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APPLICATION OF METHODS OF DECENTRALIZED SYSTEMS IN MANAGEMENT IN LEAN MANUFACTURING

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Abstract:
The emergence and subsequent popularization of lean manufacturing have become one of the most significant for improving the efficiency and productivity of operations. The use of lean manufacturing tools and methods leads to the elimination of waste in the organization. Traditional information systems that allow organizations to share information about resources while managing process performance and traceability have a number of disadvantages such as security, interoperability, and transparency. Currently, distributed ledger technology (blockchain) is widely used for this purpose. This article presents a study of decentralized management of the implementation of a distributed ledger infrastructure, which is selected based on the characteristics of the production system. This study proposes a framework that analyzes lean production methods using simulation and data envelopment analysis (DEA) to accommodate the underlying multi-objective decision-making problem. The current study examines the impact of the simultaneous application of RCA technology, lean manufacturing methods, and distributed ledger technology on the total time, costs, and time of production processes.

Key words: *complex engineering system, lean manufacturing, data envelopment analysis, blockchain, digital business ecosystem, quality dimension, process performance attribute, product lifecycle management (PLM)*

INTRODUCTION

Competition in the market of complex technical (machine-building) products (systems) requires multifunctional structures, high-quality service, short production and delivery times, increased environmental friendliness and reasonable prices. Digitization of production according to the concept of Industry 4.0 and 5.0 [1, 2] provides networking between various sensors, machines, tools and intelligent systems that are connected and can interact with each other along the entire production chain, which contributes to environmental sustainability by increasing the efficiency of the use of resources and information [3]. Manufacturing and logistics operations intelligently linked across industry lines create higher efficiency and adaptive lean manufacturing environment [4] in real time throughout the product lifecycle. Such approaches increase productivity, change the profile of the workforce, and enhance competitiveness [5]. In response to rapidly changing needs, the product development environment is becoming more open and the design process itself is becoming more complex [6]. Open systems are implemented as cloud service models, in which various market participants are combined into a single platform for providing services to the end user. This allows you to implement in the virtual space arbitrarily complex end-to-end business processes that are capable of automatically performing optimization management (end-to-end engineering) of various kinds of resources through the entire supply chain and product value creation – from idea development, design, design to production, operation and disposal (Figure 1).

Collaborative production management strategies require the management of information about the actual state of resources (raw materials, materials, electricity, machinery and industrial equipment, vehicles, production, marketing, sales) both within one and across enterprises.

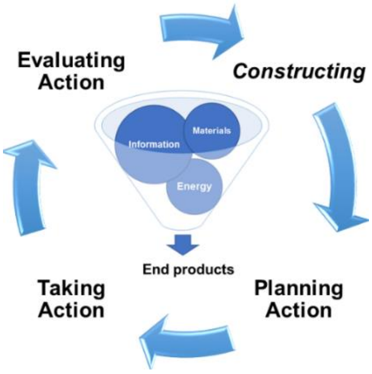

Fig. 1 The action cycle has four phases. The value chain domain covers the functions of transforming materials and other input (such as energy) into the end products

The development of information technologies, the creation of various software based on the mathematical apparatus, forms and methods of storing, processing and distributing data determined the widespread introduction of a large number of heterogeneous management systems in enterprises, organizations and industries. The lack of unified approaches to the creation of information systems for their functional purpose, software and hardware, the diversity of development companies creates the problem of interoperability. The higher the level of heterogeneity of a complex system, the more acute the problem of interoperability for the provision and evaluation of which is necessary to solve a set of scientific, technical, organizational and methodological problems. Organizations today are moving from a hierarchical to a self-organizing model. Currently, industries are implementing smart initiatives and innovative business models for digital transformation. One such initiative is the introduction of distributed ledger technology (DLT), which promises to support Industry 4.0 and 5.0. Decentralized information systems [7] developed with blockchain technology are secure and transparent. Blockchain is attracting increasing attention as a technology with a wide range of applications in various fields [8]. This study aims to promote the implementation of blockchain technology for decision making to ensure the compliance of complex technical products in mechanical engineering at their life cycle (PLM) stages in design, manufacture and operation.

