CHAPTER 12

A COMPLEX ADAPTIVE SYSTEM OF SYSTEMS APPROACH TO HUMAN–AUTOMATION INTERACTION IN SMART GRID

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12.1 INTRODUCTION

Human–automation interaction (HAI) is a typical example of a complex and adaptive phenomenon in two senses: firstly, the collaboratively performed tasks of humans and automation systems are complex and should be adapted to the changing environment; and secondly, the human–automation collaboration itself is a complex phenomenon and should be adapted to the changing environment. Thus, an HAI system can be regarded as a complex adaptive system (CAS).

An HAI scheme primarily consists of the following systems: a core task process (depending on the application field that is electric Smart Grid, in this chapter), a

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human system (as both user and operator), an automation (and control) system, an information technology (IT) system, an HAI sphere, an HAI regulator, and a surrounding environment.

A conceptual outline of this chapter is depicted in Figure 12.1, expressing three cognitive genres representing this chapter as: descriptive genre, normative/prescriptive genre, and know-how genre. The descriptive genre (the second row of the table in Figure 12.1) introduces and discusses on the following disciplines: the core concepts of complexity, CASs and system of systems (SoS) (Sections 12.2–12.5), the application domains of HAI and adaptive autonomy (Section 12.6), especially in Smart Grid (Section 12.7), and two implementation ideas of expert systems (Section 12.9) and Petri nets (Section 12.8). Going upward, the third row in table of Figure 12.1 is related to the normative/prescriptive genre of this chapter, prescribing the HAI in Smart Grids as being a CAS of systems (Section 12.7). The upmost row in the table of Figure 12.1 is relevant to the know-how genre of this chapter, presenting a realization methodology (know how) for adaptive autonomy using hierarchical Petri nets (Sections 12.9 and 12.10).

The rest of this chapter is organized as follows: Sections 12.2–12.5 discuss on the core concepts of complexity, CASs, SoS and complex adaptive system of systems (CASoS). Section 12.6 describes the automation related notions, that is, automation and HAI, followed by an investigation of the HAI models' evolution from both perspectives of dimensions and dynamism. The idea of adaptive autonomy (AA) is then introduced as a dynamic HAI scheme, followed by a classification of AA implementation methods. Section 12.7 is dedicated to a discussion on HAI in Smart Grid as a CAS and as an SoS. Petri nets are introduced as powerful tools for modeling complex systems (CxS) in Section 12.8. Section 12.9 introduces a model-based implementation methodology for adaptive autonomy concept. Finally, a Petri net realization of the adaptive autonomy expert system (AAES) is presented, followed by a performance evaluation study in Section 12.10. Section 12.11 sums up the chapter and enumerates a couple of future prospective and open questions regarding to the subject of the chapter for future research.

12.2 COMPLEXITY IN SYSTEMS SCIENCE AND ENGINEERING

12.2.1 The Nature of Complexity

Human brain is associated with the Cartesian[1] approach of decomposing problems to simpler and easier subproblems [1]; therefore, a *complex problem* is a problem which cannot easily be decomposed (reduced) to simpler subproblems.

While being indecomposable to simpler subproblems, complexity can be attributed to two different sources:

(1) The complex entity (innate complexity).

(2) The observer (cognitive complexity).

[1]Cartesian: pertaining to René Descartes (1596–1650), to whom the reductionism approach is attributed.

