NONLINEAR DYNAMICS METHODS APPLICATIONS TO PRODUCT LIFECYCLE MANAGEMENT

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The research being carried out is aimed at applying nonlinear dynamics methods in product life cycle management to improve communication between processes and achieve environmental sustainability. The purpose of the article is to create a nonlinear mathematical model for analysing product lifecycle management. Chaotic nonlinear dynamical processes of product lifecycle are deterministic but have the property that even small uncertainties in initial conditions lead to exponentially growing errors in the management that limit long-term forecasts. The emergence of chaotic behaviour in processes of product lifecycle was explored, focusing on fluctuations. The study employed methods such as systems analysis, correlation analysis, nonlinear dynamics, and the Surrogate model of chaotic Lorenz waterwheel. It was identified that sharp technological innovations as the primary drivers of short-term fluctuations impacting fixed efficiency and effectiveness of product life cycle process development. The resulting nonlinear dynamic model allowed for flexible operation, transitioning between equilibrium, periodic, and chaotic states based on coefficient values for asset growth rates and time constants reflecting product life cycle process dynamics. The research results are valuable for companies seeking to reduce their environmental impact and implement circular economy principles.

KEYWORDS

Nonlinear dynamics, CAD/CAM/CAE systems, Product Lifecycle Management, lean manufacturing, sustainability, circular economy

1 INTRODUCTION

To ensure the quality of industrial products, which are complex technical systems, an actual scientific direction of research is the justification of the effective use of technical and economic information at the stages of their life cycle and decision-making taking into account the self-coordinated interaction of processes during design, manufacture, and operation as an open system, the self-organization of which affects achieved results in meeting requirements [Dima 2010]. The life cycle management process requires considering a circular economic strategy for longevity when designing and building complex products, as well as enabling real-time collaboration between internal teams and external supply chain partners to ensure the manufacturability of designs.

In an environment of increasing global competition and rapid adaptation to ever-changing market demands, companies are trying to be competitive through cost-effectiveness, constantly seeking models and methods for assessing investments and improvement opportunities to understand how to prioritize different actions and options [Duhancik 2024]. More and more enterprises are embracing circularity as a core focus of activity and innovation [Brahma 2023, Vazquez-Santacruz 2023, Wulfert 2023]. This is facilitated by a combination of solutions such as product lifecycle management (PLM), circular economy and sustainability management tools. Effective product lifecycle management involves leveraging digital technologies across the entire ecosystem to optimize processes, eliminate complexity, and ensure seamless data flow across functional areas [Dyadyura 2017a, Abanda 2024, Yao 2024]. Through the integration of digital streams that include strategic interoperability of enterprise platforms such as CAD/CAM/CAE/PDM/PLM [Jurko 2011, Monkova 2013, Michalik 2014, Panda 2014 & 2021, Baron 2016, Mrkvica 2016, Balara 2018, Chaus 2018, Duplakova 2018, Sukhodub 2018a,b, Harnicarova 2019, Flegner 2019 & 2020] and others, the collaborative creation, management, distribution and definition of products is supported (Fig. 1).

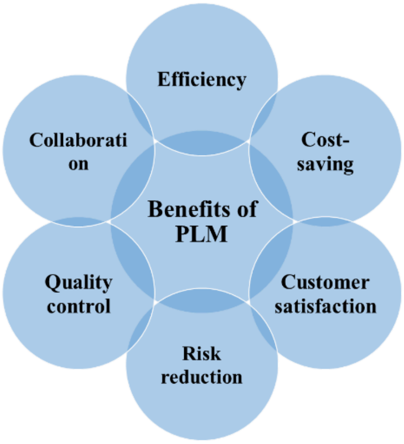

Figure 1. The specific business benefits of PLM solutions

As new technologies emerge and consumer preferences change, the stages of product lifecycle management may shift towards the use of artificial intelligence and machine learning [Zaborowski 2007, Adamcik 2014, Svetlik 2014, Rimar 2016, Olejarova 2017 & 2021, Sedlackova 2017, Catlos 2018, Labun 2018, Sukhodub 2019, Gamec 2019, Kuznetsov 2019, Murcinkova 2019, Pollak 2019 & 2020, Lim 2020, Straka 2021 & 2022, Vagaska 2021, Niu 2022, Ibn-Mohammed 2023].

