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FORMATION OF AN ADAPTIVE MODEL OF THE CONTAINER TERMINAL FUNCTIONING TECHNOLOGY

Container terminals play a crucial role in organizing rail container transportation, as they contribute to the rapid and safe handling of cargo, while also optimizing logistics processes. However, in today's environment, the existing technology for handling containers at terminals does not ensure uninterrupted operation, which worsens the quality of transportation services and does not meet all the needs of transportation stakeholders. Due to the downtime of containers and loading and unloading equipment, railways and other participants in the transportation process suffer losses. Therefore, instead of stationary cranes, the use of reach stackers is proposed in the work, and the relevance of their application is justified. The article formalizes the technology of container terminal operation in the form of a stochastic adaptive model. The criterion for the optimality of the objective function is the minimum operating costs when processing containers. The model takes into account the risk of possible financial losses associated with the failure of loading and unloading machines during container processing. Risk events are considered, which are proposed to include organizational and technical delays and force majeure circumstances in the operation of reach stackers. The risk of financial losses is represented by a polynomial distribution law and a second-order Erlang distribution density function. The proposed model of the container terminal operation technology adapts the existing technology to the unstable conditions of its operation, which allows to ensure safe working conditions and reduce the risks of railway transport workers. The study takes into account the risks of potential losses associated with the failure of loading and unloading machines during container handling. The proposed adaptive model can be used in the future when designing new container terminals, as well as for modernizing and restoring existing ones.

Key words: *container terminal, optimization of technology, container, adaptive model, risk of financial loss, reach stacker.*

Продащук С. М., Бауліна Г. С., Богомазова Г. Є., Чехунов Д. М., Формування адаптивної моделі технології функціонування контейнерного терміналу

Контейнерні термінали відіграють важливу роль в організації контейнерних перевезень залізницею, оскільки вони сприяють швидкій та безпечній обробці вантажів, а також оптимізують логістичні процеси. Однак в сучасних умовах існуюча технологія обробки контейнерів на терміналах не забезпечує безперебійну роботу, що погіршує якість транспортних послуг і не задовольняє усіх потреб учасників перевізного процесу. Через простої контейнерів та навантажувально-розвантажувальної техніки залізниці та інші учасники транспортного процесу зазнають збитків.

Тому в роботі замість стаціонарних кранів запропоновано використання ричстакерів та обґрунтовано актуальність їх застосування. У статті формалізовано технологію функціонування контейнерного терміналу у вигляді стохастичної адаптивної моделі. Критерієм оптимальності цільової функції є мінімум експлуатаційних витрат при переробці контейнерів. У моделі враховано ризик можливих фінансових втрат, пов'язаних з відмовами навантажувально-розвантажувальних машин при переробці контейнерів. Розглянуто ризикові події, до яких запропоновано віднести організаційні та технічні затримки і форс мажорні обставини у процесі роботи ричстакерів. Врахування таких параметрів в математичній моделі дає можливість оцінити втрати та збитки, що можуть виникнути при виконанні технологічних операцій з контейнерами, а також в процесі їх зберігання. Ризик фінансових втрат представлено за допомогою поліноміального закону розподілу та функції щільності розподілу Ерланга 2-го порядку. Застосування запропонованої моделі дозволить визначити оптимальні параметри роботи контейнерного терміналу, а саме кількість навантажувально-розвантажувальних машин (ричстакерів) та час їх роботи. Запропонована модель технології роботи контейнерного терміналу адаптує існуючу технологію під нестабільні умови його функціонування, що дозволяє забезпечити безпечні умови роботи та зменшити ризики робітників залізничного транспорту. Запропонована адаптивна модель може бути використана у подальшому при проектуванні нових контейнерних терміналів, модернізації та відновленні існуючих.

Ключові слова: *контейнерний термінал, оптимізація технології, контейнер, адаптивна модель, ризик фінансових втрат, ричстакер*

Formulation of the problem. Container terminals are an integral part of the railway transport infrastructure and play an important role in ensuring the successful transportation process for container shipments. The efficiency of container handling at terminals significantly affects rail transportation, and thus the optimization of container handling is becoming increasingly important [1]. Maximum efficiency can be achieved if the planning of operations and the use of equipment are well organized and coordinated [2].