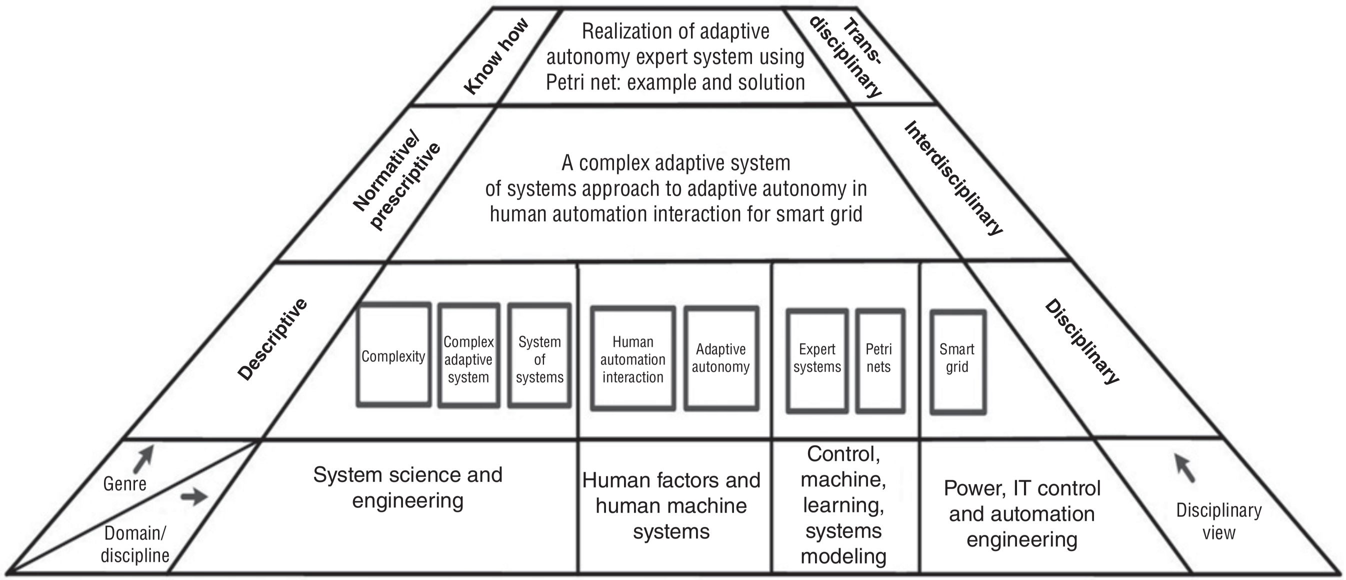

FIGURE 12.1 Conceptual outline of this chapter: genres versus disciplines/domains.

The innate complexity is the one that is inherently sourced by the complex entity itself; while the cognitive complexity is the one sourced by the observer's cognitive limits during observing an entity that is not necessarily inherently complex. The former notion is considered regardless of an observer's cognitive limits; while the latter depends on an observer's level of expertise and intelligence; thus, it does not represent a genuine expression of complexity. The former can be simply called complexity and described as a state of the world; whereas the cognitive complexity can be called as complicatedness (i.e., making confused) and described as a state of mind when responding to complexity[2][2]. In fact, many real-world problems are complex, nonlinear and unpredictable; thus, science (and engineering) is expected to devise methods to explore and tame the complexity.

In line with efforts to explore the notion of complexity and complex problems, Warren Weaver categorized the scientific problems into three classes [3]:

(1) *Problems of simplicity*: concerning two (say few, like: three, four, or five) variables, approached by Newtonian physics and calculus mathematics, belonging to the nineteenth century.
(2) *Problems of disorganized complexity*: concerning astronomical number of variables, approached by statistical or probabilistic mathematics and quantum mechanics, belonging to the twentieth century.
(3) *Problems of organized complexity*: concerning an intermediate number of variables, expectedly approached by complexity management methods, belonging to the twenty-first century.

Apparently, few-variable problems in physical sciences can be tackled by simplicity methods. They can be decomposed by a Cartesian approach to easier subproblems. However, the multivariable complex problems could not be tackled by the same simplicity methods as few variables. Weaver asserts that this weakness of simplicity methods has led the complex problems (especially in life sciences) to "*become highly quantitative or analytical in character.*" [3]

On problems of complexity, Weaver regarded the problems of complexity variables as two different scales: astronomical number of variables (problems of disorganized complexity) and large yet sizeable number of problems (problems of organized complexity).

Problems of disorganized complexity are problems in which the variables are too many and each of these many variables "*has a behavior which is individually erratic, or perhaps totally unknown.*" Weaver continues then: "... *in spite of unknown behavior of all the individual variables, the system as a whole possesses certain orderly and analyzable average properties.*" Due to the very high number of variables in problems of disorganized complexity, statistical and probabilistic methods are utilized to predict the average behavior of the whole problem. Application examples of

[2]This approach to complexity sources (innate or cognitive) is a matter of controversy; however, more investigation on this issue might be furthered in future research.

disorganized complexity can be found in insurance, telephone, and quantum physics [3].

