Socio-technical system design: a general systems theory perspective

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Abstract *— Here we intend to study the idea of socio-technical system design from a General Systems Theory (GST) perspective and develop a general framework for the design process. The study is organized around the basic ideas and the principles of GST, Cybernetics and Cognitive Systems Engineering (CSE) - two of the major trends in GST. Due to the multidisciplinary nature of GST, hence Cybernetics and CSE, the proposed design procedure includes technological, economic, and behavioral dimensions. Cybernetics provides a structural framework and helps designers to program all the activities required for control and communication. CSE, on the other hand, primarily guides designers in modeling human-machine relationships. Consequently, the design process is modeled as a socio-technical construct, integrating technical, human, organizational, economic and cultural attributes of the system. GST provides a strong theoretical context, making the framework adoptable in diverse fields, including process, manufacturing, and service industries.*

Index Terms — Socio-Technical System, System Design, General Systems Theory, Cybernetics, Cognitive Systems Engineering

INTRODUCTION

Industrial systems or organizations of modern society are complex and dynamic sociotechnical systems (STS); they have multiple interacting parties and multiple goals. They contain uncertainties in relation to complex technology and the environment that are tightly-coupled. Most of these systems or organizations are very complex, uniquely dynamic, and have to exist in a constantly changing environment; they must adapt to this change rather quickly. The daily activity and strategic control and steering of these systems or organizations are based on partly implicit norms, values and conceptions. Hence, control and management of such systems are far more difficult than controlling physical systems. The complexities created by the interactions of technology, human beings and the organization present quite serious challenges. STS paradigm has been developed over the last decades to address these issues.

It is widely acknowledged that a socio-technical approach to system development produces systems that are more acceptable to end users and to stakeholders [Reiman and Oedewald, 2007]. The origins of STS go back to 1950's when Tavistock Institute in London generated a new insight on how to combine technical capabilities and social aspects of organizations to system design. In a relatively early study, Purser [1992] interpreted the sociotechnical systems design principles for computer-aided engineering. Clegg [2000] discussed the sociotechnical principles for system design, providing a critical view of the issues involved. Carayon [2006] is another researcher who worked on human factors of complex sociotechnical systems. The STS approach was also adopted in information systems area. However, the approach and its principles failed to appeal to information systems researchers and practitioners and lost the ground to the best-practices like BPR (business process engineering) in the 1990s. Japanese lean production methods, based on total quality management (TQM) and just-in-time (JIT), and the American-based BPR became more popular approaches in industrial engineering and plant design. It is claimed that this "failure" was due to the dramatic transformation of competitive environment and difficulties involved in adopting the STS design to accommodate rising theoretical and practical needs [Ghaffarian, 2011].

The declining interest in STS theory was revitalized in the 2000's by the contributions coming from social sciences. The new socio-technical approaches in information systems suggest improvements in sociotechnical principles by relying on theories from the social sciences. Baxter and Sommerville [2010] suggest the following for improvement: (a) It is not enough to simply analyze a situation from a socio-technical perspective; this analysis must be explained to engineers; (b) many companies have invested heavily in software design methods and tools, so socio-technical approaches will only be successful if they preserve and are compatible with these methods; (c) suggestions on how socio-technical analyses can be used constructively when developing and evolving systems is needed; (d) terminology alien to engineers must be avoided so that they can generate value that is proportionate to the time invested via a socio-technical approach.

It is expected that the present paper will be addressing some of the issues summarized above. The authors' approach to STS design, as presented in this paper, can be situated within the framework of General Systems Theory (GST). In particular, the structural framework is based on the principles of Cybernetics, and the design methodology adopted is "soft" in nature, integrating cognitive aspects. It is believed that the design process proposed integrates technical, human, organizational, economic and cultural dimensions adequately.

The plan of the paper is as follows: the relationship between STS and Cybernetics, within control system design

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context, is provided in the next section. This will be followed by the presentation of the proposed design approach. The major conclusions of the work and suggestions for future research are given in the last section of the paper.

