ENSURING RESILIENCE AND AGILITY OF COMPLEX ORGANIZATIONAL-TECHNICAL SYSTEMS

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ABSTRACT

Modern organizational and technical systems have been developing in an environment that is marked by capriciousness, uncertainty, risk, variability, and evolution (CURVE factors). As organizational-technical systems grow bigger, their internal complexity increases, too, both structurally and dynamically. The article substantiates the appropriateness of employing the principles of systems engineering for managing such systems.

The authors analyzed various theoretical concepts of and practice-based approaches to the development of systems engineering in the context of ensuring the resilience and agility of complex organizational-technical systems. Using the case of power engineering and hi-tech industries, the authors show that for organizations that operate critical infrastructure facilities it is essential to make sure that the system stays functional in adverse conditions and is able to recover quickly after a failure. It is demonstrated that for addressing the above task it is critical to use instruments that nurture interdisciplinary competences in individual professionals and in teams that manage the development of complex systems and implement major innovation projects.

As part of the study, the authors also look at the possibility of using the principles of resilient systems design and the fundamental principles for agile systems engineering when managing critical infrastructure facilities.

Keywords: agility, critical infrastructure, CURVE factors, organizational and technical system, resilience, systems engineering.

1 INTRODUCTION

The authors define an organizational-technical system (OTS) as a network of groups of professionals from various domains that interact between each other and, despite possibly being part of different business structures, work for the same goal that is usually associated with the development of a system (business), exploration of new technological areas and markets, and adoption of breakthrough technologies.

In literature, the term "organizational and technical system" is often used a synonym of "socio-technical system" that was first introduced by E.L. Trist in the early 1960s [1]. However, the two definitions have a number of differences that are significant in the context of this study. For example, [2] notes that socio-technical systems focus on the interests and needs of the person and their relationships with technical aids (in terms of ergonomics), whereas in OTSs the emphasis is placed on managing the operation and development of such systems (technical guidelines, legal framework, organizational structures, business processes).

A socio-technical system assigns the same priority for *current* production performance indicators and employee work performance, while in OTSs the emphasis is shifted towards sustainable development of the system on the basis of projections of *its future* internal and external parameters (organizational links, development management) [3]. Another difference is that the organizational and technical subsystems within an OTS are intermingles, whereas in socio-technical systems each of the constituent subsystems has rather clear borderlines despite their interrelation [4].

Apart from the attributes that are typical of complex systems in general, a complex organizational and technical system has the following features [5–8]:

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1. an active role of man-machine complexes that develop in a technological breakthrough mode and make it possible to launch production and provide services that use smart process integration tools;
2. the need to optimize the lifecycle of major projects that often change the structure of the organization implementing them;
3. multi-agent (network) decision-making with regard to the further development of the system.

It appears particularly interesting to study organizational - technical systems that form critical infrastructure. The functioning of such system involves a large number of various interactions that are determined by such properties as unpredictability, capriciousness, and the need for constant change. Some studies of the authors [9–11] demonstrate that competences of individual staff members (managers, engineers, analysts, information security experts) or of interdisciplinary teams that utilize unique tools play the key role in managing the development of such systems. It is such teams that drive structural change in OTSs making them more flexible and reliable.

2 PROBLEM OF RESILIENCE AND AGILITY IN CONTEMPORARY SYSTEMS ENGINEERING

As systems grow bigger, more complex and have a bigger environmental impact, they are required to meet tougher safety and reliability standards in changing conditions. All too often, faults in the operation of complex systems are of systemic kind. A branch of systems engineering that is concerned with building resilience systems – resilience engineering – employs methods that help avoid disasters by taking preemptive steps and increasing the adaptability and resilience of the system (its recovery after a failure).

The scholarly and engineering communities started to actively discuss the problem of systems resilience after the publication of [12]. Today, various groups of scholars look at resilience in a broader context, bringing such domains as ecology, sociology, psychology, management, engineering into the debate. The principles of resilient systems are starting to be used by risk managers and cyber security experts [13–15]. As the term "resilience" is getting widely used in various fields of science, for the purpose of this research we are going to use the definition that is accepted in systems engineering:

Resilience is the ability of a system to continue to have the required functionality in adverse conditions [16]. A typical taxonomy of resilience systems is shown in Fig. 1.