The other class of complex problems is the class of organized complexity, which deals with a sizable number of variables that are interrelated into an organic whole [3]. Problems of organized complexity lay on a spectrum, somewhere between few-variable methods of simplicity and astronomical number of variables methods of disorganized complexity. Application examples of organized complexity include: "*what is the description of aging in biochemical terms? Do complex proteins 'know how' to reduplicate their pattern? On what does the price of wheat depend? How can currency be wisely and effectively stabilized?*" [3]. Reference 4 associates the organized complexity with a *significant* emergent behavior in the complex problem elements.

12.2.2 Complex Systems

Systems—like problems—can be complex, and CxSs are systems whose study leads to complex problems. A system can be complex from one point of view, while not complex from another point of view; as Bouwmans *et al.* states "*systems that have the potential to be 'complex' (by any formal definition we would adopt), do not necessarily show complex behaviour [behavior] under all conditions.*" [5] Similar to a complex problem, a *complex system* is a system that cannot easily be decomposed to simpler subsystems [1].

CxSs, as most definitions of CxS suggest, are unpredictable in their behavior. However, the complex system components' behavior might be either known (predictable or deterministic) or unknown (unpredictable or stochastic). This unknown behavior of system components might be caused by either unpredictable or stochastic nature of a finite number of individual components or by astronomical number of deterministically natured components. Thus, we can argue that the unpredictable system components only can be associated with disorganized complexity, while predictable system components can be associated with organized complexity. Table 12.1 represents a source–problem description of CxS classification in which a system may belong to one (or two) of the four classes of A–D.

As in Table 12.1, the complexity classes can be described as follows:

- Complexity Class A: systems with innate source of complexity and organized complexity problem.

TABLE 12.1 Source–Problem Representation of Complex Systems Classes

Source of complexity →			
↓Relevant problem of complexity	↓System components	Innate	Cognitive
Organized	Predictable	Class A	Class B
Disorganized	Unpredictable	Class C	Class D

- Complexity Class B: systems with cognitive source of complexity and organized complexity problem.
- Complexity Class C: systems with innate source of complexity and disorganized complexity problem.
- Complexity Class D: systems with cognitive source of complexity and disorganized complexity problem.

We defined a *complex system* as *a system which cannot easily be decomposed (reduced) to simpler subsystems*. Nevertheless, many different definitions of complexity have been presented, based on different perceived sources and types of complexity that depend on the discipline and application field. A couple of useful and concise definitions of complexity are presented here, followed by a discussion on its view on source–problem of complexity.

One of the most concise and most well-known definitions of complexity[3]is: "*The complexity of a system is the degree of difficulty in predicting the properties of the system, given the properties of the system's component.*" This definition of complexity is credited to Weaver [1, 6], although Weaver's paper itself does not directly (or even indirectly) point to the given definition. Even we could assert that Weaver's description for disorganized complexity is opposite to that given in this definition, where he states: "*one in which each of the many variables has a behavior which is individually erratic or perhaps totally unknown*" [3]. Therefore, we conclude that the above mentioned definition of complexity points to the organized complexity problems, disregarding the complexity source (i.e., Classes A and B, in Table 12.1). In fact, according to major writings in complexity, the organized complexity is the main type of complexity in the twenty-first century.

In Reference 7, Edmonds reviewed several definitions of complexity and finally proposed a concise definition as "*that property of a language expression which makes it difficult to formulate its overall behaviour [behavior] even when given almost complete information about its atomic components and their inter-relations.*" This definition also points to the organized complexity problem, disregarding the complexity source (i.e., Classes A and B, in Table 12.1).

