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Transmorphance of socio-technical systems: A conceptual framework for adaptive security

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Abstract: The article presents a new conceptual framework for analyzing and ensuring the security of socio-technical systems based on the fundamental difference between functionally stable and evolutionarily dynamic systems. Unlike the former, which are organized around clearly defined functions, the latter are structured by ontological invariants and exhibit the properties of complex adaptive systems: nonlinear dynamics, emergence, self-organization, and path dependence.

It has been shown that traditional approaches to ensuring the security of socio-technical systems: robustness, survivability, and resilience - are proving insufficiently effective in an era of growing complexity of such systems and increasing environmental volatility. These approaches are primarily focused on maintaining or restoring the initial state of the system, rather than ensuring the possibility of its fundamental transformation. The growing interconnectedness and dynamic nature of current socio-technical systems require new theoretical foundations capable of accounting for radical structural changes while preserving the identity of the system.

Based on five key axioms of complex systems: non-locality and multiplicity of components, emergence, nonlinear dynamics and path dependence, self-organization and adaptation, the authors introduce the concept of transmorphance – the ability of evolving socio-technical systems to survive radical structural transformations while preserving the ontological invariants that define the identity of the system. Transmorphance conceptually surpasses existing approaches by offering a paradigm of adaptation through change of form rather than preservation.

The concept is empirically confirmed by a comprehensive analysis of the evolution of Jewish statehood over nearly three millennia. The analysis reveals key mechanisms of transmorphance, including the evolution from centralized territorial structures to distributed networks of autonomous communities linked by common legal norms and symbolic codes.

Comparative analysis allows us to distinguish transmorphance from related concepts, in particular from antifragility and adaptive capacity from resilience literature. While antifragility focuses on extracting benefits from volatility within existing structural forms, transmorphance implies fundamental morphological transformations. Unlike adaptive capacity, which usually implies gradual optimization, transmorphance involves discrete transformations similar to phase transitions that change the basic paradigm of the system's functioning.

The proposed approach expands the theoretical foundations of socio-technical system security management and offers new adaptation strategies in an era of high systemic volatility. Practical implementation of the theory includes the need to increase the adaptive potential of such systems and develop adaptive mechanisms capable of using crises as opportunities for systemic evolution.

Keywords: socio-technical systems, complex systems, transmorphance, adaptation, emergence, self-organization, resilience, robustness, information security management, adaptive potential.

1. Introduction

Current socio-technical systems operate in conditions of increasing complexity and uncertainty, where traditional approaches to security are proving to be of limited effectiveness. Classical concepts of robustness, survivability, and resilience, focused on maintaining or restoring the initial state of the system, are insufficient for systems that must adapt to radically changing environmental conditions.

In response to these challenges, there is a need for new theoretical approaches that can take into account the specifics of evolving systems and their adaptive capabilities. Of particular interest are systems that demonstrate the ability to survive through fundamental transformation of their structure while maintaining their basic principles of functioning.

The aim of the research is to develop a conceptual framework for analyzing adaptive strategies of complex socio-technical systems and to introduce a new concept of transmorphance as a form of ultimate adaptability. The scientific novelty of the work lies in the operationalization of a fundamentally new mode of system adaptation that surpasses existing approaches to ensuring the security of complex systems.

2. The dichotomy of socio-technical systems

If we consider socio-technical systems not from an engineering and operational perspective, but from a systemic and ontological perspective, we discover a fundamental dichotomy that structures the multitude of these systems into two fundamentally different categories: functionally stable and evolutionarily dynamic systems.

The first category is functionally stable systems. This is the world of factories and plants, power stations and data centers – technological ensembles in which the entire structure and activity are subordinated to a clear and unchanging function: the production of a product, the transformation of resources into material or information goods. Their architecture bears the stamp of determinism, and human participation here is reduced to a mechanistic role, strictly regulated and therefore potentially reproducible by a machine, robot, or artificial intelligence.

The second category is evolving socio-technical systems. These are states and organizations, commercial companies and social institutions, religious communities and national entities – the living fabric of society that forms its internal structure.

Such systems are based not on functions, but on deep principles, norms, laws, and values – invariants that determine the ontological essence of the system. Invariants act as an integrative matrix, binding diverse elements into a coherent whole, determining both the internal logic of self-organization and the nature of external communication. This is the semantic infrastructure of the system, its symbolic code, expressing its mission and forming the basis for its interaction with other systems in the space of cooperation or conflict.