LITERATURE REVIEW

The works [9, 10, 11, 12] show that the management of a complex technical product in PLM systems becomes more open, which is often associated with crowdsourcing, and the design process becomes more complex throughout its life cycle, from the creation of an intangible concept to the disposal of the product. Due to the large number and variety of elements of complex products, managing information is also a challenge. The paper [13] shows that additional problems arise due to the need to exchange information between participants. A product lifecycle management process typically involves various participants from different groups working together to process various information. Therefore, it is essential to effectively collect, share and manage design-related information. From this point of view, a proper Product Design Life Cycle Information Model (PDLIM) [14] is essential to collect, share and manage information. The level of complexity of a typical production system has increased due to the emergence of more complex technologies (both in products and in production systems) that require experience in several areas to implement.

This article [15] investigates the hierarchy of the manufacturing system, which consists of a set of interrelated processes aimed at converting information, knowledge, energy, materials, and other resources into value for the consumer based on the principles of lean production. Modern manufacturing systems are becoming more and more complex to manage. The problems that need to be solved are associated with a significant number of time-varying parameters, large time delays, high non-linearity of processes, and a complex relationship between input and output parameters. Depending on the parameters of internal components and characteristics of external conditions, the state of manufacturing systems can change in an unpredictable manner. The paper considers many types of discrete states in which the system can be. The estimation of the probability of finding the manufacturing system in any of the given states was carried out using discrete Markov analysis. The paper [16] considers the possibility of using distributed ledger technology (DLT) in PLM systems at manufacturing enterprises. Potential benefits of this approach include decentralization, openness and interoperability of automation systems for manufacturing enterprises [17, 18, 19].

Distributed Ledger Technology (DLT) is a digital ledger that records all transactions that take place in an immutable and decentralized way. It includes several components (eg, hardware, software, protocol) that are developed and managed by different groups of participants (Figure 2) [20]. In the works [21, 22, 23], the blockchain is considered as a database stored in several places that maintains ever-increasing records or "blocks" that are timestamped and linked to the previous block in such a way that it cannot be canceled due to the consensus algorithm, which is used to “link” blocks to each other. The paper [24, 25, 26, 27] considers the prospect of application in the field of intellectual production.

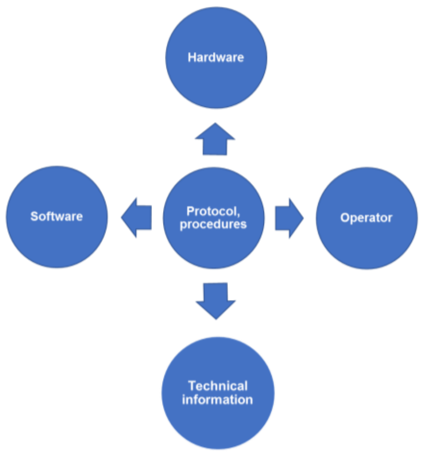

Fig. 2 Structure of the production process maintenance system

The key issues of this field, such as distributed collaborative production, industrial big data sharing and security, transparent logistics and supply chain, naturally align with the core characteristics of blockchain technology. Features such as traceability and data security, decentralized consensus, and decentralized process execution make it an important technology for smart manufacturing, especially in product lifecycle management (PLM) [28, 29, 30]. The paper [31] summarizes the key features of blockchain in specific PLM scenarios. The application or potential application of the blockchain in each section of PLM is studied in detail, both technical and non-technical problems of applying the blockchain in PLM to achieve more efficient applications are indicated. Blockchain technology has a wide application in supply chains [32], which allows you to quickly determine the place of origin of products, helps to increase transparency, control and risk management in achieving regulatory requirements, track deliveries, and automatically take the resulting actions. The paper [33] proposes a structured methodology for making important technical design decisions to maximize the benefits of blockchain systems in project management and presents directions for new blockchain research. It is worth paying attention to the synergy between blockchain and IoT [34, 35, 36].

Companies face a number of challenges and issues when considering implementing popular blockchain solutions [37], in particular for managing complex technical products in PLM systems.