The scientific and engineering communities agree on the attributes of resilient systems. A resilient system has such features as capacity, flexibility, tolerance, and cohesion [12, 17]. Capacity means the ability of the system to survive in adverse conditions; flexibility is the ability of the system to adapt to a threat; tolerance the ability of the system to avoid a drastic loss of functionality; cohesion is the ability of the system to act as a unified whole in the face of a threat.

Principles of the architecture of resilient systems [12, 17–27] have been developed in order to endow new systems with the above attributes. Table 1 classifies and details some of these principles.

In the case of complex organizational-technical systems (for example, critical infrastructure systems) it is sufficient to ensure their resilience. The ability of a system to function in a changing environment should be factored in at the design stage. High costs and risks of reduced functionality make it irrational to apply this principle to the entire system, but it is highly reasonable to do that with regard to individual components of the system structure.

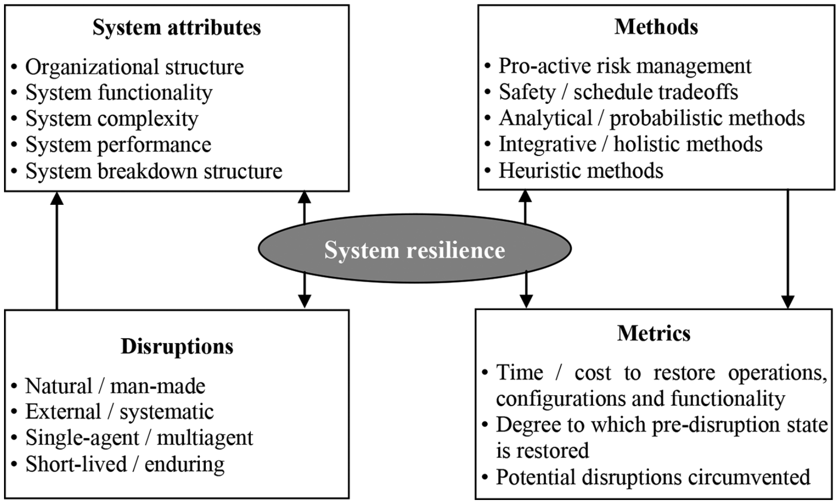

Figure 1: Conceptual framework for system resilience (adapted from [18]).

Table 1: Principles of resilient system design.

Basic principle	Definition	Supporting principles of the second level
Absorption	The system should be capable of withstanding destructive forces of a certain nature and degree	• Margin is the design security level that must exceed the supposed level of destructive impacts • Hardening means the system should have sufficient resistance to deformation • Context spanning means the system architecture should envisage the maximum destruction level as well as a wide scope of destruction • Limit degradation means that the absorption capability should prevent the system from losing functionality due to aging or poor maintenance
Restructuring	The system should be able to change its structure	• Authority escalation means that authority to manage crises shall escalate in accordance with the severity of the crisis • Regroup means that the system must restructure itself if a threat becomes real
Cross-scale interaction	Each of the system components should be capable of communication, cooperation and interaction with any other component	Knowledge between nodes means all components of the system must know what the others are doing Human monitoring implies that an automated system must understand the intent of the operator Automated system monitoring means that a human must understand the intent of the automated system Intent awareness means that all nodes of a system must understand the intent of other units

(*Continued*)

Table 1: (*Continued*)

Basic principle	Definition	Supporting principles of the second level
		• Informed operator a human must be kept informed about all aspects of the automated system • Internode impediment means that there should not be administrative or technical obstacle to the interactions among elements of a system.
Human in the loop	There should always be human in the system when the need occurs for human cognition	• Automated function means it is preferable for humans to perform a function rather than automated systems when conditions are acceptable • Reduce Human Error –standard strategies should be used to reduce human error • Human in Control- humans should have final decision making authority unless conditions preclude it
Modularity	The functionality of the system should distributed among its nodes in such a way that the failure of one of them does not bring the other ones to a halt	N/A
Neutral state	Human agents should delay in taking action to make a more reasoned judgement as to what the best action must be	N/A

Among the factors of the environment that necessitate designing so-called agile systems are capriciousness, uncertainty, risk, variation, and evolution. Taken together, they form the acronym CURVE.