GENERAL SYSTEMS THEORY, CYBERNETICS, COGNITIVE SYSTEMS ENGINEERING, AND SOCIOTECHNICAL SYSTEMS

GST has the following goals: (1) to formulate generalized systems theories including theories of systems dynamics, goal-oriented behavior, historical development, and control processes; (2) to work out a methodological way of describing the functioning and behavior of systems objects; (3) to elaborate generalized models of systems [Skyttner, 2001and 2006]. GST assumes that all kinds of systems (concrete, conceptual, abstract, natural and man-made) have common characteristics. There are various trends in GST that can be adopted for analysis, control, and design of complex systems. They have similarities, but they also provide different perspectives. Rudolf Seising [2010] studies the relationship between cybernetics, system(s) theory, information theory and fuzzy sets and systems. He thinks that Cybernetics and Shannon's communication theory were influential on two scientific areas: systems theory and information theory. Furthermore, he suggests that Bertalanffy's ''General System Theory" – or simply ''systems theory" became even more famous in humanities in the 1960s, with a mixed success.

Automation can be defined as the execution by a mechanism or a machine of a function that was previously carried out by a human [Parasuraman & Riley, 1997]. In general terms, automation systems can be designed through one of the following approaches [Hollnagel & Woods, 2005]: in The Left-over principle, technological parts of the system are to do as much as feasible, from an efficiency point of view, while the rest are left to the operators to do. The capabilities and limitations of human beings are not taken into consideration in an explicit manner. In The Compensatory Principle or Fitt's List, capabilities and limitations of humans and machines are compared on a number of salient dimensions, such as speed, power output, consistency, information capacity (transmission), memory, reasoning/computation, sensing, and perceiving. Control system is then designed, allocating functions to humans and machines in an "optimal" manner. The Complementarily Principle and Function Congruence, which became popular in the 1990s aims to sustain and strengthen the human ability to perform efficiently and therefore considers the work system in the long term, including how work routines change as a consequence of learning and familiarization. Here the main concern is the ability of the system to sustain acceptable performance under a variety of conditions rather than the temporary level of efficiency.

Cybernetics is a strand of GST where living systems are studied through analogy with physical systems, interpreting feedback theory and control, self-regulation and automation into a comprehensive perspective. Philosophically speaking, Cybernetics is based on a constructivist view of the world objectivity, derives from shared agreement about meaning. Hence, control is concerned with these activities, not only among the parts of a system, but also between it and its environment. The aim of control is to achieve a condition of equilibrium, which is the maintenance of order. Organizational Cybernetics or Managerial Cybernetics seems to offer valuable models for organizational design. In particular, the Viable System Model (VSM) developed by Beer views an organization as a living organism with a brain rather than a static system as suggested by organizational charts, and considered to be significant in organizational design [Jackson, 2000 and 2003].

Designing control or automation systems as socio-technical constructs were expressed by many researchers in the past. Rousseau [1977] reported that "studies in job design and Socio-Technical Systems Theory emphasize the importance of job characteristics to employee satisfaction and motivation, hence the success of the resulting system." Martin, Kivinen, Rijnsdorp, et.al. [1991] stated that "automation that is appropriate for application in realistically complex socio-technical domains should be based on an integrated understanding of the technical, human, organizational, economic and cultural attributes of the application". Among others, similar arguments are put forward by Parasuraman and Riley [1997], Hollnagel and Woods [2005], and Rasmussen, Pejtersen, et.al. [1994]; the latter two works are considered important in Cognitive Systems Engineering (CSE). According to Hollnagel and Woods [2005], CSE was formulated in the 1980s as a proposal to overcome the limitations of the information processing systems (IPS) paradigm, which is the conventional paradigm in human-machine system design. Here the focus is on how system parts communicate with each other. The Joint Cognitive Systems (JCS) paradigm, on the other hand, developed by Hollnagel and Woods tends to focus on how the joint system performs as a whole. This approach appears to be relatively closer to the "spirit of GST". The originators think that better control systems can be designed via the use of this paradigm. Rasmussen, Pejtersen, et. al. [1994] also suggest that CSE is a powerful approach for human-machine system design, and it is applicable across a spectrum of single machine systems, socio-technical systems, and whole organizations, ranging from process and manufacturing industries, to military and service systems. Millitello, Lintem, and Dominguez [2009] present a CSE approach to system design in defense industry which brings out the cognitive aspects of system design successfully.