Advancements in artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT) facilitate enhanced data collection and analysis in modern enterprises. This capability fosters improved productivity and cost reduction prospects, positioning companies for greater efficiency and competitiveness. The pursuit of technology also creates opportunities for better communication. Product development and management are becoming increasingly tighter with cross-functional teams working together to bring products to market [Zaloga 2019 & 2020, Elahi 2023]. To support this trend, new methods and approaches are being developed that allow instantaneous strategic decisions to be made in real time [Acerbi 2020, Ding 2022, Ren 2022, Chu 2023]. These tools continue to make it easy for team members to collaborate no matter their location. As consumers become more environmentally conscious, companies can become more responsive to sustainability demands [Kivimaa 2019, Sassanelli 2020, Zhang 2020]. Product lifecycle management systems can support this trend by providing tools to measure and manage sustainability throughout the product lifecycle, from design to end-of-life disposal. This includes smart, scalable ways to measure waste or environmental impact [Dyadyura 2017b, Macala 2017, Pandova 2018 & 2020]. It also means smarter and cleaner ways to transfer products throughout their life cycle or to consumers. The key is to ensure strategic alignment between stakeholders and set (and continuously manage) appropriate expectations. When making both strategic and tactical decisions, you have to take into account multiple goals and rely on complex and sometimes contradictory criteria. The disadvantage of the existing models of life cycle processes (Fig. 2) in cases where complex technical products are designed and manufactured to order (a limited number of products of the same type) is their fragmentary nature, the inconsistency of the results and the inability to reflect the most general, fundamental non-linear regularities of the organizational and technical mechanism of a sequential the formation of emergent properties in the period from the justification of their development to the end of operation and further disposal [Jurko 2011, Cacko 2014, Anisimov 2019, Harnicarova 2019]. The purpose of the research in this paper is to create a scientifically based basis for decision-making to ensure compliance of information, material and energy resource costs with established requirements based on the self-coordinated interaction of processes during design, manufacture and operation.

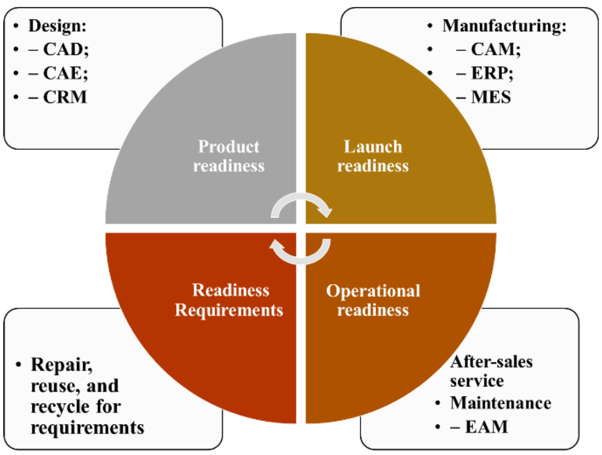

Figure 2. The main stages of the system of the life cycle

2 MATERIALS AND METHODS

This study considers the modern life cycle, which is a set of interconnected technical, economic, social and other systems, the process of functioning of each of which includes obtaining information, its analysis, decision-making and their implementation. The joint interaction of the processes (Fig. 3) of design, manufacture and operation is studied as an open system. A decisive condition for ensuring the optimal final result of a nonlinear system of interconnected processes in the design, manufacture and operation of complex technical systems is the presence of non-equilibrium states, which are provided by material, energy and information flows $\{x_{ij}\}$ acting both within the system of life cycle processes and under the conditions of its interaction with the external environment. Mathematically, the maximum flow problem is formulated as follows: find non-negative values of x_{ij}, for all interacting processes, that maximize

$$\upsilon = \sum_{j=1}^{n} x_{0j} = \sum_{i=0}^{n-1} x_{in} \qquad (1)$$

subject to restrictions:

$$0 \le x_{ij} \le b_{ij}, i, j = \overline{0,n}; \quad i \ne j \qquad (2)$$

$$\sum_{i=0}^{n-1} x_{ik} - \sum_{j=1}^{n} x_{kj} = 0, \quad k = \overline{1, n-1} \qquad (3)$$

