-Physical Systems" Professor Zegzhda considers methods for assessing the CPS information security indicators, while, in fact, equating the concepts of "information security" and "sustainability", such as using hierarchically adaptive graphs, and fractal estimates based on stochastic dynamics models. Therefore, in the absence of perturbations, the author proposes to formalize the CPS stationary state as follows. Let "ρ" be a stationary state and "ε" be a small, closed contour around "ρ". The state "S" is stable if for any given "ε" it is always possible to find δ (ε) such that any trajectory of movement located inside will not reach the boundary ε.

In general, for N-dimensional system, dynamic equations of a system have the form:

$$\frac{d_{x_i}}{d_t} = f_1(x_i, \ldots, x_N, \underset{Q}{\rightarrow}) \quad (1)$$

where $i \in \overline{1,\ N}$, $\underset{Q}{\rightarrow}$ is the vector of the system parameters [11].

At the same time, we distinguish the terms "sustainability" and "security", and consider that these provisions are not quite applicable in the field under study. The above determines the need to justify a specific approach to assessing CPS sustainability.

3.3.2. Integral CPS Sustainability Assessment

In our opinion, the reference orientation, as mentioned in Sections 3.2.1 and 3.2.2, requires construction of a normative model that characterizes the CPS target state; that is, "as it should be". This model is aimed at achieving a certain state of the CPS. The best sustainable state of the CPS corresponds to the normative (reference) order of indicators movement measures that characterize CPS sustainability. Such a normative order of indicators is an "ideal model" of the CPS, which can be used as a starting point for assessing the actual dynamic state of the system.

The dynamic normative (standard), which is understood as a set of indicators arranged in such a way as to ensure the actual maintenance of the reference order and the achievement of a better state of CPS sustainability, in our opinion, should be a reference (starting point) when choosing the mode of CPS operation.

The actual ordering of indicators by their growth rates serves as a reflection of the results of the taken and implemented decisions. Ideally, the actual ordering of indicators should include all the set ratio standards in the dynamic normative (DN). The closer the actual ordering of indicators is to the normatively established one, the more the normative correlations recorded in the DN are fulfilled. It is obvious, that the CPS state, in which all the requirements are met, can be described as the most sustainable. Therefore, the assessment of CPS sustainability is based on estimation of the proximity of the actual and normative established in the DN orders of indicators' change rates.

The algorithm for estimating the CPS sustainability for a nonlinear DN is presented in Figure 1 and includes the following steps.