Cybernetics and CSE do not exclude each other. On the contrary, they are complementary approaches to system design. Cybernetics tends to provide a structural framework, and help designers to program all the activities required for control: information processing, decision, and communication. CSE, on the other hand, mainly guides the designer in modeling human-machine relationship in the process. STS design involves work across multiple boundaries and requires better integration of the various disciplines and sub-disciplines; collaboration of people is needed in the design phase, as well as in the implementation, adaptation, and improvement phases. Carayon [2006] reports the design of health care and patient safety and of computer security system and shows the importance of human factors throughout these phases. Hirschhorn, Noble and Rankin [2001] examine the case of redesign of a chemical pilot plant, leading to a reconsideration of basic STS concepts. Lin and Chen [2000] study the impact of social factors on the success of automation, and conclude that social factors significantly predict the degree of success of automation; a proper alignment between technical and social factors are highly valued for the implementation of automation.

Molleman and Broekhuis [2001] state that several authors have questioned the usefulness of the STS tradition as a source of continuing theoretical and practical insight into problems associated with stability and change in complex STS. They argue that for the study of large-scale STS to move "beyond STS theory," it is important that explicit comparisons between these different traditions be made. Kaghan and Bowker [2001] compare STS theory and actor network theory (ANT) and examine how STS and ANT can be viewed as responses to rationalist/functionalist research on large sociotechnical systems. They propose a new pragmatic framework for socio-technical systems engineering (STSE) which builds on the (largely independent) research of groups investigating work design, information systems, computer-supported cooperative work, and cognitive systems engineering (CSE). Papamichail and Robertson [2005] integrate decision making and regulation in the management control processes and develop a generic model of the management control process. This system can interact directly with operational processes, implementing closely bound control and evolution. Paucar-Caceres and Wright [2011] propose a framework to reflect on the development of four information systems (IS) paradigms; (1) positivist/normative; (2) soft/interpretive; (3) critical/pluralistic; and (4) constructivist/2nd order cybernetics. They conclude that Information Systems Research is moving away from the normative/positivistic paradigm associated with hard-oriented methodologies.

Some researchers view systems thinking and system design issues from a managerial science or social sciences point of view. Jackson [2000 and 2003] suggests that critical systems thinking is one of the few approaches available to management scientists for analyzing complex societal problems and intervening to resolve them.

One of the applications along these lines was reported by Gang, Shaobo, and Qingfei. They explore the relationship between organizational environment, inter-organizational coordination, IT support, and the effectiveness of inter-organizational coordination via applying cybernetics and information processing theories. Hong, Sawyer, and Sommerville [2006] make use of cybernetics point of view and control theory to define a requirement engineering (RE) process control system; they look at its dynamic and steady-state performance, and identify the steps involved in designing, analyzing and improving such systems. Similar ideas can be seen in the work reported by Morel, Panetto, Zaremba, et.al. [2003]. They suggest that automation engineering should be integrated into the systems engineering approach to achieve a holistic approach. Therefore, they think, the technical operational manufacturing system will emerge from the deployment of an ad hoc combination of formal and informal partial models, leading to the Integration in Manufacturing (IiM) systemic paradigm. This paradigm, they argue, will "organize humans and machines as a whole system, not only at the field level, but also at the management and corporate level to produce an integrated enterprise system". Ivanov, Sokolov, et. al. [2010] also dealt with some of these issues while designing a multi-structural framework for planning and operations control for an adaptive supply chain via the use of a cybernetic structure that involves control theory, operations research, and agent-based modeling.

THE SYSTEM DESIGN FRAMEWORK DEVELOPED

The authors of this paper believe that highly complex systems cannot be designed with a single "super" methodology or approach. Views similar to this are expressed by many researchers in the field. One can find numerous applications in literature where more than one methodology or methods are combined to achieve a good design. A typical design study is reported by Bahiri & Tabrizi [2010], where systems thinking and theory of constraints are used, in a holistic manner, in locating a new distribution center in supply chain system. The approach known as Total Systems Intervention, developed by Flood and Jackson, addresses this particular question [Flood and Carson, 1993], [Jackson, 2000], and [Jackson, 2003]. Flood and Carson [1993] state the following: "It is our view that the future prospects of management science will be much enhanced if (a) the diversity of "messes" confronting managers is accepted, (b) if work on developing a rich variety of methodologies is undertaken, and (c) if we continually ask the question: "What kind of problem situation can be 'managed' with which sort of methodology?"