Today's level of container processing at terminals does not fully satisfy the growing demand for quality transport services and the requirements of all participants in the transport and production chain of cargo transportation. Railways and other subjects of the transport process have losses due to non-productive downtime of containers and loading and unloading machines (LUM) at container terminals [3] and increased operating costs.

In modern conditions, it is important to implement scientifically based technological solutions while saving costs through the rational use of LUM to improve the quality of the container terminal. The formation of the optimal technology for the functioning of the container terminal of the railway station is an urgent and difficult task in connection with the growth of demand for high-quality transport services and requirements for the promptness of cargo delivery. To ensure the optimal technology, it is necessary to take into account various factors that affect the amount of necessary loading resources to ensure safe and continuous operation even in unstable conditions.

Unstable conditions are defined as unpredictable changes that affect the efficiency of material, energy and labor resources. For example, changes in the cost of energy and materials, which makes it necessary to adapt resource saving strategies and introduce flexible, adaptive technologies; equipment wear and tear and the need for modernization, which increase the risks of inefficient use of resources and require innovative approaches to energy saving; updating the regulatory framework for environmental standards, which requires new approaches to waste disposal and resource saving; climate change and force majeure (accidents, weather conditions, natural disasters, global crises), which complicate the operation of terminals. Therefore, it is now necessary to take into account the risks that threaten the stable operation of terminals. This approach will make it possible to find optimal solutions for minimizing operating costs and increasing safety when recycling containers.

Analysis of recent research and publications. Many scholars draw attention to the promising prospects for the development of container transportation both in Ukraine and worldwide in their works [4–6]. It was determined that their rapid development requires the search for effective technical, technological and organizational solutions.

Many scientific studies are devoted to the technology of container terminal functioning. Terminal capacity is often limited by the presence of bottlenecks in the technological process. Thus, article [7] presents the structure and proof of the concept for a cycle of bottleneck mitigation consisting of three stages: bottleneck classification, detection, and elimination. An empirical approach was used to find the cause of the identified bottleneck and proposed appropriate measures to eliminate it. To eliminate the imbalance in the operational load of terminal resources, [8] proposes a solution for an innovative mode of planning and optimising unloading operations.

A study [9] has shown that most of the additional costs incurred during container transportation arise at the initial and final stages. Such costs are caused by the probabilistic nature of the processes when finding containers at container terminals. These processes have a certain level of uncertainty. Their random nature causes additional downtime of containers and a decrease in the quality of customer service. In order to reduce the negative impact of probabilistic factors, it is necessary to develop an automated container transportation technology. To achieve this goal, a model of stochastic optimization of the process of formation and promotion of container trains to seaports was developed using the mathematical apparatus of the theory of random flows.

In [10], several simulation models were developed to analyze the operation of a specific container terminal, and dynamic internal changes in components corresponding to different terminal operation scenarios were identified. These models were developed to highlight the cause-and-effect relationships that exist within the system and to determine how these relationships contribute to the overall operation of the container terminal. However, the authors of the study [11] developed a two-stage stochastic optimization model under conditions of uncertainty regarding the arrival of containers at the container terminal. To solve the model, two heuristic algorithms are proposed: an algorithm based on column generation and a search algorithm with prohibitions. Numerous experiments conducted by the authors of the article confirm the effectiveness of the proposed algorithms.

The authors of article [12] proposed a risk-oriented technology for managing the operation of a port terminal and port when organizing container transportation. At the same time, the risks of station and port losses due to the occurrence of risky events were taken into account. Study [13] proposes a two-stage model for allocating storage space in order to minimize its volume, taking into account stacking technology and the volume of incoming and outgoing containers. An annealing simulation algorithm based on heuristics (SAAH) and an improved heuristic algorithm based on moving horizon (HARH) are presented.

The formation of multimodal container logistics terminals is important for the realization of the country's export potential. Their optimal operation can ensure a high level of reliability, safety, and quality of service [14]. In addition, logistics container terminals are aimed at ensuring the functionality and reliability of transport services. In addition, logistics container terminals are designed to ensure the functionality and reliability of transport services, contributing to the acceleration of material flows and their continuity, and reducing the cost of moving products from production sites to consumption sites by 30–40 % [15]. Such a result can be obtained thanks to a more efficient logistics scheme and optimization of transportation routes.