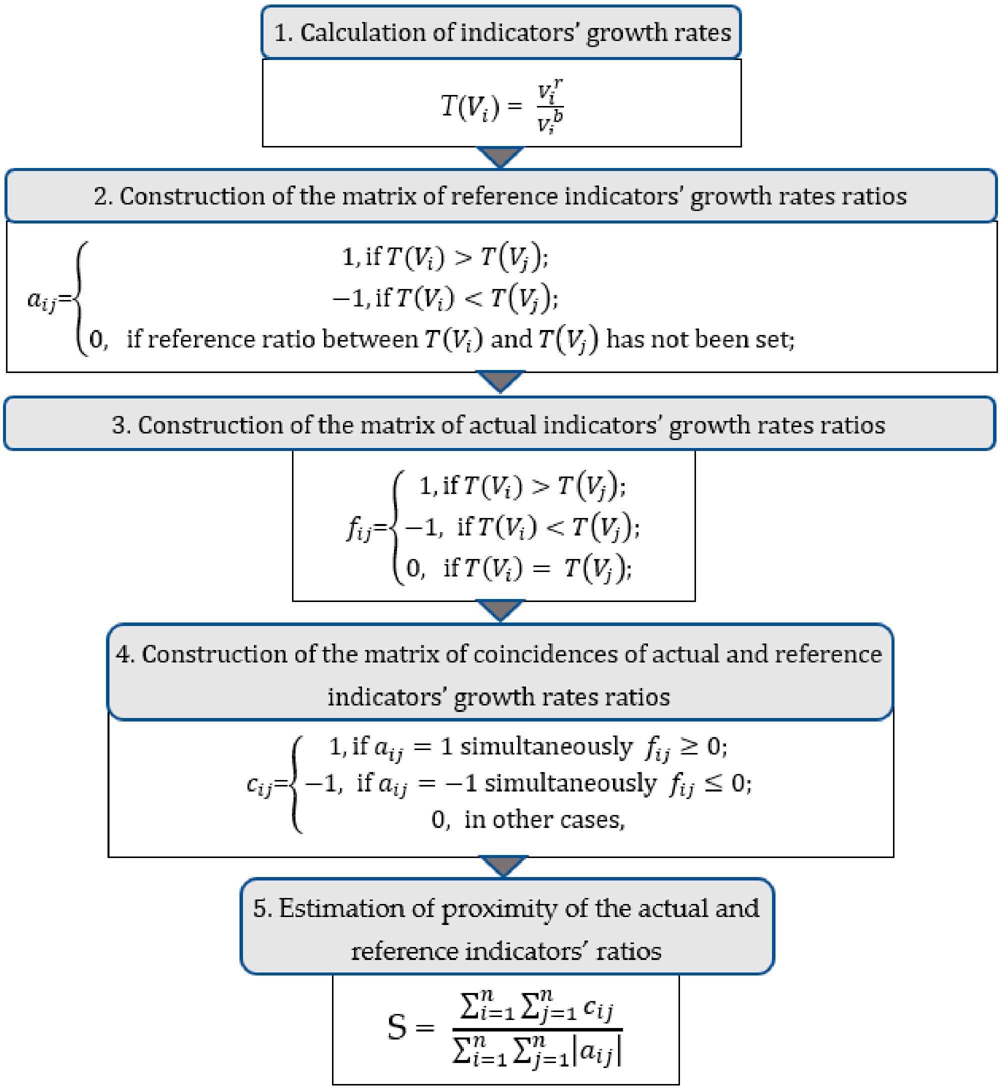

Figure 1. Algorithm for assessing CPS sustainability.

(1) First of all, it is necessary to calculate the indicators' growth rates for the analyzed period of time:

$$T(V_i) = \frac{V_i^r}{V_i^b} \tag{2}$$

where:

V_i^b, V_i^r are absolute values of the i-th indicator in the base and reporting periods, respectively;

$T(V_i)$ is the growth rate of the i-th indicator in the reporting period.

(2) Construction of the matrix of reference indicators' growth rates ratios (DN) A = $\{a_{ij}\}_{n\times n}$:

$$a_{ij}=\begin{cases} 1, \text{ if } T(V_i) > T(V_j); \\ -1, \text{ if } T(V_i) < T(V_j); \\ 0, \text{ if reference ratio between } T(V_i) \text{ and } T(V_j) \text{ has not been set;} \end{cases} \tag{3}$$

where:

n is the quantity of indicators in the DN;

a_{ij} is an element of the matrix of reference ratios between the growth rates of indicators;

i, j are the numbers of indicators (indicators are numbered in the DN in any order);

V_i, V_j are indicators, having the i-th and j-th numbers, respectively;

$T(V_i) > T(V_j)$ and $T(V_i) < T(V_j)$ are the reference ratios between the growth rates of indicators.

(3) Construction of the matrix of actual indicators' growth rates ratios F = $\{f_{ij}\}_{n\times n}$:

$$f_{ij}=\begin{cases} 1, \text{ if } T(V_i) > T(V_j); \\ -1, \text{ if } T(V_i) < T(V_j); \\ 0, \text{ if } T(V_i) = T(V_j); \end{cases} \tag{4}$$

where:

n is the quantity of indicators in the DN;

f_{ij} is an element of the matrix of actual ratios between the growth rates of indicators;

i, j are the numbers of indicators (indicators are numbered as well as in the DN);

$T(V_i)$, $T(V_j)$ are the actual growth rates of the i-th and j-th indicators, respectively.

(4) Construction of the matrix of coincidences of actual and reference indicators' growth rates ratios C = $\{c_{ij}\}_{n\times n}$:

$$c_{ij}=\begin{cases} 1, \text{ if } a_{ij} = 1 \text{ simultaneously } f_{ij} \geq 0; \\ -1, \text{ if } a_{ij} = -1 \text{ simultaneously } f_{ij} \leq 0; \\ 0, \text{ in other cases,} \end{cases} \tag{5}$$

where:

n is the quantity of indicators in the DN;

a_{ij} is an element of the matrix of reference ratios between the growth rates of indicators;

f_{ij} is an element of the matrix of actual ratios between the growth rates of indicators;

c_{ij} is an element of the matrix of coincidences of the actual and reference indicators' growth rates ratios;

i, j are the numbers of indicators (indicators are numbered as well as in the DN).

(5) Estimation of proximity of the actual and reference indicators' growth rates ratios:

$$S = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} |a_{ij}|} \tag{6}$$

where:

S is the assessment of the CPS sustainability;

N is the quantity of indicators in the DN;

a_{ij} is an element of the matrix of reference ratios between the growth rates of indicators;

c_{ij} is an element of the matrix of coincidences of the actual and reference indicators' growth rates ratios;

i, j are the numbers of indicators in the DN.

The presented analytical model not only describes the target sustainable state of a CPS, but also allows due to assessment to achieve the best results of managing CPS functioning.

It is important to note that CPS sustainability may increase or decrease in different periods of time. At the same time, an increase in stability may not always mean that only positive changes have occurred, i.e., changes that caused the fulfillment of those reference relations that were not previously fulfilled. The growth of sustainability may also be accompanied by new violations of the ratios set in the DN. In this regard, along with the assessment of CPS sustainability, it is recommended to assess the variability of its state, which characterizes changes in the structure of completed and unfulfilled relationships in terms of the direction of these changes to implementation of the set goals in the DN.