Two system methodologies are selected to serve as the backbone for the framework in the present work:

Cybernetics and Joint Cognitive Systems (JCS). They are both general enough to accommodate a range of hard and soft design issues in a range of applications. However, they need to be supported by other methodologies or approaches as the situation demands.

1. THE CYBERNETIC CONTROL STRUCTURE

Most of the control hierarchy structures can be based on the cybernetic or general control system structure shown in Figure 1[Skyttner, 2001 and 2006]. Because of its generality, it can be adopted at different levels of a control hierarchy for different purposes. This is how it works: In this basic control cycle, the receptor (sensor or detector) registers various stimuli. After its conversion into information, it is sent to the controller unit. The comparator (or discriminator) compares this value with a desired standard, and the difference, being a corrective message, is implemented by the effector (activator). Through monitoring and response feedback to the receptor, self-regulation is achieved. The controller may take a more sophisticated role when it includes a goal-setter with its standard reference, and a decider (selector). Some controllers may also include a designer which formulates both the goals and the decision rules of the system. In all layers of the hierarchy, particularly at the higher levels, the design may require that the system has learning capabilities. The most significant advantages of living systems are considered to be adaptation by learning [Skyttner, 2001 and 2006]. In a learning system, the rules must be adjusted in such a way that a successful behavior is reinforced, whereas an unsuccessful behavior results in modification.

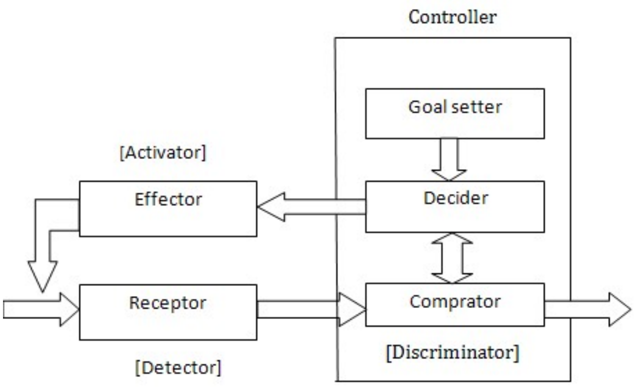

FIGURE. 1
A GENERAL CONTROL SYSTEM

The designer needs to make use of managerial cybernetics at the upper level of the hierarchy. Managerial Cybernetics provide the guideline for designing an appropriate organizational structure, including (a) specification of the organization's subtasks and partition of work; (b) design of communication between subsystems; (c) definition of areas of decision-making and authority; (d) design and development of control systems and co-ordination of efforts toward the organizational goal. The automation and control hierarchy may also involve the use of decision support systems. The advances seen recently in computer and communication technologies certainly increased the importance of decision making and decision support in complex systems, particularly at managerial levels.

2. THE CONTROL HİERARCHY

GST's law of Requisite Variety states the following: control can be obtained only if the variety of the controller is at least as great as the variety of the situation to be controlled. In relation to this principle, Hollnagel and Woods' [2005] classify the control system design approaches as follows: Designing for Simplicity, and Designing for Complexity. The former is based on reducing the demands on tasks or increasing the controller capacity, or doing both. Although it seems that it is possible to handle the system complexity by reducing the mismatch between the demand and capacity, the resulting system will have a built-in limitation. This is due to what is known as the n+1 fallacy: the system is designed to handle n number of possible states, but there is always the state n+1 that has not been accounted for. Designing for Complexity, on the other hand, is based on the premises that complexity cannot be reduced to an arbitrary low level. In other words, the Law of Requisite Variety should be satisfied; that is the controller or operator should have at least as much variety as the system to be controlled. Since the designer cannot reduce the requisite variety through interface design, she/he has no choice but to increase the variety of the controller. The resulting system is bound to perform relatively better since complexity of the reality is acknowledged rather than simplified. In fact, experiences seem to indicate that designing for simplicity is possible if one can transform the complexity involved according to a set of well defined rules, which is hardly the case in the real world. In short, these researchers suggest the following: 'rather than designing for a simple world that does not exist, the goal should be to design for the complex world that does.'