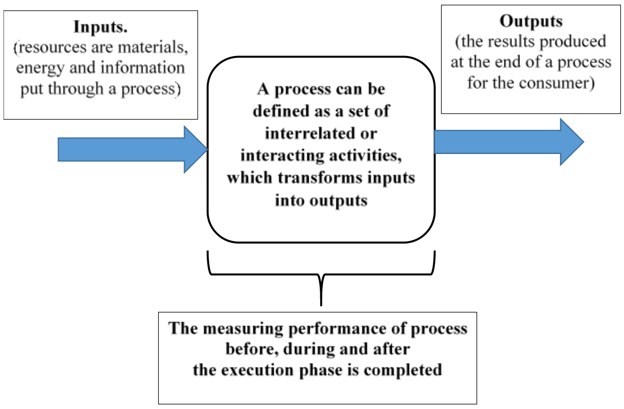

Figure 3. Schematic representation of the process of the life cycle

Equation (1) reflects the value of the maximum flow, which is equal to the material, energy and information resources used during the interaction of life cycle processes. Condition (2) means that the material, energy and information flows for each interaction must be non-negative and do not exceed the throughput of the interaction. Condition (3) means that material, energy and informational resources for each interaction must comply with conservation laws. At the same time, the criterion for optimal management of life cycle processes is usually a set of technical and economic parameters, and the limitation is the internal environment of the enterprise and strategic goals and objectives of its development.
Material, energy and information resources are maintained in the life cycle system. The laws of resource conservation manifest themselves only in the interaction of processes (at least two). Bandwidth refers to the maximum amount of material, energy and information resources that can be transferred from process 1 to process 2 μ a link in one hour.
With certain parameters of material, energy and information resources, the product life cycle will have chaotic results. At the same time, if the amount of resources during the execution of the process does not change, then the intensity will be a constant value. If the number of resources takes on different values, then the duration of the process can be different, and accordingly, the intensity will be variable. In this case, three states are possible.
The requirements D_i^j of one of the processes are greater than the capabilities C_i^j of the other $D_i^j > C_i^j \Rightarrow P_i^j$. This is due to the fact that the internal development of one of the processes of the life cycle system, which is supported by the connection with the external environment, increases its needs and, accordingly, continuously increases the requirements D_i^j. As a result, a new additional connection can be formed, which affects the process and contributes to increasing its capabilities C_i^j.
The capabilities C_i^j of one of the objects of the macrosystem are equal and the same capabilities of another object, which results in an equal position between the neighboring objects of the macrosystem $D_i^j = C_i^j \Rightarrow I_i^j$.
The requirements of one of the objects of the macrosystem are less than the capabilities of another object $D_i^j < C_i^j \Rightarrow O_i^j$, in this case there is an anticipatory development. At the same time, with the help of the object's connection with the external

environment, the requirements are increased, and the system again strives for an equilibrium state.

In a general form, the assessment of requirements and capabilities can be presented

$$D_i^j = \sum_{j=1}^{N} a_i \cdot q_i , \quad C_i^j = \sum_{j=1}^{K} b_i \cdot g_i \qquad (4)$$

where q_i, g_i are relative characteristics of compliance of technical and economic indicators of products and processes with the needs and capabilities of the *j*-th stage of the life cycle;

a_i, b_i are weighting factors that take into account the importance of the *i*-th technical and economic indicators for assessing the requirements and opportunities of the *j*-th stage of the life cycle;

N is the number of technical and economic indicators.