The agile architecture pattern (AAP) incorporates three critical components: (1) a roster of drag-and-drop encapsulated modules that enable the designed functionality; (2) a passive infrastructure of minimal but sufficient rules and standards pull the modules together; and (3) an active infrastructure that designates specific responsibilities for sustaining agile operational capability.

For the system being developed to be able to rapidly and effectively respond to changes in the environment, it should be both proactive and reactive [28].

Proactive responses are usually triggered from within and are aimed at applying new knowledge (or implementing new opportunities for already accumulated knowledge) in order to create new value. For sustaining proactive change, the system should be capable of the following:

- module mix evolution: new modules with required functional properties are added, and inadequate modules are removed;

- improved performance of the modules in assembly thanks to their improved functionality;
- infrastructure improvement in line with evolving needs and opportunities;
- new configurations of individual modules and the roster of available modules in response to new situations that require something different in capability.

Reactive changes are generally triggered by events which demand a response. That could be a new opportunity that needs to be addressed, or a threat that needs to be countered. Reactive responses are usually associated with the properties of the systems that determine their resilience and sustainability. To respond reactively, the system should be capable of:

- correction in order to decrease the likelihood of a dysfunction and reduce recovery time if the dysfunction occurs;
- variation that is provided by module availability for an adequate response to change;
- expansion through the inclusion of new modules on the roster and use of external resources;
- reconfiguration through the employment of new modules and removal of the unused ones as well as by recycling previously disconnected modules.

3 NEW REQUIREMENTS FOR HUMAN RESOURCES

Today, management models are undergoing transformation under the influence of various global trends, With regard to the subject matter, the following ones need to be highlighted.

Super dynamic transformations in technology renewal and transfer in the global space. The ability to navigate quickly in the changing reality, foresee changes, embrace constant change has become a decisive competitive edge for any business. In this context, the goal of smartization in management is to increase the preparedness for *anticipatory action*, which means being flexible and being able to adapt to new conditions faster than your competitors by seeing new opportunities in the situation. That results in considerable shifts in managerial decision-making algorithms toward a higher level of smartization.

Broader system relationships between markets, industries, businesses and extra complex technologies and the digital environment. The trend can be easily observed in all hi-tech research-intensive industries. The growing complexity of emerging technological systems, the penetration of AI into every link of the technological chain, customized production and customer relations on the basis of cyber-physical systems, the use of virtual structures for international cooperation call for new tools and management methods [29]. Increasingly often, managers are faced with the task of promoting the newest technology in domestic and international markets, making decisions about the prospects of their application with regard to their technical characteristics. Managers need to be able to speak “the same language” with developers and producers of new equipment and operations personnel, to understand the specific features of ecosystem marketplaces, research-intensive services and their practical applications [30–32].

Past experience is being pushed off the throne by the ability to view an emerging and rapidly evolving situation *holistically*. Moreover, it becomes essential for a manager to be able to foresee looming changes. In order to be able to do that, they need to be proficient in methodology, possess strategic thinking skills, be handy with analytical support tools and instruments for designing the future. They should be able to see interdisciplinary connections, especially between the drivers of technological change.

It is obvious that a new generation of managers will be engaged in breakthroughs in technology, create new markets and overhaul existing production facilities. The key changes will be concerned with considerable improvements to productivity on the basis of smart systems, a diversity of economic and marketing for customer relations, the adoption of systems that guarantee the safety, reliability, sustainability and energy efficiency of production. For their part, major technological innovations enable profound organizational transformations, the arrival of new principles of maintenance and repair services for industrial facilities, and optimization of their life cycle.

Managers are in for qualitatively new tasks, such as:

- identification of global trends and ensuing threats and opportunities and quick adaptation to evolving circumstances;
- analysis and foresight in application to global, domestic and regional markets for technology, capital, knowledge, and competences;
- design of complex adaptive systems with innovative properties and management of their life cycle;
- finding optimal solutions factoring in multiple risks;
- management of big international projects involving virtual teams;
- interaction with experts from various domains.