Thus, the considered studies are aimed at improving a certain link of the technological process of the container terminal. In addition, the impact of the risk of possible financial losses on the container handling process has not been sufficiently studied. Therefore, it is advisable to study the technological cycle of processing containers at the container terminal, taking into account the delays that may occur during their processing and lead to possible financial losses.

The purpose of the article is to develop an adaptive model of the technology of container terminal operation, taking into account the risk of financial losses that threaten its stable and safe operation.

Presenting main material. Container terminals must ensure convenient and safe execution of cargo and commercial operations with the lowest costs in the time set by the technological process. In addition, the use of modern LUMs, which ensure the necessary and sufficient intensity of container processing at container terminals, is important for the organization of effective container maintenance. Therefore, in the work, instead of stationary cranes, the use of reach stackers, which carry out cargo operations with containers at the container terminal, is proposed.

The replacement of stationary cranes with reach stackers is a relevant option for container handling in unstable conditions. Reach stackers are more mobile and flexible because they can move throughout the container terminal [16] and along railroad tracks. In today's environment, the speed of container processing can be critical. Ukraine's energy infrastructure is constantly under significant strain, which seriously complicates the operation of container terminals. They are forced to operate in a reduced mode instead of round-the-clock due to energy saving requirements. Additional difficulties arise during power outages, which lead to the shutdown of electrically dependent LUMs. This leads to a backlog of containers at the terminals, additional downtime as container trains continue to arrive on time due to the use of diesel locomotives. It is the use of reach stackers that will be able to solve these problems. The operation of the reach stacker does not depend on the state of the power grid, which ensures continuous container handling at the terminal [17]. In addition, reach stackers significantly reduce container handling time [18] due to their fast and accurate placement on sites of any shape.

Reach stackers have a built-in stabilization system, which allows them to withstand greater static and dynamic loads, as well as to work more efficiently on different types of container terminal covers and uneven surfaces. This ensures an increase in the level of driver safety during operation.

Reach stackers allow efficient use of resources, as they can perform many functions independently, replacing the work of many people. This makes it possible to reduce the number of personnel and increase the efficiency of work. Also, their functionality allows you to stack containers in 4-5 tiers, effectively using the terminal area. Richstackers help optimize loading and unloading processes when time is of the essence. They also provide more precise handling of containers, which avoids damage and reduces repair costs.

To determine the optimal technology for the operation of a container terminal, an adaptive model is proposed that takes into account unstable operating conditions. The optimality criterion of this model is the minimum operating costs *R*. To formalize the technology of the container terminal, the theory of inventory management is applied.

The target function of the model for determining the optimal technology for the operation of the container terminal:

$$R(M_i, T_i) \to \min \tag{1}$$

with restrictions

$$\begin{cases} m_i P_{sti} \le Q_{pr} \\ M_i^{\min} \le M_i \le M_i^{\max}, \\ T_i^{\min} \le T_i \le 24 \end{cases} \tag{2}$$

where M_i is the quantity of LUM for processing containers of the *i*-th type, pcs.; T_i is the working hours of the LUM when processing containers of the *i*-th type at the container terminal, h.; m_i is the number of containers of the *i*-th type, pcs.; P_{sti} is the static load of the *i*-th type container, t/cont.; Q_{pr} is the processing capacity of the container terminal, t.

$$R = R_{zb} + R_{pr} + R_{tr} \rightarrow \min, \tag{3}$$

where R_{zb} are the container storage costs, UAH; R_{pr} are the risk of financial losses due to downtime of the LUM, UAH; R_{tr} are the container recycling costs, UAH.

The volume of containers at the container terminal is described by the equation relating the volume of containers at the container terminal at time t with the volume at a later time t'. Q_t is the volume of containers at the container terminal at a moment in time t, Q_{ar} is the arrival of containers at the container terminal (up to the maximum volume) in the interval from t to t' and Q_s is the sending containers. The physical volume of containers at the container terminal at the time t' is defined as $Q_{t'} = Q_t + Q_{ar} - Q_s$. The cycle of changing the volume of containers at the container terminal is shown on Fig. 1.