Price gives an interesting definition of complexity: *"[life is] ... a property of improbable complexity possessed by an entity that works to keep itself out of equilibrium with its environment."* [8] (Quoted from [9]). Based on Dawkins's notion, Price states that a measure of system complexity is the degree in which it defies the thermodynamics equilibrium. For instance, if a dead bird is thrown into the air, it obeys the laws of mechanics, going up and falling down in a parabola; while a live thrown bird runs away, disregarding laws of mechanics. Price's definition points to the innate source of complexity and the organized complexity problem ("*improbable complexity*"), pointing to Class A of Table 12.1.

[3]When we define complexity, the definition of complex system is in hand: Complexity is "the quality or condition of being complex" (Oxford English Dictionary). A complex system is a system which embodies the attribute of complexity.

Kinsner presents another view on definition of complexity: "*a large number of interacting elements with many degrees of freedom whose individual behaviour [behavior] could not be traced back or predicted*" [10]. Kinsner's definition regards unpredictable behavior of individual components (disorganized complexity). However, he has not mentioned that "*could not be traced back or predicted*" is sourced to the observer (cognitive complexity) or to the complex entity itself (innate complexity). Thus, Kinsner's definition points to Classes C and D of Table 12.1.

From another point of view, J. N. Warfield defines complexity as a state of mind: "*that sensation experienced in the human mind when, in observing or considering a system, frustration arises from lack of comprehension of what is being explored*" [11, 12]. Warfield's definition of complexity as a state of mind applies to the cognitive source of complexity, yet disregarding the problem of complexity (organized or disorganized), i.e., mentioning Classes B and D in Table 12.1.

To sum up, D. K. Hitchins has commented as: "*Most definitions have something to say about an inability to predict the behaviour [behavior] of the whole system, knowing the behaviours [behaviors] of the interacting subsystems*" [13]. Further, on the characteristics of a complex system, he has added: "*We are talking about non-linear interactions, emergence, open systems (which adapt as they exchange energy, information and material with their environment). We also appear to be suggesting degrees of self similarity, with subsystems in systems and sub-subsystems within subsystems*" [13]. Hitchin's description on CxS belongs to Class A of Table 12.1.

We will discuss on characteristics of CxS more in the next subsections.

12.2.3 Complexity Measures

In science and engineering, we study classifications and taxonomies in order to attribute certain relevant characteristics to certain classes. Of course, almost all of those taxonomies and classifications are not crisp classifications; on the contrary, they are mostly fuzzy ones. Consider the class of tall people: why we might be interested in classifying people into tall and short sets? Because we can attribute some features to those classes of tall and short people: tall people need bigger spaces in cars, higher chairs or tables in offices, etc. This classification obviously helps us in facilitating peoples' lives; however, the tall people class is rather fuzzy and we cannot strictly say who is tall. But should we stop thinking about facilitating tall people, by an excuse of the tall people class being fuzzy? We would say no. Complexity is similar in the way that it is fuzzy too; we can talk about degrees of complexity. Some systems are strongly complex; whereas, some systems are weakly complex. So we accept that the complex system boundary is fuzzy, and acknowledge the sophistication of the definition of complexity and its characteristics.

In fact, cognition and management of systems are considered as main gains of the complexity theory. Therefore, complexity measures could lead to understanding the emergence phenomena in physical, biological, and societal systems and clarifying the level of randomness and correlation. Moreover, it can contribute to enhancing

TABLE 12.2 Measuring Complexity Type Classification by Reference 10

Measuring Complexity Classification	Description (difficulty of describing . . .)
Structural	*m*-dimensional object
Dynamical	The patterns of systems trajectory
Functional	The functionality of the system
Synergetic	The level of societal development
Design	Difficulty of designing, embodiment, verification, testing, and maintaining

the perceptual and cognitive processes and it could also determine self-organization [10].