Blockchain consensus algorithms belong to the Byzantine fault tolerance. There are many ways to achieve Byzantine fault tolerance. In the blockchain space, there are also various consensus algorithms, each with different solutions to the problem for optimal efficiency. This paper discusses one of the ways to build a consensus algorithm for making reasonable and optimal decisions at the stages of the life cycle of complex technical systems, taking into account the principles of lean manufacturing. The analysis of the achievement of consensus in complex systems is based on the use of the logic apparatus. The logical-probabilistic method described in the works [38, 39] offers two stages: writing the functions of the algebra of logic and its transformation to one of the standard forms of transition to substitution; substitution of all logical variables and operations and calculation of the desired probability. In this paper, a new idea of the method is presented, which consists in an additional stage of partial replacement of logical variables to reach consensus. The modification of the logical-probabilistic method presented in [40, 41] makes it possible to analyze the consensus of various blockchain structures in some cases of much greater complexity than the main methods [42], and to give satisfactory estimates at intermediate stages of solving problems.

RESEARCH METHODOLOGY

We use the scientific hypothesis [43], which consists in the fact that the life cycle processes of complex technical products are implemented by complex multifunctional and multicomponent systems that can include three jointly acting components – a complex of technical means (CTM), software (SW) and operational staff (OS). At the same time, in order to consider issues regarding a certain (j-th) function, a group of technical, software and ergatic (human operator (or a group of operators)) elements involved in the performance of this function is selected from the composition of all elements of the system. This group of parts forms the j-th functional subsystem (j-th FSS or FSSj) of the system under consideration. It is this FSSj that is subject to analysis when considering the characteristics of the system in terms of the jth function it implements. In the composition of the FSSj subsystem (as well as in the composition of the system as a whole), in the general case, three components can be distinguished (Figure 3):

– a group of technical means involved in the implementation of the j-th function (the j-th functional subsystem of the CTM – FSS_{CTMj});
– a group of software tools involved in the implementation of the j-th function (the j-th functional subsystem of software – FSS_{SWj}). Software means subsystems or system elements consisting of computer programs, related procedures, documentation and data related to the operation of the subsystem or element;
– ergatic support group (operational personnel) participating in the implementation of the j-th function (the j-th functional subsystem of the OS – FSS_{OSj}).

On the basis of the role in the performance of a certain function, the following are distinguished: functional subsystems; constructive subsystems can be distinguished by design features; by information features – information subsystems, etc. The analysis of the functioning of the system is greatly simplified if its structure is constructed in such a way that the subsystems distinguished by functional and constructive features coincide.

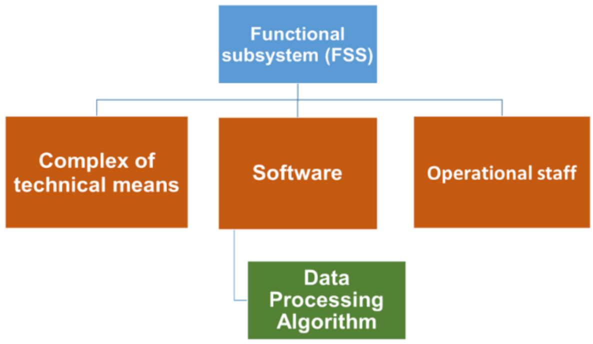

Fig. 3 Functional subsystems at life cycle stages of complex technical systems

Thus, the system of functions forms the characteristics of the functional subsystems of the X_{FSS}. By the levels of the hierarchy, it is possible to determine the relationship between the set of functions (F) and the set of groups of funds (FS_{CTM}, FS_{SW}, FS_{OS}). The concept of lean manufacturing covers all levels of the value stream, from the interaction of organizations in the supply chain (interorganizational level 1) to the level of specific operations (level 4). The functional system (FSS) is the general (node) of Byzantine stability (Figure 3). All nodes in the blockchain life cycle network of a complex technical system must communicate with each other and find a way to reach consensus, which leads to methods that we call consensus algorithms. to achieve Byzantine fault tolerance, each node (FSS) in the network must communicate with each other.

The diagram (Figure 4) shows the transfer of information from node to node along one of the ways to reach an agreement.