It has to be noted that it is technology in the broadest sense – from targeted scientific research and engineering development projects to innovation implementation – that is a bundle of interdisciplinary connections [33, 34]. This makes it essential for an effective manager to be knowledgeable about the engineering basics of production and trends in science and technology. The authors believe that industries with super-complex technologies that can be potentially hazardous to the global eco-system (critical infrastructure industries), such as power engineering, the nuclear and aerospace industries, petrochemical production, transport, engineering and telecommunication infrastructure in cities require that managers first master the most complex interdisciplinary connections between equipment, economy, environment, and the human factor. They need to acquire versatile professional knowledge and be aware of the technical and technological specifics of the industry, the unprecedented responsibility and role of the industry in the economy.

The electric power industry serves as an illustrative example. The electricity and capacity market operates according to a certain algorithm with fairly rigid dependence on complex technological features of electric power production and mode restrictions. The production plan is determined by the operational modes of generating and grid capacity, the place of a power plan in the load schedule of the energy system and instructions issued by operational dispatch units. When considering the issue of cost and pricing, factors must be taken into account that influence the efficiency of generators and operating modes of power plants in the grid. The reliability of power supply has the priority over financial efficiency. It must comply with standards imposed by regulatory authorities and is controlled by the grid operator that maintains operating modes.

The main tools employed for *strategic management* in power engineering are rather special, too: creation and maintenance of strategic capacity reserve, flexibility of generation to eliminated uncertainties of the electrical load schedule; the energy company's policy on renewal of capital assets, demand-side management and reliability. The introduction of the Smart Grid technology makes the scientific and technological and engineering side of electrical power production and its impact on the effectiveness and timeliness of managerial decisions far more complex.

The uncertainty of the environment which energy companies operate in has grown unprecedentedly in general (financial and political crises; man-made disasters, an unstable economic situation of major energy consumers) and shows

1. the probabilistic nature of demand for electrical power and capacity temporally and region-wise;
2. instability of the stock market and inability of the banking system to provide loans to the electrical power sector due to the lack of long-term funds;
3. constantly changing tariff and energy market regulations;
4. irregular dynamics of domestic prices of fuel, natural gas above all;
5. uncertainty in the energy equipment market and about the cost of construction of major energy facilities.

It is also important that an energy company has to adequately respond to numerous regulatory activities performed by industry oversight agencies as part of the national energy policy (regional energy policy). For example, this concerns long-term capacity reserves and the expansion of electrical connections between grids in order to increase the system reliability of power supply. It is also necessary to build customized peaking power plants in specific grids to maintain the capacity balance as load schedules are expected to become increasingly uneven in regions because of an accelerated growth in the number of non-industrial consumers with peaky consumption patterns. Another important task is to develop small-scale (distributed) generation in regions, which would help offset the economic inertia of the "big" electrical power industry. It is also crucial to promote demand-side management programs as they introduce systemic changes to the energy company's relations with consumers.

Similar examples of cascades of interdisciplinary challenges for industries related to critical infrastructures make it necessary to create special mechanisms to ensure the sustainable development of complex OTSs, which, on the one hand, allow systems to maintain operational reliability, and, on the other, improve their adaptation to a changing external environment.

4 RESULTS AND DISCUSSION

Efforts aimed at designing and constructing systems and keeping them operational require teamwork that is aimed at reaching common goals and is based on holistic vision. In order to effectively perform systems engineering activities, it is necessary to make sure that the capabilities and dynamics of the team match the tasks being handled.

A systems engineering team can consist of professionals who each is responsible for a specific technical process (a requirement engineer, a systems architect etc.). It is also possible to form teams that maintain individual subsystems and are coordinated by a central team. Ideally, the team format should correspond to the distribution of roles, responsibilities, and authority in the project. The roles of the team members are determined by the structure that is in line with the strategy of the organization.

We shall illustrate this with a case from the authors' experience of forming interdisciplinary teams for the technological overhaul of a complex OTS – a large energy company that incorporates various power plants (a condensation power plant, a CHP, an HPP), several regional heating supply companies and its own engineering and technical center. The installed electrical capacity of the company is 1,256 MW; installed heating capacity is 5,886 Gcal/h. The type and scale of the company's business make it possible to classify it as a critical infrastructure system.