Evolving systems behave not like machines, but rather like living organisms, demonstrating the ability to self-organize, adapt, and evolve [1]. Their dynamics obey the nonlinear laws of complex systems, and transformations occur through cascades of bifurcations, phase transitions, and emergent processes.

The difference between these two types of systems is not a trivial classification based on functional characteristics – it expresses a deeper difference between two modes of system existence. One is the world of closed, functionally oriented, linearly describable "machines," the other is the world of open, transforming, self-organizing "organisms" [2]. Consequently, managing and ensuring the security of these systems requires not just different tools, but a different mode of thinking, capable of taking into account nonlinearity, multiplicity of states, emergence, and path dependence.

3. Five axioms of complex systems

The science of complexity, which emerged as a response to the crisis of reductionism in the natural and social sciences, provides the necessary conceptual apparatus here. Its central heuristic is the understanding of a system as an ensemble of interactions in which the properties of the whole are not derived from the properties of the parts, but manifest themselves as emergent effects arising in the process of nonlinear coordination between components [3-5]. In this logic, the behavior of a system is determined not so much by its composition as by the configuration of its connections, their synchronization, density, isomorphisms, and feedback modes. Moreover, in complex systems, these connections are not static: they can evolve, reconfigure, disappear, and reappear, forming a new system ontology in real time.

This understanding leads us to five key axioms of complex systems that should be used as a starting point when developing management and security strategies [6]:

Non-locality and multiplicity of system components. Complex systems consist of many components that interact with each other and with the environment in various ways. Each component can perform multiple functions, engage in diverse interactions, and generate nonlinear effects at different levels of organization. These components are often combined into network nodes and can themselves represent entire subsystems – so-called systems-of-systems. This means that the ontological status of a component is relative: in one context, it can be an element, in another – an entire structure with internal dynamics. The behavior of such systems is non-local: a local change can cause global effects. Information itself is not so much transmitted as generated within interactions. This means that reducing the behavior of a system to its parts is logically untenable: there is no linear correlation between knowledge about the parts and understanding of the whole.

Emergence. One of the key characteristics of complex systems, radically distinguishing them from simple or linearly aggregatable systems, is emergence – a phenomenon in which the behavior of the whole cannot be deduced from the properties of its constituent elements [7]. In simple systems, even those with a large number of components, macroscopic properties can be predictably reconstructed from microscopic ones. In other words, knowledge of the parts gives knowledge of the whole. However, in the case of complex systems, this rule ceases to work. Here, the behavior of the whole cannot be derived from the properties of the components. This is not a lack of knowledge, but a fundamental property of complex systems.

That is why complex systems require not just different approaches to safety, but a new philosophy in which the interaction of system elements becomes primary in relation to their composition and properties. In this context, emergence is not an anomaly, but a necessary condition for the existence of complexity.

Nonlinear dynamics and path dependence. Complex systems evolve unevenly and, as a rule, irreversibly. Their behavior can be chaotic, but not random, rather sensitive to initial conditions. They do not return to their previous state – they evolve. Unlike mechanistic systems, whose behavior can be described as a linear function of time and input, complex systems exist in time differently: not as a repetition, but as a process of becoming, in which small fluctuations can lead to radical reorganizations.

Complex systems are generally nonlinear in nature: their variables change asynchronously, sometimes with delays, sometimes with exponential acceleration. Moreover, many such systems demonstrate multiple stability regimes – they can remain stable under certain conditions but become extremely vulnerable when approaching critical thresholds. It is at these points that bifurcations are possible – moments when the system goes into a different state, irreversibly changing the trajectory of its development.

Some systems exhibit chaotic behavior: they remain deterministic at the level of calculations and forecasts, but unpredictable in practice.

Of particular importance is the phenomenon of path dependence: in complex systems, the future is determined not only by the current state but also by the entire history that preceded it [8].

This means that security strategies for complex systems cannot be reduced to simple reactions to external influences, to a linear "threat-response" scheme. In conditions of nonlinear dynamics, structural sensitivity, and path dependence, any adaptive transformation is not isolated but embedded in a chain of previous decisions, each of which not only corrects the trajectory but redefines the configuration of the future. This is why the security of such systems cannot be achieved through local optimization – it requires deep strategic thinking.