In Reference 10, Kinsner introduced five types of complexity: structural, dynamic, functional, organizational, and design complexity which are summarized in Table 12.2. He also introduced different ways to express complexity which include: (i) local or global, (ii) single scale or multiscale, (iii) algorithmic or probabilistic, (iv) absolute, differential, or relative, (v) static or dynamic, (vi) average or asymptotic, and (vii) arithmetic or logical. Therefore, according to Reference 10, complexity can be measured in five types and expressed in seven ways. This two-dimensional (2D) classification of complexity types and ways is represented in Figure 12.2 in which, the seven ways of expressing complexity are shown in the horizontal plane, while

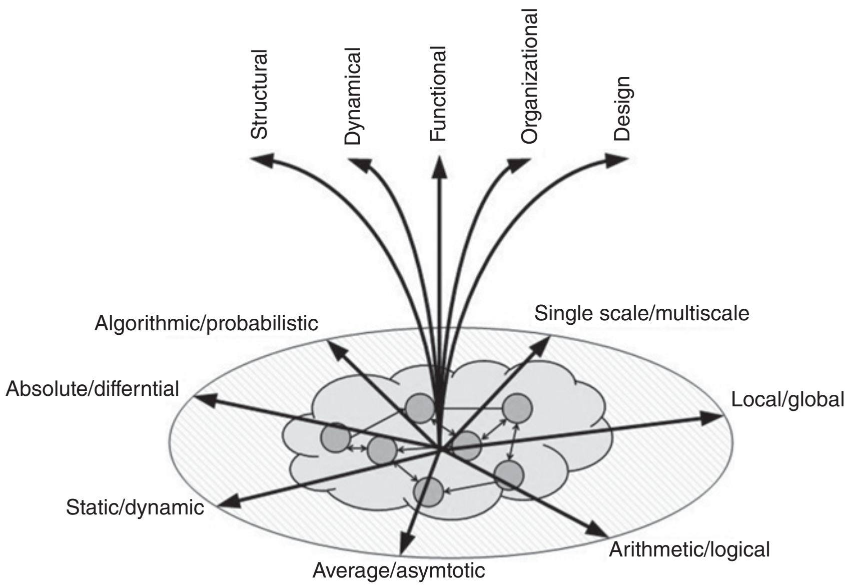

FIGURE 12.2 Two-dimensional classification of complexity types and ways according to Reference 10.

the five types of complexity are shown in vertical axes. A comprehensive survey on complexity measurement is presented in References 10, 14–17.

Alongside with definitions provided for complexity in relevant subsections (12.2.1 and 12.3.2), it is worthy to mention some forms of complexity categorized by Reference 18 "*as:*

(a) *Lack of knowledge in characterizing the behavior of process (Unit Behavioral Complexity).*
(b) *Complexity of computational engine associated with a subprocess (Computational Complexity).*
(c) *Difficulties in characterizing the interconnection topology (Interconnection Topology Complexity).*
(d) *Organizational alternatives for decision making (Organizational Complexity).*
(e) *Variability, uncertainty and multi-level couplings in the system's organization in describing the overall system organization (System of Systems Complexity).*
(f) *Large scale dimensionality impacting on methodologies (Large Scale Complexity)*
(g) *Heterogeneous nature of sub-processes, resulting in behavior (Hybrid Behavioral Complexity).*
(h) *Variability and/or uncertainty on the system's environment during the lifecycle requiring flexibility in organization and operability (Lifecycle Complexity)*".

12.2.4 Complexity-Related Terms in Literature

Figures 12.3 and 12.4 show the number of articles including *complexity* and *complex system* in their titles, by decade since 1950 from the two sources of *ISI Web of*

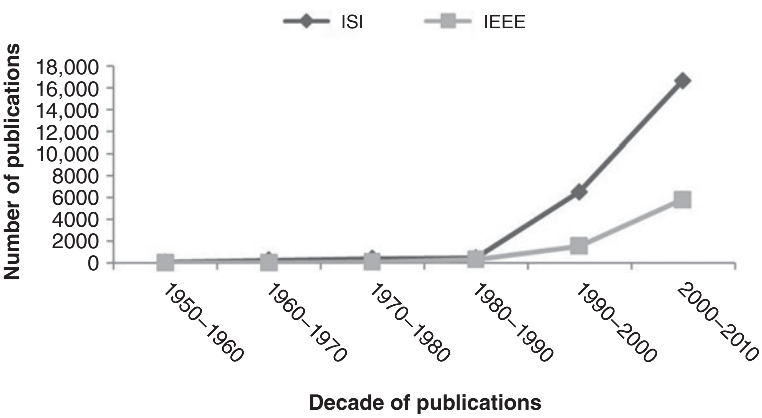

FIGURE 12.3 Number of titles containing *Complexity* by decade in ISI Web of Knowledge and IEEEXplore.