4. Discussion

It is necessary to note that analysis of the special literature on the research topic has shown that the closest to the subject and object of this study is the work of Professor Zegzhda [11] "Approaches to Estimation of the Security of Cyber-Physical Systems". That is why we have taken the important relevant provisions of this scientific work as a basis for discussion. In this work the author uses the term "attractor"—the field of phase space, in which all the trajectories of the CPS have come over time, and from which the system in the sustainable state has not departed. At the same time, the author notes that the system's development is an irreversible transition to another trajectory, which is described by a strange attractor. In relation to a security task, this means irreversible changes in the system that have arisen as a result of a sudden emergency situation or a cyber-attack. In our opinion, development of the system may not necessarily be associated with the transition to a different trajectory; it may occur along the initially selected trajectory. The irreversibility of such a transition is also a controversial issue. Besides, we consider that the task of ensuring the sustainability of CPS functioning and development is precisely to overcome possible threats as quickly as possible with minimal resources (proactive management) or obstacles that have already arisen—realized risks that led to negative deviations from the target (normative) values of CPS sustainability indicators (reflex managing action on the cause of the problem), and return to the previously chosen development trajectory. Otherwise, a change in the development trajectory may lead to a different, unexpected result, and will cause the substitution of the goals of CPS functioning and development. In addition, it should be noted, that the author pays attention to the issues of protection mainly from external threats. At the same time, it is important to take into account not only external, but also internal risks when assessing CPS sustainability. We agree with the opinion of the scientist that it is appropriate to use the concept of homeostasis, which means the ability of an open system to maintain the constancy of its internal state through coordinated parts of the system aimed at maintaining dynamic equilibrium, the desire of the system to restore lost equilibrium, and to overcome the effects of the external environment, when assessing CPS sustainability.

In general, summing up, it is important to note that in comparison with the considered approach to assessing CPS functioning proposed by Professor Zegzhda, we offer firstly, to investigate the issues of assessing sustainability and security (including information aspect) of the CPS in relationship. Secondly, information security is, of course, a very important aspect of analysis and evaluation for management purposes in modern conditions of the growing number of cyber threats and cyber-attacks, at the same time, it is only one of the numerous aspects (properties, stability vectors) of the CPS. That is why, we propose to conduct a comprehensive assessment that reflects the complexity of the properties of this system from a functioning point of view and the ability to achieve the set targets in the development process. Thirdly the advantage of the proposed methodology is its ability to take into account the state of the object in dynamics, which is very important for ensuring CPS sustainable development in conditions of high uncertainty and turbulence. In this regard, the results of this study will serve as a basis for continuing the scientific discussion about indicators and methods of CPS sustainability assessment.

The findings demonstrate that the main CPS properties, mentioned above in Section 3.1.3: «high power consumption» and «creation product value» are reflected, respectively, in the blocks «Technical sustainability and benefits» and «Economic sustainability & benefits», supposed by the authors of the work [35] for assessment of energy 4.0 sustainability. In our research this aspect is given important attention, but it is not the only one.

Besides, we consider, that the proposed indicator for assessing CPS sustainability—"CPS energy efficiency ratio (index)" (in Section 3.2.2) is a comprehensive indicator that allows estimation of the level of both the current and target state of the "Technological sustainability and benefits" aspect of energy sustainability based on Industry 4.0, considered in [35]. In general, the results of the study serve as the development of scientific provisions on the use of prospect theory in the field of ensuring sustainable development of subjects in the context of Industry 4.0, taking into account energy efficiency.

The results of the study in the field of CPS sustainability estimation may be used as a basis for development of the deterministic CPS models, which are proposed in [28].

In addition, the scientific provisions of this work may be used in development of industry solutions in the field of CPS application; for example, in IoT e-health when modeling energy-efficiency using artificial intelligence as shown in [36–40]. Moreover, as noted in [33], according to experts, systems built on the basis of CPS allow provision of technological leadership and, hence, competitive advantages in many sectors of the digital economy including healthcare, transport, energy, construction and others.

5. Conclusions

Summing up our study, it is important to note that we have coined the term "CPS sustainability" and have offered key performance indicators for assessing CPS sustainability. Besides, we have developed methodology for estimating CPS sustainability based on an integral dynamic normative model. This constitutes the scientific novelty of our research results. Our study showed that the presented analytical model for assessing CPS sustainability is both complex and systemic. The system shows the dynamic normative reflects the dynamics of indicators in their mutual relations, i.e., it allows setting and evaluation of goals that cannot be formalized by any indicator separately. It is complex because its construction assumes use of indicators that reflect various aspects of CPS sustainability, regardless of the measurement units that used for them.

We conclude that assessment and ensuring CPS sustainable development will lead to creation of new and more effective management systems, and technical means (machines, equipment and mechanisms). The use of the proposed model for assessing CPS sustainability will allow it to be managed at a qualitatively new level based on the results of an objective estimation of the current and forecast states of the management object under various alternative scenarios and the choice of a rational solution by comparing the expected results for each of the alternatives considered and analyzing the degree of their compliance with the current target settings due to its consistency and complexity.

In general, the results serve as the basis for improving the CPS management system to increase effectiveness and efficiency of its functioning and development. The results can be further used in the development of algorithms for the automated design of digital production in conditions of Industry 4.0, as well as in conducting a factor analysis of CPS sustainability.

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Abbreviations

CPS	cyber-physical system
IT	information technology
ICT	information and communications technologies
SME	small and midsize enterprises

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