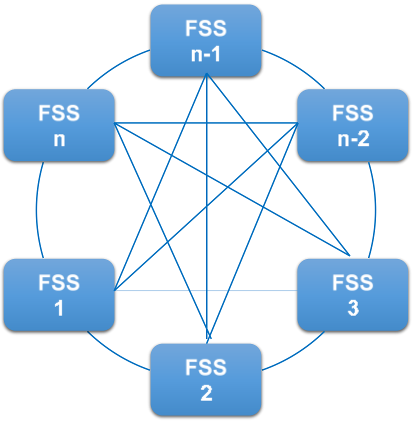

Fig. 4 Distributed Ledger Technology Framework

The probability that node i is in consensus is p_i, and the arc connecting node *i* to node *j* is *j* – p_{ij}. In Byzantine fault tolerance, p_i and p_{ij} mean the probabilities of reaching a consensus within a given time *t*. It is assumed that in each element of the network there may be "refusals" from reaching an agreement and failures of various nodes are independent events. Under these assumptions, it is necessary to find the probability that the network is in a state of consensus at the moment of information transfer from node n. The absence of some arcs is taken into account in the final formula of a fully connected network by setting $p_{ij} = 0$.

Procedures for partial substitution in the transition from a function of the algebra of logic to a mixed form of the probability function and subsequent substitution of the remaining logical variables are based on theorems from the algebra of mixed forms.

Theorem. The algebra function of logic [44]:

$$F(X) = [(\wedge_{f\in K_0} x_j)^{\sigma_0} f_0(X_0)][\vee_{i=1}^{n}(\wedge_{j\in K_i} x_j)^{\sigma_i} f_i(X_i)], \quad (1)$$

where:

X and X_i are vector arguments of logical functions *F* and f_i, respectively;

σ_i is a constant coefficient equal to 0 or 1;

x_i is irreversible logical variables for all $j \in K = \cup_{i=0}^{n} K_i$,

f_i is logic algebra functions of an arbitrary form, is a form of transition to substitution.

It corresponds to the mixed form of the probability function:

$$\mathrm{P_F} = \mathrm{P(F(X)=1)} = \mathrm{P(f_0, f_1, \ldots, f_n)} = \left(1 - \mathrm{a}_0^{\mathrm{f}_0}\right) \cdot \left(1 - \prod_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{a}_\mathrm{i}^{\mathrm{f_i(X_i)}}\right), \quad (2)$$

$$a_i = (1-\sigma_i) \cdot b_i + \sigma_i \cdot (1-b_i), b_i = \prod_{j\in K_i} p_i, \quad p_j = P(x_j = 1). \quad (3)$$

In formula (2), the operation of raising to a power is defined as: $a^f = a$ for $a^f = 1$ for $f = 0$.

Let's assign the variable x_i to the node with number ij, and the variable x_{ij} to the arc and compose the logical function of the network consensus using a recurrent procedure. For a network of one node (*n* = 1), the logical function $f_1 = x_1$. For a network of two nodes, due to the serial connection of its FSS:

$$f_2 = x_2 \cdot x_{21} \cdot x_1 = x_2 \cdot x_{21} \cdot f_1.$$

For network consensus of three nodes, it is enough that there is one of two possible ways to reach an agreement. Therefore, the network consensus logic function:

$$f_3 = x_3 \cdot (x_{31} \vee x_{32} \cdot x_2 \cdot x_{21}) \cdot x_1 = x_3 \cdot (x_{31} \cdot f_1 \vee x_{32} \cdot f_2).$$

For an arbitrary n, a path to reach an agreement (n, 1) is possible, or one of the paths passing through the node *i* = 2, 3, … *n* – 1 , with which this node has a direct connection. It follows that the logical consensus function of the network under consideration is:

$$f_n = x_n \cdot (x_{n1} \cdot f_1 \vee x_{n2} \cdot f_2 \vee \ldots \vee x_{n,n-1} \cdot f_{n-1}), \quad (4)$$

where:

$$f_i = x_i \cdot (x_{i1} \cdot f_1 \vee x_{i2} \cdot f_2 \vee \ldots \vee x_{i,i-1} \cdot f_{i-1}), \quad i = 1, \overline{n-1}. \quad (5)$$

In formula (4), all logical variables with an index containing n are irrevocable. According to the theorem, this formula is the form of the transition to substitution, and it corresponds to the shifted form of the probability function:

$$P(f_n = 1) = P_n(f_1, \ldots, f_{n-1}) = p_n \cdot \left(1 - \prod_{i=1}^{n} q_{ni}^{f_i}\right), \quad q_{ni} = 1 - p_{ni}. \quad (6)$$