The ECOM (The Extended Control Model) developed by [Hollnagel and Woods, 2005] is shown in Figure 2. This model basically provides means of describing how a joint cognitive system (JCS) can perform on several layers of control in a hierarchical system. The model is made up of several concurrent control loops, some of which are closed-loop or reactive type, others are open-loop or proactive type, and some others are mixed. The tracking at the low end includes the activities required to keep the JCS within specified performance boundaries – these boundaries may be related to efficiency, safety, etc. The goals and criteria for the activities involved in this layer are determined by the regulating layer. The activities here are primarily closed-loop type. Regulating is basically a closed-loop activity, but may involve some anticipatory control. The activities at this layer may not take place automatically, therefore may require some attention and effort. The plans and objectives for this layer are provided by the monitoring layer. However, the goals and plans provided may be changed, depending on the circumstances. At the monitoring layer, the objectives are set and plans are activated into actions.

The targeting layer is concerned with targeting or goal setting. Some sub goals and activities may be generated too, following the goal-setting procedure; some of these may be automated or supported by information systems, while others may be related to performance criteria. The goal-setting activity is definitely open-loop type, implemented by a nontrivial set of actions, and often covering an extended period of time.

3. SOME REMARKS ON THE DESİGN PROCEDURE

A large system per se normally signifies a greater complexity as more subsystems and more processes are in operation simultaneously. Consequently, a certain level of complexity in the control of large-scale systems cannot be avoided. Below the reader will find a summary of GST principles [Skyttner, 2001 and 2006] that are directly related to system design.

The law of requisite hierarchy of GST states that the weaker and more uncertain the regularity capability, the more hierarchy is needed in the organization of regulation and control to get the same result. The redundancy of potential command principle of GST, on the other hand, says that in any complex decision network, the potential to act effectively is conferred by an adequate concatenation of information. System stability is also a difficult issue to resolve in complex systems. GST has the following principles in relation to system stability that must be considered in system design: Basin of stability principle: complex systems have basins of stability separated by thresholds of instability. A system dwelling on a ridge will suddenly return to the state in a basin.

Viability principle: viability is a function of the proper balance between autonomy of subsystems and their integration within the whole system, or the balance between stability and adaptation; Steady-state principle: for a system to be in a state of equilibrium, all subsystems must be in equilibrium. All subsystems being in a state of equilibrium, the system must be in equilibrium; Redundancy of resources principle: maintenance of stability under conditions of disturbance requires redundancy of critical resources;