The dynamics of the state change process in general can be described by a system of differential equations

$$\begin{cases} \frac{dD}{dt} = f_1(D,C), \\ \frac{dC}{dt} = f_2(D,C), \end{cases} \qquad (5)$$

where $f_1(D,C)$ and $f_2(D,C)$ are non-linear functions with respect to D, C that are continuously differentiable in some region *DOC* (or in the entire plane). To solve such a system, it is necessary to use the phase plane method, which allows considering the behavior of the system on the (*D, C*) plane.

Each point of the phase plane determines the state of the system at a given moment in time. The movement of the configuration point $(D(t), C(t))$ along the phase plane (phase trajectory) corresponds to a change in the state of the system. A set of phase trajectories defines the phase portrait of the system. The differential equations of the phase trajectories are of the

$$\frac{dD}{dC} = \frac{f_1(D,C)}{f_2(D,C)} \quad \text{or} \quad \frac{dC}{dD} = \frac{f_2(D,C)}{f_1(D,C)} \qquad (6)$$

After solving these equations, it is possible to obtain the integral function of the phase trajectories. Under the conditions $dC/dD = \infty$ and $dD/dC = 0$, we obtain a curve at the points of intersection with the phase trajectories, the latter have a horizontal tangent. Under the conditions $dD/dC = \infty$ and $dC/dD = 0$ we get a curve at the intersection points of which with the phase trajectories, the latter have a vertical tangent.

The main task of a qualitative study of this dynamic system is to find out the qualitative picture of the phase plane breakdown on the trajectory or to establish the topological structure of this breakdown. The topological structure refers to all properties that remain invariant with respect to the topological (mutually unique and mutually continuous) transformation of the plane into itself. The general results of the qualitative theory show that a huge number of systems behave in the same way. To understand the qualitative picture of the solution of system (5), it is enough to know not the behavior of all phase curves, but to find out only the position and type of special points for which the direction of the tangent is not determined. To find singular points of system (5), it is necessary to fulfill the conditions $dD/dt = 0$ and $dC/dt = 0$. At the same time, system (5) takes the form

$$f_1(D,C) = f_2(D,C) = 0 . \qquad (7)$$

Solving this system of equations, we obtain a set of singular points (Di, Ci), where i=1,...,n. The equilibrium position (special point) can be stable or unstable. The concept of stability of dynamic systems is of great practical importance. In particular, the nature of the evolution of the system from the state of equilibrium depends significantly on the stability of a special point. In the case of unstable equilibrium, as a result of even small initial deviations, the system leaves the steady state, and its movement becomes complicated, or it passes to another steady state, far from the initial one. That is why it is important to study the nature of the stability of dynamic systems [Zaloga 2019 & 2020].

When modeling the life cycle using nonlinear dynamics methods, it is assumed that the design, manufacturing, and operation processes are characterized by the duration τ (execution time) and the corresponding production functions *Y (F,G,Q).* Then the speed of the process per unit of time is determined by the ratio

$$dI = \frac{dY}{d\tau} . \qquad (8)$$

The life cycle process system can be accurately approximated by a Lorentz-like system of three equations. According to the synergistic approach, a self-organizing system is defined by self-consistent equations that relate the intensity of execution of the processes of design $dF/d\tau$, manufacturing $dG/d\tau$ and exploitation $dQ/d\tau$ with the values of the functions F, G, Q, which can be considered as control parameter, concatenated field and order parameter respectively.

The throughput of the interaction of processes is equal to the smallest of the throughputs of the processes included in this interaction, i.e.

$$\theta = \min_{(i,j)\in\mu} \{\overline{b}_{ij}\} \qquad (9)$$

To determine the residual capacities of the interaction of processes and their symmetric relationships, we subtract θ from the elements b_{ij}^-, and add θ to the elements b_{ji}^-.

Graphically, this can be depicted as the angular position $\theta_n(t) = \theta(t) + 2 \cdot \pi \cdot n/N$ where $\theta(t)$ is the orientation of the process in relation to the following processes in the life cycle (Fig. 4).