Self-organization. One of the most mysterious and fundamental properties of complex systems is self-organization – the ability to form stable, coherent structures in the absence of an external plan or central control [9]. Unlike technical designs, in which order is imposed from outside, in self-organizing systems order arises from within, as a result of multiple, local, often simple interactions between elements that together produce non-trivial global patterns of behavior. In this dynamic, "control" does not disappear, but is distributed – it is not concentrated in a single point, but integrated into the fabric of interactions, manifesting itself in the form of feedback loops, correlations, synchronizations, and local agreements.

Such a system is not controlled – it controls itself, not because it is inherently intelligent or goal-oriented, but because the structure of interactions contains an internal logic of coordination capable of stabilizing behavior, generating new forms and, under certain conditions, evolving.

In the context of ensuring the security of complex evolving systems, the phenomenon of self-organized criticality is of particular interest – states in which the system naturally tunes itself to the boundary between chaos and order, remaining in a zone where even a minor event can trigger an avalanche-like restructuring, and the entire structure becomes sensitive to microscopic fluctuations. The patterns that emerge often have self-similar properties, reflecting the fractal organization of the system, in which the local repeats the global, and the small is structurally similar to the large.

Self-organization affirms the possibility of order without directives, and therein lies its fundamental importance for understanding the principles of ensuring the security of socio-technical systems, since it is precisely in the ability of a system to spontaneously organize itself – in continuous coordination, redistribution, and reorganization – that the key to viability lies in a world where stable structures are inevitably destroyed.

Adaptation. Unlike simple systems, complex systems do not strive for static resilience – they evolve, continuously restructuring themselves in response to disturbances, risks, and fluctuations in the environment [10]. The basis of their development and security is not a return to their previous state, but the ability to maintain functional identity through transformation of form. This is the fundamental difference between the behavior of a simple object moving toward equilibrium (such as a pendulum decaying to its minimum point) and the behavior of a complex system capable of reorganizing itself in the process of adaptation [11].

Survival strategies based on the ability of complex systems to self-organize and adaptively restructure their structure go far beyond not only robustness and survivability, but even resilience, which until now has been interpreted by most as merely the ability of a system to return to its original state. In the context of ensuring the security of socio-technical systems, the concepts of robustness and resilience are undoubtedly important, but they are focused on maintaining the status quo rather than transformation.

While robustness implies resilience to change and resilience implies recovery from incidents, the characteristic response of complex systems to destructive influences is adaptation – not a return to the original state, but a structural, functional, and behavioral restructuring that ensures survival in new conditions.

4. The concept of transmorphance

To describe this form of extreme adaptability, we propose the term ***transmorphance***. Transmorphance can be defined as a property that determines the ability of evolving socio-technical systems to adapt through radical structural transformation – changing their internal architecture, development trajectory, functional and resource contours, while preserving the ontological invariants that define their systemic identity.

Transmorphance can be realized through gradual, continuous changes and the accumulation of small adaptations, or through discrete, abrupt transformations similar to phase transitions or bifurcations. In both cases, it aims to achieve a new, more effective form of systemic existence in changing conditions.

A transmorphant system does not resist change or attempt to reproduce the old order – it uses destabilization as a condition for the emergence of a new form that is better adapted to the environment, in which functional coherence is achieved at a different level of organization. In this sense, transmorphance is not simply a result, but a mode of dynamic adaptation activated when traditional security strategies prove inadequate. Unlike robustness, survivability, and resilience, which can be described in terms of quantitative deviations and a return to normal, transmorphance requires a rethinking of the norm itself – the system survives not by preserving its form, but by its ability to change its form.

In an era when familiar paradigms of development and security are losing their predictive and protective power, the conceptual horizon of the security domain must be expanded beyond resilience in its classical understanding. It is in this context that transmorphance can become a necessary criterion for ensuring the survival of socio-technical systems in conditions where environmental volatility is not a temporary anomaly but a stable background, and stochasticity acquires the status of a systemic characteristic.

5. Empirical validation: the transmorphance of Jewish statehood

The unique history of the Jewish political system provides an exceptional case for empirical validation of the concept of transmorphance. For nearly three millennia, this system has demonstrated the ability to undergo radical structural transformation while preserving ontological invariants. Created by Saul (c. 1020 BCE), the Jewish state possessed all the attributes of a classical political organization: centralized power, a territorial base, and an institutional structure that included some combination of a tribal federation, a monarchy, a priestly theocracy, and the rule of prophets. However, successive destructive influences – the Babylonian (586 BCE) and Roman (70-135 CE) conquests – led to the complete destruction of the territorial and institutional form of the state.