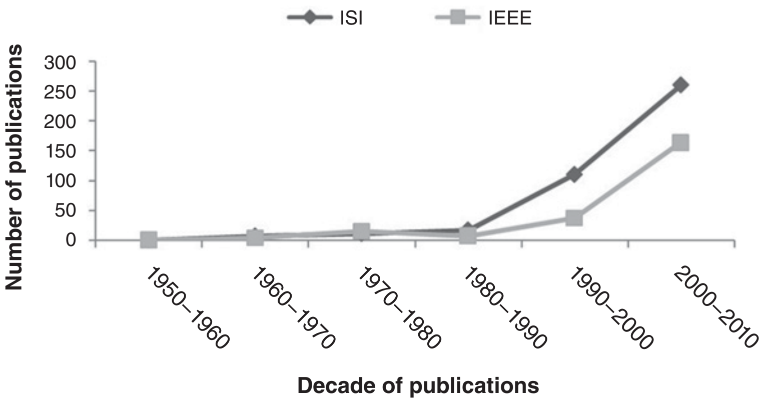

FIGURE 12.4 Number of titles containing *Complex System* by decade in ISI Web of Knowledge and IEEEXplore.

Knowledge and *IEEEXplore*. As shown, these concepts were introduced before 1950s; however, it was during 1980s that researchers showed considerable interest in these areas. Since then, the number of publications on *complexity* and *complex system* has been exponentially increasing due to growing application of these concepts in a variety of disciplines.

The industrial need, as well as research on complexity in systems science and engineering, has led to the introduction of several complexity-related terms: CASs and SoS, to be discussed in the next sections. Figures 12.5 and 12.6 show the number of articles including *CAS* and *SoS* titles respectively by decade since 1950 in *ISI Web*

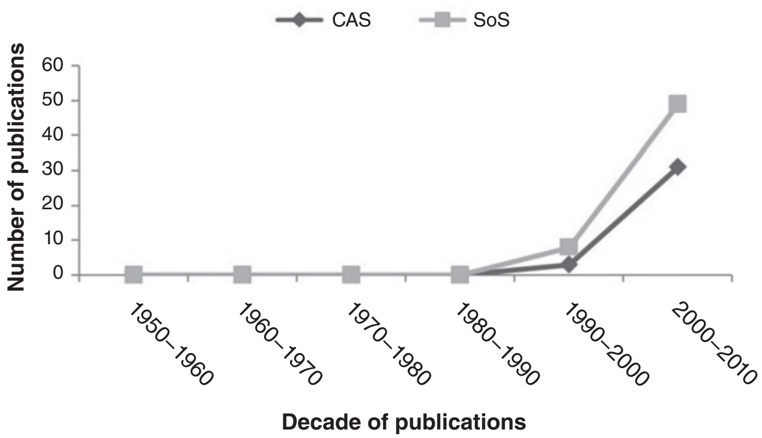

FIGURE 12.5 Number of titles containing *Complex Adaptive System* and *System of Systems* respectively by decade in ISI Web of Knowledge.

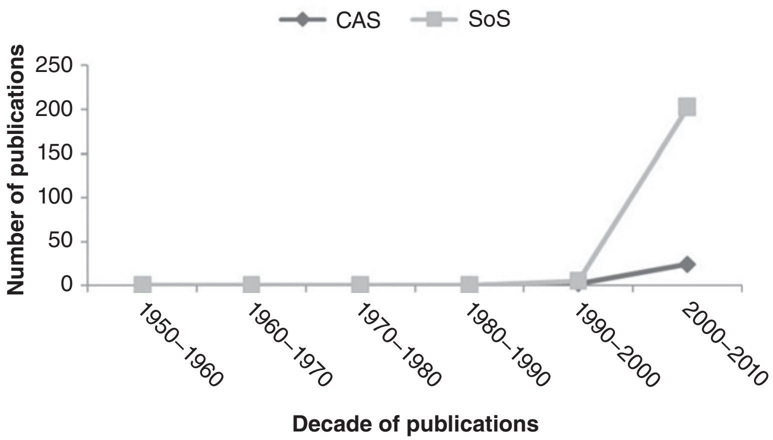

FIGURE 12.6 Number of titles containing *Complex Adaptive System* and *System of Systems* respectively by decade in IEEEXplore.