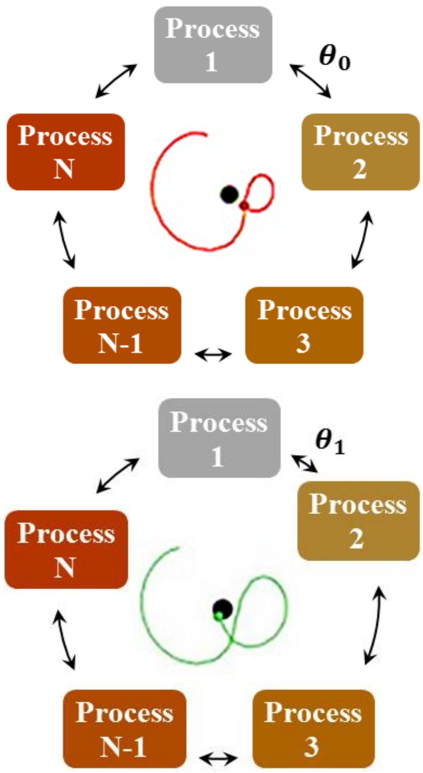

Figure 4. Model of a chaotic product lifecycle management

The use of the model for choosing effective modes of implementation of the compatible interaction of functional subsystems allows to evaluate each variant of the design of complex technical products from the point of view of the expenditure of material, energy and information resources for its design, manufacture and operation. Analyzing the advantages and disadvantages of these options, they choose the most optimal one from the point of view of meeting the established requirements. We will study Ford's tabular algorithm [Haakman 2021] for finding the maximum flow in the interaction of life cycle processes, which will consist of a number of steps.

We record the interaction capacities of life cycle processes in a table of size $(\boldsymbol{n}+\mathbf{1}) \times (\boldsymbol{n}+\mathbf{1})$, where $(\boldsymbol{n}+\mathbf{1})$ is the number of interacting processes. If the throughput of the direct connection between processes is greater than zero, and the inverse connection symmetrical to it is equal to zero, then enter the element $\boldsymbol{b_{ij}}$ into cell $(\boldsymbol{i},\boldsymbol{j})$, and enter zero into cell $(\boldsymbol{j},\boldsymbol{i})$; if $\boldsymbol{b_{ij}} = \boldsymbol{b_{ji}} = \mathbf{0}$, then cells $(\boldsymbol{i},\boldsymbol{j})$ and $(\boldsymbol{j},\boldsymbol{i})$ are not filled.

3 RESULTS AND DISCUSSION

For the system of life cycle processes of a complex technical product, which is depicted in Figure 4, we find the maximum material, energy and information flows between process 1 and process N. The numbers that are written above the arcs and edges in Fig. 5 mean throughputs.

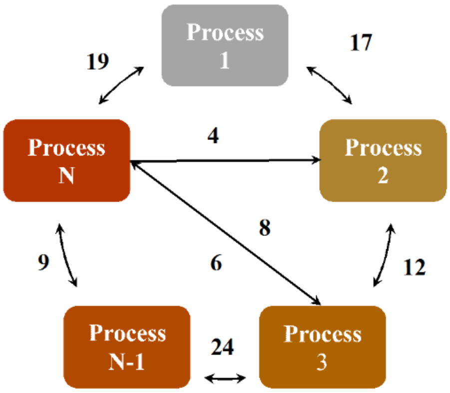

Figure 5. Aggregate lifecycle processes and their throughputs

We form a matrix of the throughput capabilities of the life cycle processes of a complex technical product (Table 1).

Table 1. Calculation results (Preliminary phase)

	(*)	(1)	(1)	(2)	(3)
Process i	Process 1	Process 2	Process 3	Process N-1	Process N
Process j	1	2	3	N-1	N
Process 1	–	17	19-	–	–
Process 2	0	–	4	12	–
Process 3	0^+	4	–	8	(9-)
Process N-1	–	12	6	–	24
Process N	–	–	0+	0	–

First stage.