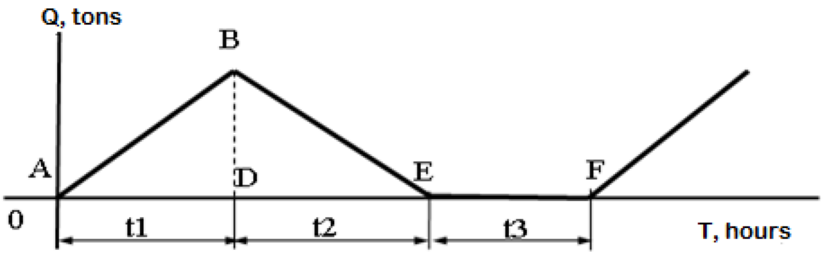

Fig. 1. The cycle of changing the volume of containers at the container terminal

Source: compiled by the authors

Fig. 1 shows that there is a cycle of changing the volume of containers at the container terminal. Its initial volume is zero, and growth continues during period t_1. Containers are then dispatched during period t_2 if there are sufficient mechanization facilities or until the volume of containers to be dispatched reaches zero, or there are not enough wagons and cars to dispatch the containers. From this moment, a downtime of LUM begins, which continues during the period t_3. Then this cycle, which has a duration of $t_1 + t_2 + t_3$, is repeated.

Currently, the maximum processing capacity of container terminals is defined as the amount of cargo in containers with which it is possible to carry out cargo operations at the same time, and the term of these and auxiliary operations. But the maximum processing capacity is calculated taking into account the maximum technical equipment, which does not always correspond to reality. In the paper, it is proposed to determine not the maximum, but the optimal processing capacity of the container terminal, taking into account its optimal technical equipment and setting certain parameters of the terminal operation.

So it's time to carry out cargo operations with containers of the *i*-th type at the container terminal

$$t_{nv} = \frac{k_{sdv} m_i P_{sti}}{M_i P_i^{LUM}}, \tag{4}$$

where k_{sdv} is the ratio of double operations; P_i^{LUM} is the productivity of LUM when processing containers of the *i*-th type.

Time for maneuver operations

$$t_{man} = 2t_{fr} + m_i(t_p + t_{re} + t_c), \tag{5}$$

where t_{fr}, t_p, t_{re}, t_c is the average time for feeding-retrieving, placing, rearranging and collecting containers of the *i*-th type at the container terminal, respectively, h.

Working hours of the LUM when processing containers of the *i*-th type at the container terminal

$$T_i = \left(1 - \frac{1}{365} T_{ri}^{LUM}\right)(24 - T_i^{mv}) - T_{addi}^{LUM}, \tag{6}$$

where T_{ri}^{LUM} is the length of stay of the NRM in a non-working state, h.; T_i^{mv} is the time when the *i*-th cargo front is out of operation, taking into account unstable operating conditions, h.; T_{addi}^{LUM} is the time of LUM execution of additional warehouse operations per day with containers of the *i*-th type, h.

$$T_{addi}^{LUM} = \frac{m_i P_{sti} k_s}{M_i P_i^{LUM}} \tag{7}$$

where k_s is the warehouse processing ratio.

Taking into account that in the work instead of stationary cranes it is proposed to use reach stackers, as well as to perform overloading of containers according to the direct option, the determination of the optimal processing capacity of the container terminal will be equal to

$$Q_{pc}=\sum_{i=1}^{n}\frac{\left(\left(1-\frac{1}{365}T_{ri}^{LUM}\right)(24-T_{i}^{nw})-\frac{m_iP_{sti}k_s}{M_iP_i^{LUM}}-\frac{m_iP_{sti}(1-k_p)k_s}{M_iP_i^{LUM}}\right)m_iP_{sti}}{2t_{fr}+m_i(t_p+t_{re}+t_c)+\frac{k_{sdv}m_iP_{sti}}{M_iP_i^{LUM}}}, \tag{8}$$

where n is the number of containers by type (20-foot, 40-foot), pcs.; kp is the coefficient of direct overload according to the direct option.

When constructing cargo storage costs, geometric ratios were used to determine optimal work parameters. Storage costs are the product of C_{zb} (container storage costs) and the area of the triangle ABE. The height BD of the triangle ABE determines the maximum processing capacity of the container terminal, and its base AE is equal to $t_1 + t_2$.