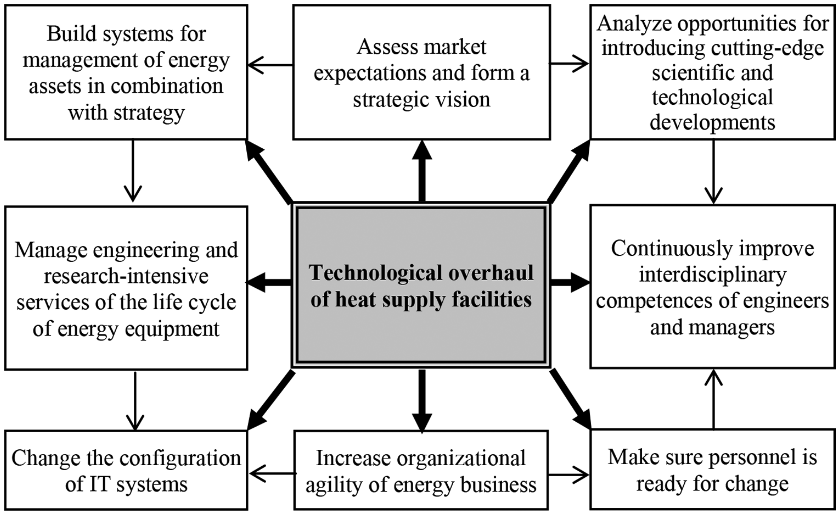

Figure 2: Tasks of organizational overhaul of OTS.

Figure 2 shows the logic of the tasks that emerge in the course of a technological overhaul. The tasks have multiple aspects to them and arise from the need to increase the agility of the OTS, which would subsequently boost modernization processes and help overcome the inertia that is typical of "big" entities in the energy sector. At the same time, the system needs to become more agile, for example, in terms of its capability to restructure itself and better interactions among the components of the OTS. That needs to be done for meeting the priority requirement for a reliable and uninterrupted power and heat supply.

In other words:

- the principles of resilience enable the organizational-technical system (the energy company in question) to stay viable;
- the principles of agility applied to individual elements of the system trigger modernization process in individual units and ensure the development of the system as a whole.

Individual processes (business areas) within the company that are connected with the technological overhaul of heat generation facilities and networks are subject to the CURVE factors defined in Table 2.

In order to mitigate the above factors, a decision was made to set up so-called interdisciplinary breakthrough teams within the company that would consist of professionals in various domains. By engaging the teams in strategy-building activities, the development and testing of forward-looking technical and economic solutions that corresponded to the vision, it was possible to present three innovative projects to the company management within a fairly short period of time (18 months). The projects were aimed at new market exploration, renovation of capital assets and launch of new production facilities, reform of the corporate culture and a transition to the professional development of the personnel. Interdisciplinary teams address problems that cannot be solved within the existing paradigm (internal architecture of the company). That's why their task is to change the traditional approach to systemic development and business processes. aT the same time, the members of the team continue to head

Table 2: CURVE-factors of environment in application to the studied OTS.

Factor		Characteristics	
		Proactive	Reactive
C	**C**apriciousness: unknowable situations	Unitended consequences of the use of new technical solutions; personnel training and adaptation programs are future-oriented; require change in established practice and envisage interactions with customers who have specific demands for energy supply	Energy efficiency programs implemented by consumers; possible establishment of free zones in the area whose tenants have unconventional requirements for electricity supply; proficiency of young specialist lags behind market demands
U	**U**ncertainty: randomness with unknowable probabilities	Uncertain compatibility (behavior) of equipment and automation solutions of different types and by different producers	Major consumers increase and decrease consumption depending on market situation; development of on-site and small-scale generation
R	**R**isk: randomness with knowable probabilities	Technological development of facilities (technical overhaul plans), launch and decommission of capacity, staff training contracts with training contractors	Electricity and gas tariff regulation; impact of climate on consumption
V	**V**ariation: knowable variables and associated variance ranges	Testing, fine-tuning and utilization of new technological solutions at existing facilities, different proficiency levels	Facilities with different service life, operational parameters and specifications
E	**E**volution: gradual successive developments	Development and implementation of corporate development strategy (including, technology, social, environmental and other aspects)	Launch of new facilities equipped with cutting-edge equipment, upgrades to machines during major repairs, natural process of recruitment, dismissal and reemployment of staff

their units and promote ideas to their co-workers. So-called growth points appear. They do not destroy the system, but ensure the flexible development of its individual components.