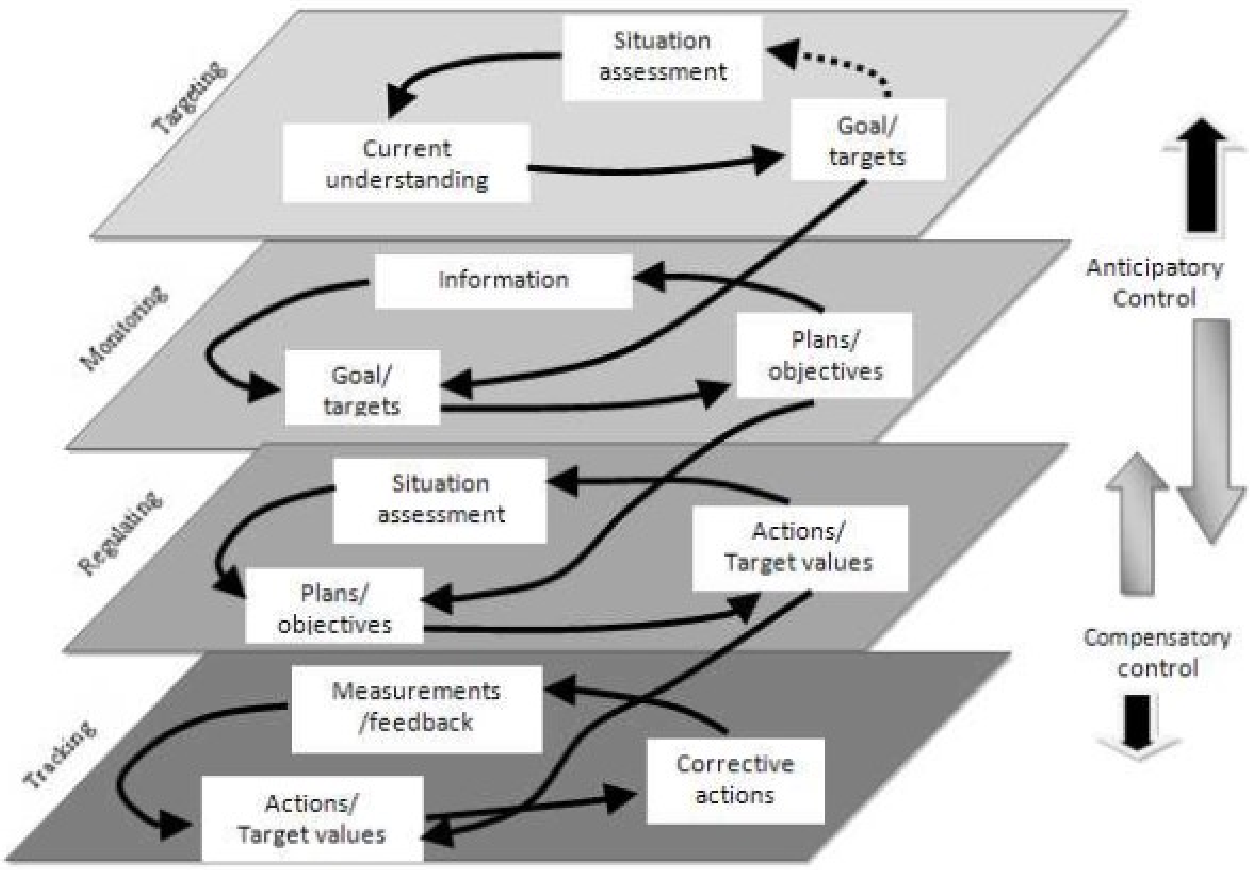

FIGURE. 2
THE ECOM (THE EXTENDED CONTROL MODEL)

Relaxation time principle: system stability is possible only if the system's relaxation time is shorter than the mean time between disturbances; Negative feedback causality principle: given negative feedback, a system's equilibrium state is invariant over a wide range of initial conditions (equifinality); Homeostasis principle: a system survives only so long as all essential variables are maintained within their physiological limits; The variety-adaptability principle: systemic variety enhances stability by increasing adaptability; The flatness principle: the wider their base in relation to their number of hierarchic levels, the more stable organizational pyramids will be. A larger number of independent actors increase stability.

The system separability principle: system stability increases as the mean strength of interaction between components is decreased. Stability is enhanced by separating the elements of the system from one another; the buffering principle: stability is enhanced by maintaining a surplus. An unused reserve cannot however help the systems; the patchiness principle: the lack of capacity to use a variety of resources leads to instability. Rule-bound systems, stipulating in advance the permissible and impermissible, are likely to be less stable than those that developed pell-mell; the principle of adaptation: for continued system cohesion, the mean rate of system adaptation must equal or exceed the mean rate of change of environment.

The classical view of decision support is based on normative decision making process within the framework of information processing paradigm. In the JCS paradigm, 'a more descriptive or naturalistic approach' is suggested [Hollnagel and Woods, 2005]. It is fairly well known that even the most sophisticated AI-based intelligent systems or expert systems cannot cope with complex reality; they reduce the complexity to their level. Hence, they can provide only partial answers to ill-defined problems. Also, fully automated systems based on heuristic processes are known to be problematic. In short, extreme caution must be exercised in automating and in building decision support systems in human-machine systems.

Further research on the topic may be conducted in the following directions: (1) the proposed cybernetic structure and the cognitive model (ECOM) need to be well integrated; (2) the roles and the practical implications of all the GST principles must be defined formally in the design procedure; (3) a more detailed study on the role and implementation of decision support systems should be conducted; (4) the framework must be tested on real- world systems, such as on design of control systems for supply chains.

CONCLUSİONS

In this paper, the major issues involved in socio-technical system design in general, and control system design in particular, were explored from a General Systems Theory (GST) perspective. A framework based on a cybernetic structure and a cognitive system model was developed. This framework also includes some principles of GST that need to be considered in design. The design process described views the system to be designed as a socio-technical construct, integrating technical, human, organizational, economic and cultural attributes. Some directions for further research are also stated.

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