Therefore, the costs are equal

$$R_{zb}=\frac{1}{2}C_{zb}Q_{nep}(t_1+t_2), \tag{9}$$

where C_{zb} is the hourly cost of storing a ton of cargo, UAH/t-h.

The risk of financial losses due to the downtime of the LUM, taking into account the probability of LUM being at the container terminal, different in their condition, is determined as follows:

$$R_{pr}=C_{prm}M_i\frac{x!}{x_1!x_2!x_3!}p_1^{x_1}p_2^{x_2}p_3^{x_3}\left(2\mu\right)^2\int_{t_b}^{t_e}t_3^2\cdot e^{-2\mu t_3}dt_3, \tag{10}$$

where C_{prm} is the cost of an hour of downtime of one LUM, UAH/mach.-h.; x_1, x_2, x_3 is the number of out-of-service LUMs due to organizational delays, the number of out-of-service LUMs due to technical delays (technical malfunctions), the number of LUMs in forced downtime due to force majeure, respectively; x is the number of LUMs that are idle, at the same time $x = x_1 + x_2 + x_3$; p_1, p_2, p_3 are the probabilities of having non-operational LUMs at the container terminal due to organizational delays, LUMs with technical malfunctions, LUMs in forced downtime due to force majeure, respectively. At the same time $p_1 + p_2 + p_3 = 1$; t_b, t_e is the beginning and end of the reporting period, respectively; t_3 is the average duration of downtime of LUM, h; m is the service intensity.

Research has established that the number of LUMs in various states and their idle time are random variables. The polynomial distribution law was used to determine the probability of being at the container terminal of LUM, which differ in their condition. The idle time of the LUM t_3 is subject to the Erlang distribution of the 2nd order, which is taken into account when determining the risk of financial losses in formula (10). An assessment of the actual value of the risk will allow to objectively present the volume of possible losses and determine the ways of their minimization.

Container recycling costs are

$$R_{tr}=Q_{pc}C_{tr}, \tag{11}$$

where C_{tr} is the cost of processing one ton of cargo in a container, UAH/t.

The objective cost function for the selected work technology in the expanded form is:

$$\begin{aligned}R\left(M_i,\ T_i\right)=&\frac{C_{zb}}{2}\sum_{i=1}^{n}\frac{\left(\left(1-\frac{1}{365}T_{ri}^{LUM}\right)(24-T_{i}^{nw})-\frac{m_iP_{sti}k_s}{M_iP_i^{LUM}}-\frac{m_iP_{sti}(1-k_p)k_s}{M_iP_i^{LUM}}\right)m_iP_{sti}}{2t_{fr}+m_i(t_p+t_{re}+t_c)+\frac{k_{sdv}m_iP_{sti}}{M_iP_i^{LUM}}}(t1+t2)+\\&+C_{prm}M_i\frac{x!}{x_1!x_2!x_3!}p_1^{x_1}p_2^{x_2}p_3^{x_3}\left(2\mu\right)^2\int_{t_b}^{t_e}t_3^2\cdot e^{-2\mu t_3}dt_3+\\&+\sum_{i=1}^{n}\frac{\left(\left(1-\frac{1}{365}T_{ri}^{LUM}\right)(24-T_{i}^{nw})-\frac{m_iP_{sti}k_s}{M_iP_i^{LUM}}-\frac{m_iP_{sti}(1-k_p)k_s}{M_iP_i^{LUM}}\right)m_iP_{sti}}{2t_{fr}+m_i(t_p+t_{re}+t_c)+\frac{k_{sdv}m_iP_{sti}}{M_iP_i^{LUM}}}C_{tr}\to\min.\end{aligned} \tag{12}$$

The implementation of the model showed that it is possible to determine the optimal technology of the container terminal's operation under unstable conditions. The simulation was performed in the MATLAB environment (Fig. 2).

The calculation was carried out for the container terminal of station L with the existing volumes of container processing. The minimum operating costs amounted to UAH 4,258.45 ($115) for the operation of two reach stackers for 8 hours of their operation, which is 14 % less than with the existing operating parameters of the terminal.