Critical to understanding transmorphance is that the physical destruction of state structures did not lead to systemic collapse. Instead, the system adapted through radical reconfiguration, while preserving key ontological invariants: the legal tradition (halakha), rabbinic authority dating back to the Sanhedrin and based on a continuous chain of transmission of authority, communal structures of self-government, and a symbolic code of collective identity. Rabbinic Judaism is built on Jewish tradition, adapting to new realities. Temple rituals were replaced by prayer services in synagogues. In the diaspora, Jewish communities in Islamic and Christian countries enjoyed a significant degree of self-government, with autonomous institutions, including rabbinical religious courts and independent banking and tax systems.

A key mechanism of transmorphance was the evolution of administrative structures: from a territorially centralized state to a distributed network of autonomous communities (kehilot/kagals) linked by common legal norms and symbolic codes. In medieval Europe, Jewish communities in the diaspora were organized around the kehilla: a semi-governmental body authorized by local authorities to manage civil and religious Jewish life. This is a classic example of transmorphant adaptation: the system survived not by preserving its original form, but by its ability to undergo radical morphological transformation while retaining its functional identity. The restoration of statehood in 1948 completed the cycle of transmorphance, demonstrating the system's ability to return to its territorial-institutional form after almost two thousand years of dispersed organization.

6. Comparative analysis with existing concepts

Transmorphance as a concept of adaptive security requires clear positioning in relation to existing theoretical approaches, primarily N. Taleb's antifragility and adaptive capacity from the literature on resilience.

Transmorphance and antifragility. Antifragility is defined by Taleb as a property where systems not only resist shocks but also benefit from them, becoming stronger under stress [12]. As Taleb emphasizes: "Antifragility is beyond resilience or robustness. The resilient resists shocks and stays the same; the antifragile gets better" [13]. However, there are fundamental differences between antifragility and transmorphance. Antifragility focuses on the ability to benefit from volatility within the existing structural form, while transmorphance implies a fundamental morphological transformation. If an antifragile system improves under stress while maintaining its basic architecture, a transmorphant system survives through a radical change in that architecture while preserving ontological invariants.

Transmorphance and adaptive capacity. In the literature on resilience, adaptive capacity is defined as the ability of a socio-ecological system to cope with novelty, uncertainty, and change without losing its basic functionality [14]. Research shows that adaptive capacity is an "essential characteristic of resilience" and is closely related to system complexity, since "system complexity is a necessary condition for resilience" [15]. However, adaptive capacity is usually conceptualized in terms of gradual changes and gradual optimization of existing structures. Transmorphance, on the other hand, implies discrete, abrupt transformations similar to phase transitions, where a system can radically change the way it is organized.

The key difference of transmorphance is that it operationalizes not just the ability to change, but the ability to change the way one changes. If adaptive capacity describes a system's potential to modify itself in response to external influences, then transmorphance characterizes the ability to undergo a metamorphosis – a transition to a qualitatively different form of existence while maintaining systemic identity. In this sense, transmorphance is a second-order concept that describes not adaptation within a given paradigm, but the transformation of the paradigm of system functioning itself.

7. Conclusion

This study develops a new conceptual framework for understanding and ensuring the security of evolving socio-technical systems in conditions of systemic volatility. Based on the fundamental distinction between functionally stable and evolutionarily dynamic systems, the work introduces the concept of transmorphance as a survival strategy that surpasses traditional approaches of robustness, survivability, and resilience.

The theoretical contribution of the research lies in the operationalization of a fundamentally new mode of adaptation, in which a system preserves its ontological identity through radical morphological transformation. Unlike existing concepts focused on maintaining or restoring system form, transmorphance involves the use of destabilization as a mechanism for transitioning to more effective modes of organization. Empirical validation using the example of the evolution of Jewish statehood demonstrates the practical applicability of the concept for analyzing long-term adaptive processes in complex systems.

The practical implications of the study are related to the need to rethink security management strategies in an era of increasing uncertainty. Transmorphance points to the need to develop adaptive mechanisms capable not only of responding to crises but also of using them as opportunities for systemic reconfiguration. This requires abandoning linear thinking in favor of approaches that take into account nonlinearity, emergence, and path dependence.

Areas for further research include developing metrics for assessing the adaptive potential of systems, studying the conditions that facilitate or hinder transmorphant transformations, and analyzing the role of artificial intelligence and digital technologies in shaping the transmorphant capabilities of current organizations. Of particular interest is the study of how the principles of transmorphance can be integrated into the design of institutional structures and political processes to enhance their adaptive security in the face of global challenges.

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