Figure 3 depicts interactions with an Interdisciplinary Breakthrough Team (iTeam). The figure was constructed on the bases of architectural patterns of agile systems.

Breakthrough teams boast the following competences (capabilities).

1. They see what happens beyond the system boundaries and understand how it will affect it.
2. The can estimate the feasibility of transformations (considering resources, intellectual potential, time) and select instruments (means) for executing them.

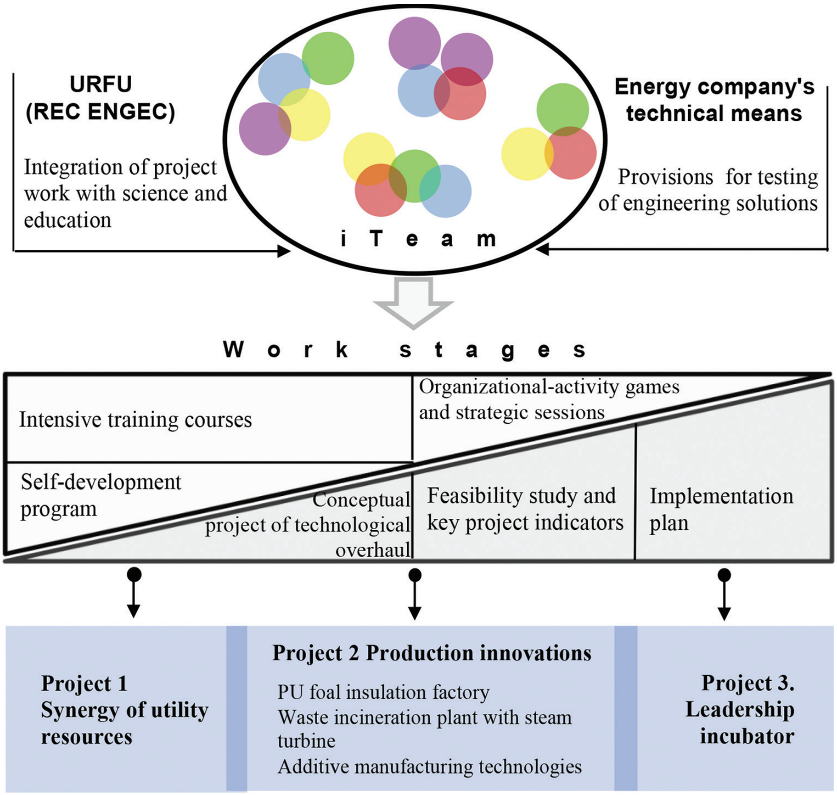

Figure 3: Formation of interdisciplinary teams for technological overhaul.
Note: The color circles indicate that the team includes professions in different domains.

3. They realize what transformations need to happen in the mindset of staff members and identify growth points in the process.
4. They have conceptual design skills.

In general, it was possible to make the OTS in question more agile by

- engaging the management in a discussion of the initiatives and securing the top managers' support for the teams;
- carefully selecting members of the teams, who were subjected to a series of diagnostic procedures and special procedures that boost teamwork at different stages;
- developing simultaneously engineering and organizational solutions, which made it possible to minimize transformation risks in the company;
- active participation of REC ENGEC consultants as moderators, who provided a holistic vision of technological overhaul tasks and of the end result.

5 CONCLUSION

Elements of critical infrastructure must be highly resilient and, at the same time, be capable of development and rapid response to operation conditions. By sticking to the principles of resilient systems design, it is possible to maintain the required functionality in adverse conditions and add components to the system that ensure its development and transformation.

The most acute problem in the implementation of the latter possibility stems from the inertia of an organizational system and the difficulty of striking the balance between the required resilience and agility. The problem cannot be handled without serious organizational transformations that have to be conducted by interdisciplinary teams.

The method of agile systems-engineering that was developed as part of systems engineering could be used for assembling and training such teams. However, the method needs some adjustment due to the specific goals that breakthrough teams are faced with and their conditions they operate in.

Research into the training of such teams for a major energy company made it possible to identify critical competences (capabilities) that such a team need to possess.

The mechanism of integrating such teams into the system of critical infrastructure facilities need further elaboration so that the potential of such teams could be exploited to the full and the balance between the resilience and agility of the system in general is maintained.

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