In formula (6), the logical variables included in the function f_{n-1} and containing *n* – 1 in the index are irreversible. Since the structure of formulas (4) and (5) is the same, we find:

$$P_{n-1} = P(f_{n-1} = 1) = p_{n-1} \cdot \left(1 - \prod_{i=1}^{n-2} q_{n-1,i}^{f_i}\right), \quad (7)$$

From formulas (10) and (11) according to the formula of total probability, we obtain:

$$P_n(f_1, \ldots, f_{n-2}) = P_{n-1} \cdot P_n \cdot (f_1, \ldots, f_{n-1}, 1) + (1 - P_{n-1}) \cdot P_n(f_1, \ldots, f_{n-2}, 0) = p_n \cdot \Big[p_{n-1} \cdot \left(1 - \prod_{i=1}^{n-2} q_{n-1,i}^{f_i}\right) \cdot \left(1 - q_{n,n-1} \cdot \prod_{i=1}^{n-2} q_{ni}^{f_i}\right) + \left(q_{n-1} + p_{n-1} \cdot \prod_{i=1}^{n-2} q_{n-1,i}^{f_i}\right) \cdot \left(1 - \prod_{i=1}^{n-2} q_{ni}^{f_i}\right)\Big]. \quad (8)$$

Now composing the expression for the probability $\mathrm{P}(f_{n-2} = 1)$ we will replace the logical variables with the index n – 2. Then:

$$P_n(f_1, \ldots, f_{n-3}) = P(f_{n-2} = 1) \cdot P_n(f_1, \ldots, f_{n-2}, 1) + [1 - P(f_{n-2} = 1)] \cdot P_n(f_1, \ldots, f_{n-3}, 0)$$

After n substitution steps, the desired expanded form of the probability function, which is a system of nested formulas, will be obtained. The compactness of the notation provides a quick result.

RESULTS AND DISCUSSION

As the initial data, the network structure, links between randomly selected nodes, the availability factors of each node and the direction of communication, and the path selection algorithm are specified. It is assumed that the path selection algorithm allows one to uniquely build a priority series of paths between the selected nodes, and therefore the latter can be considered as one of the ways to specify the algorithm. Acceptances of agreements in the network are independent events. The transmission time of the message is short compared to the time between adjacent changes in the state of the elements of the chosen path, and therefore no new changes in the state of the path occur during the transmission. It is necessary to determine the probability of passing the transmitted message through the node, arc or group of paths of interest to us. In the stationary section of the network, the same probability has the meaning of the share of all messages passing through the given elements of the network [45]. Consider an FSS network of n = 5. Network agreement acceptance logic function:

$$f_5 = x_5 \cdot (x_{51} \cdot f_1 \vee x_{52} \cdot f_2 \vee x_{53} \cdot f_3 \vee x_{54} \cdot f_4), \tag{9}$$

where:

$f_4 = x_4 \cdot (x_{41} \cdot f_1 \vee x_{42} \cdot f_2 \vee x_{43} \cdot f_3),$
$f_3 = x_3 \cdot (x_{31} \cdot f_1 \vee x_{32} \cdot f_2),$
$f_2 = x_2 \cdot x_{21} \cdot f_1,$
$f_1 = x_1.$

Substituting x_5, x_{5i}, $i = \overline{1.4}$ by formula (6) we get:

$$\begin{gathered} P_5(f_1, f_2, f_3, f_4) = p_5 \cdot (1 - q_{51}^{f_1} \cdot q_{52}^{f_2} \cdot q_{53}^{f_3} \cdot q_{54}^{f_4}), \\ P_4(f_1, f_2, f_3) = p_4 \cdot (1 - q_{41}^{f_1} \cdot q_{42}^{f_2} \cdot q_{43}^{f_3}), \\ P_3(f_1, f_2) = p_3 \cdot (1 - q_{31}^{f_1} \cdot q_{32}^{f_2}), \\ P_2(f_1) = p_2 \cdot (1 - q_{21}^{f_1}), \\ P_1 = p_1 \end{gathered} \tag{10}$$