1. Using Table 1, we find any path with positive throughput from process 1 to process N. To do this, mark the column (Process 1) (*). In the row (Process 1), positive elements are located in columns (Process 2; Process 3). Therefore, we mark these columns at the top with the number 0 (the number of the row in question). Next, we look through the row elements whose numbers coincide with the numbers of the marked columns. Looking through the line (Process 2) we mark the column number 2 (Process N-1); Looking through the next line (Process 3), we mark column 3 (Process N). Since process N-1 is a sink, the marking process is completed and the required interaction is (Process 3; Process 4). We mark the element $b_{3\mathrm{N}-1} = 9$ with a "–" sign, and the element $b_{\mathrm{N}-13} = 0$, symmetrical to it, with a "+" sign. Since the column (Process 3) is marked with number 1, we mark the element $b_{13} = 19$ with a "–" sign, and the element $b_{31} = 0$ with a "+" sign. As a result, we get the interaction $\mu_1 = (Process1 - Process3 - Process\mathrm{N}-1)$.

2. Determine the bandwidth of the found interaction:

$$\theta_1 = min\{b_{13}^-, b_{3N-1}^-\} = min\{19{,}9\} = 9$$

3. The capacity of the arcs of the found interaction is reduced by $\theta_i = 9$, and the interactions symmetrical to them are increased by the same amount. We obtain Table 2.

Table 2. 1st stage calculation results

	(*)	(1)	(1)	(2)	(N-1)
Process i	Process 1	Process 2	Process 3	Process N-1	Process N
Process j	1	2	3	N-1	N
Process 1	–	17^-	10	–	–
Process 2	0^+	–	4	12^-	–
Process 3	9	4	–	8	0
Process N-1	–	12^+	6	–	24^-
Process N	–	–	9	0^+	–

Second stage.

1. Having marked the columns of table 2 and arranging the signs, we find the path $\mu_2 = (Process1 - Process2 - Process\mathrm{N}-1 - Process\,\mathrm{N})$. In this case, the elements $b_{12}, b_{2N-1}, b_{\mathrm{N}-1\mathrm{N}}$ will be marked with the "–" sign, and the symmetrical elements $b_{21}, b_{N-12}, b_{\mathrm{NN}-1}$ will be marked with the "+" sign.

2. Path capacity μ_2

$$\theta_2 = min\{b_{12}^-, b_{2N-1}^-, b_{N-1N}^-\} = min\{17{,}12{,}24\} = 12$$

3. Changing the interaction capacities to θ_2, we obtain Table 3

Table 3. 2nd stage calculation results

	(*)	(1)	(1)	(3)	(N-1)
Process i	Process 1	Process 2	Process 3	Process N-1	Process N
Process j	1	2	3	N-1	N
Process 1	–	5^-	10^-	–	–
Process 2	12	–	4	0	–
Process 3	9^+	4	–	8^-	0
Process N-1	–	24	6^+	–	12^-
Process N	–	–	9	12^+	–

Third stage.

1. Having marked the columns, we find $\mu_3 = (Process1 - Process3 - Process\mathrm{N}-1 - Process\mathrm{N})$

2. Interaction flux value μ_3

$$\theta_3 = min\{10{,}8{,}12\} = 8$$

3. Having calculated the new interaction capacities, we obtain Table 4.

Table 4. 3rd stage calculation results

	(*)	(1)	(1)		
Process i	Process 1	Process 2	Process 3	Process N-1	Process N
Process j	1	2	3	N-1	N
Process 1	–	5	2	–	–
Process 2	12	–	4	0	–
Process 3	17	4	–	0	0
Process N-1	–	24	14	–	4
Process N	–	–	9	20	–

Fourth stage.

The column (Process 1) is marked with a sign (*). Looking through the 1st row, we mark the columns (Process 2, Process 3) with number 1. Continuing to look through the rows, we make sure that the columns (Process N-1, Process N) cannot be marked. Therefore, there is no longer any positive-bandwidth interaction from (Process 1) to (Process N).