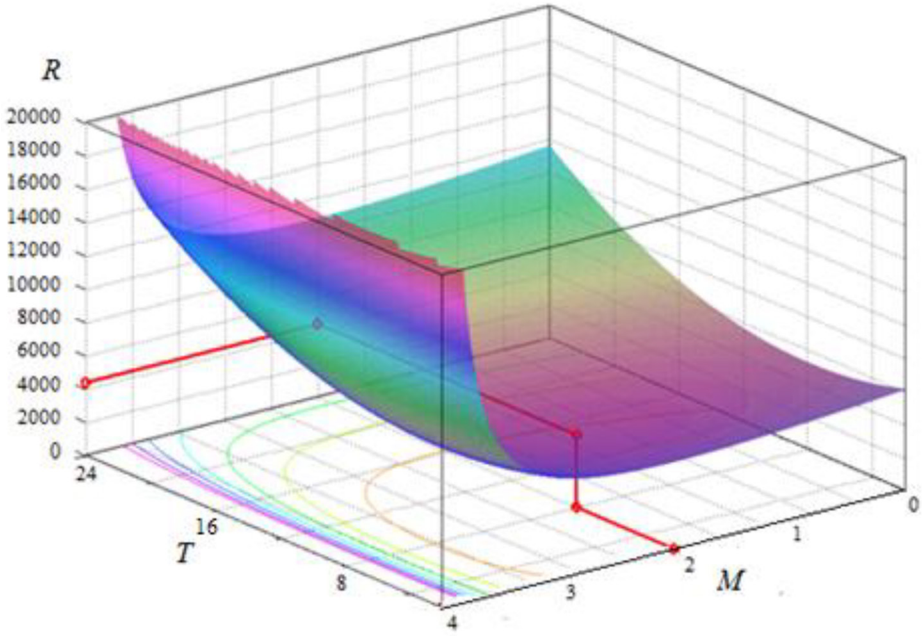

Fig. 2. Dependence of operational costs on the number of LUM and their time of operation

Source: compiled by the authors

The developed adaptive model can be considered quite universal in its structure. At the same time, only the parameters of the model will change, depending on the specifics of the operation of a certain container terminal, cargo operations and local conditions. Thus, a significant achievement of this study is the creation of a stochastic adaptive model of the container terminal functioning with optimal technical equipment in unstable conditions.

A considerable number of mathematical models for optimizing container terminal operations have been developed and reviewed in the literature. However, the studies have only examined certain aspects of the technological cycle of container handling at terminals. It should be noted that in many scientific works [12, 13], when formalizing the technology of terminal operation, container processing, and the process of organizing container transportation, the optimal technical equipment of the container terminal was not taken into account. However, the authors of the study [13] took into account time and weight constraints in the developed model.

An exclusive feature of the proposed model, unlike the studies analyzed in the article [9–11], is the consideration of the possible risk of losses due to the occurrence of risky events that threaten the stable and safe operation of the container terminal of the railway station. In developing a model aimed at minimizing all possible manipulations in the process of loading containers at the terminal, the authors of [1] did not take into account possible losses due to malfunctions of loading equipment. In addition, the mathematical optimization model proposed in article [2], which simultaneously takes into account the distribution of warehouse space and the use of crane equipment for tactical management of a container terminal, does not take into account possible losses associated with the failure of the necessary equipment.

This study considers risk events, which include organizational and technical delays and force majeure in the process of the LUM operation. Taking into account such parameters in the mathematical model makes it possible to estimate losses and damages that may occur during technological operations with containers, as well as during their storage.

Conclusions. Studies of the container terminal functioning technology in modern conditions have proven that the existing technical equipment does not ensure the stability and safety of work. This causes significant losses and reduces work efficiency. Therefore, in the paper, instead of stationary cranes, the use of reach stackers is proposed and the relevance of their use is substantiated.

Under such conditions, a stochastic adaptive model was developed to determine the optimal technology for the functioning of the container terminal in order to minimize both operational costs and financial losses directly related to container processing. When forming the model, the optimal processing capacity of the container terminal with optimal technical equipment and certain operating parameters was taken into account. The concept of risk was used to model financial losses associated with the possibility of unwanted events. At the same time, the risk of losses in the event of LUM downtime due to the occurrence of risky events that threaten the stable and safe operation of the container terminal was taken into account. When determining the magnitude of the risk of financial losses, the random nature of the studied components is taken into account. The polynomial distribution law and Erlang distribution density function of the 2nd order were used. The proposed technology can be used in the future in the design of new container terminals and in the modernization of existing ones.

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