At the second step, we replace $x_4, x_{41}, x_{42}, x_{43}$ and, according to formula (8), we have:

$$\begin{gathered} \mathrm{P}_5(\mathrm{f}_1, \mathrm{f}_2, \mathrm{f}_3) = \mathrm{p}_5 \left[\left(1 - \mathrm{q}_{41}^{\mathrm{f}_1} \cdot \mathrm{q}_{42}^{\mathrm{f}_2} \cdot \mathrm{q}_{43}^{\mathrm{f}_3}\right) \cdot \left(1 - \mathrm{q}_{51}^{\mathrm{f}_1} \cdot \mathrm{q}_{52}^{\mathrm{f}_2} \cdot \right.\right. \\ \left. \mathrm{q}_{53}^{\mathrm{f}_3} \cdot \mathrm{q}_{54}\right) \cdot \mathrm{p}_4 + \left(\mathrm{q}_4 + \mathrm{p}_4 \cdot \mathrm{q}_{41}^{\mathrm{f}_1} \cdot \mathrm{q}_{42}^{\mathrm{f}_2} \cdot \mathrm{q}_{43}^{\mathrm{f}_3}\right) \cdot \left(1 - \mathrm{q}_{51}^{\mathrm{f}_1} \cdot \right. \\ \left.\left. \mathrm{q}_{52}^{\mathrm{f}_2} \cdot \mathrm{q}_{53}^{\mathrm{f}_3}\right)\right] \end{gathered} \tag{11}$$

After the third-fifth steps we finally find

$$\begin{gathered} \mathrm{P}_5 = p_1 \cdot p_5 \cdot \{p_2 \cdot p_{21} \cdot [p_3 \cdot (1 - q_{31} \cdot q_{32}) \cdot [p_4 \cdot \\ (1 - q_{41} \cdot q_{42} \cdot q_{43}) \cdot (1 - q_{51} \cdot q_{52} \cdot q_{53} \cdot q_{54}) + \\ (q_4 + p_4 \cdot q_{41} \cdot q_{42} \cdot q_{43}) \cdot (1 - q_{51} \cdot q_{52} \cdot q_{53}) + \\ (q_3 + p_3 \cdot q_{31} \cdot q_{32} \cdot q_{33}) \cdot [p_4 \cdot (1 - q_{41} \cdot q_{42}) \cdot \\ (1 - q_{51} \cdot q_{52} \cdot q_{54}) + (q_4 + p_4 \cdot q_{41} \cdot q_{42}) \cdot (1 - q_{51} \cdot \\ q_{52})]] + (1 - p_2 \cdot p_{21}) \cdot [p_3 \cdot p_{31} \cdot [(1 - q_{41} \cdot q_{43}) \cdot \\ (1 - q_{51} \cdot q_{53} \cdot q_{54}) \cdot p_4 + (q_4 + p_4 \cdot q_{41} \cdot q_{42}) \cdot \\ (1 - q_{51} \cdot q_{52})] + (q_3 + p_3 \cdot q_{31}) \cdot [p_4 \cdot p_{41} \cdot (1 - q_{51} \cdot \\ q_{54}) + p_{51} \cdot (q_4 + p_4 \cdot q_{41})]]]\} \end{gathered} \tag{12}$$

This network, in addition to nodes 5 and 1, contains thirteen more elements and it would be necessary to take into account 2^{13} = 8192 incompatible situations in the enumeration of hypotheses. Orthogonalization and slicing also lead to time-consuming procedures.

CONCLUSIONS

In this way, we have developed potential DLT technologies for efficient and intelligent integration solutions based on the principles of lean manufacturing. In day-to-day manufacturing operations, blockchain can be incredibly useful for managing assets and minimizing production downtime. The modified logical-probabilistic method makes it possible to analyze the probabilistic characteristics of information networks of the life cycle of complex technical products and, with partial notification of switching nodes, which are functional half-systems, take into account dynamic priorities when choosing a path and multicast messages. As a result of partial substitution, the so-called mixed form of the probability function appears, which includes both probabilities and logical variables. It simultaneously uses two systems of operations: logical Boolean algebra and arithmetic. After some transformations of the mixed form of the probability function, the remaining logical variables are gradually replaced to pass to the desired expanded form of the probability function. Combined with predictive and prescriptive analytics, IoT-based blockchain technology could eventually become the most automated and fail-safe way to keep a plant running.

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