The subset R forms labeled processes (Process 1, Process 2, Process 3) (Table 4), the subset R - unlabeled processes (Process N-1, Process N). The cut with the minimum capacity forms an interaction whose initial processes belong to the subset R, and the final processes belong to the subset $\bar{\mathrm{R}}$. Thus, the cut with the minimum throughput

$(R^*, \bar{R}^*) = \{(\text{Process } 2, \text{Process N} - 1), (\text{Process } 3, \text{Process N} - 1), (\text{Process } 3, \text{Process N})\}$.
Indeed, by removing the interactions of the cut, we block all the relationships between the initial process and the final one. Cut throughput

$$b(R^*, \bar{R}^*) = b_{2N} + b_{3N-1} + b_{3N} = 12 + 8 + 9 = 29$$

The final stage.
We subtract the corresponding elements of Table 4 from the elements of Table 1, and we obtain Table 5.

Table 5. 4th stage calculation results

Process i / Process j	Process 1	Process 2	Process 3	Process N-1	Process N
Process 1	–	12	17	–	–
Process 2	-12	–	0	12	–
Process 3	-17	0	–	8	9
Process N-1	–	-12	-8	–	20
Process N	–	–	-9	-20	–

The positive elements of Table 5 characterize the magnitude of interaction flows between processes. Therefore $x_{12} = 12$, $x_{13} = 17$, $x_{2N-1} = 12$, $x_{3N-1} = 8$, $x_{3N} = 9$, $x_{N-1N} = 20$, and for all other interactions the fluxes are equal to zero. The value of the maximum flow is equal to the sum of the elements of the 1st row or the sum of the elements of N column of Table 5.

$$\upsilon = \sum_{j=1}^{4} x_{0j} = 12 + 17 = \sum_{i=0}^{3} x_{i4} = 9 + 20 = 29$$

As can be seen, $\upsilon^* = b(R^*, \bar{R}^*)$. The relationships of the cut (R^*,R̄^*) are saturated with flow $(x_{2N-1} = b_{2N-1} = 12, x_{3N-1} = b_{3N-1} = 8,\ x_{3N} = b_{3N} = 9$.
Taking into account information about the previous state of the processes at the stages of the life cycle significantly changes their current state. In order to ensure the technical and organizational unity of the execution of the totality of works at the stages of the residential complex, a hierarchical system of indicators of the effective use of functional subsystems has been developed, which determines the final result - the value of the production output. In this context, it is possible to apply lean production methods to increase productivity due to the elimination of losses [Lis 2023].
Thus, the expansion of the scale and the complication of information relationships at the stages of the life cycle requires the improvement of decision-making methods to ensure the compliance of complex technical products with the established requirements. Increasing customer requirements for the quality of products and the dynamism of the design, manufacturing and operation processes necessitate the maximum use of all potential opportunities for observation, assessment and decision-making when using technical and economic information. The basis for ensuring compliance of product characteristics with specified requirements is a single integrated information model of the life cycle, which allows describing process interrelationships and acts as a single source of information for decision-making. The need to improve the life cycle processes of complex technical products to improve quality and reduce cost creates conditions for applying a system approach and special methods of decision-making regarding the effective use of technical and economic information.

CONCLUSIONS

With the development of modern industry, the objects of life cycle management of technical systems are becoming increasingly complex, which creates many new problems associated, for example, with a large number of time-varying parameters, long time delays, high non-linearity of processes and complex communication between input and output parameters. In today's conditions of intensive development of information technologies, consumer requirements for products and services are constantly changing. Reliable technical and economic information about the consistency of process results is necessary to make informed decisions about ensuring that products comply with the established requirements. Even if practitioners want to implement new production technologies, they lack comprehensive tools to support their decisions regarding both cost and sustainability. The need for further development of an interdisciplinary approach, methodology, theory and practice of researching universal manifestations of the transition from ordered to unstable and chaotic modes of functioning of the system of life cycle processes of complex technical products based on modern system concepts determined the direction of scientific research in this work. Models of the life cycle of production are used to estimate how to plan the expenditure of information, material and energy resources. The paper proposes scientifically based approaches to increase the efficiency of the use of technical and economic information at the stage of manufacturing complex products. This can be especially important for businesses seeking to comply with regulations or consumer demand for more environmentally friendly products. The greatest effect should be expected in a comprehensive approach to the use of the considered models with an orientation to the possibility of building process structures that are self-organizing, which will allow us to count on the so-called synergistic effect.

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