of Knowledge and *IEEEXplore*. As seen, both CAS and SoS concepts are rather new and it was after 1990 that research interests in these concepts increased drastically, specially on SoS.

Figures 12.7 and 12.8 show the number of articles including *CAS* and *SoS* titles respectively by year during last two decades in *ISI Web of Knowledge* and *IEEEXplore*. As seen, both CAS and SoS concepts are rather new and it was after 1990 that research interests in these concepts increased drastically, specially on SoS.

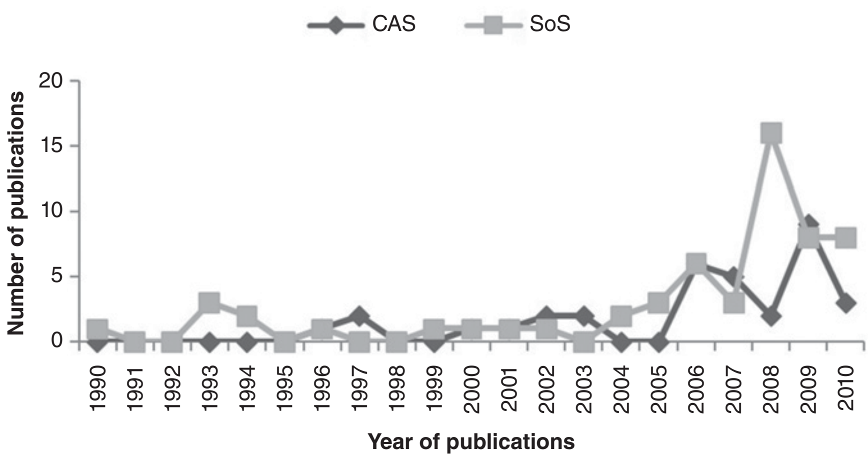

FIGURE 12.7 Number of titles containing *Complex Adaptive System* and *System of Systems* respectively by year in ISI Web of Knowledge.

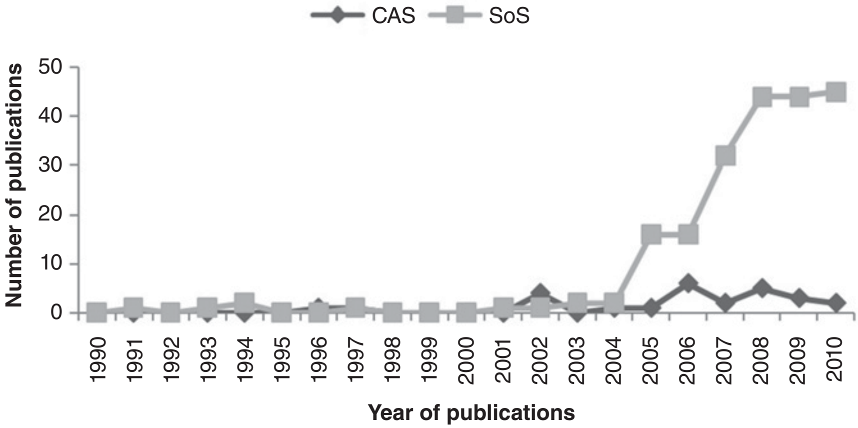

FIGURE 12.8 Number of titles containing *Complex Adaptive System* and *System of Systems* respectively by year in IEEEXplore.

12.3 COMPLEX ADAPTIVE SYSTEMS

12.3.1 What are Complex Adaptive Systems?

The term *Complex Adaptive Systems* (CASs) was coined at the *Santa Fe Institute* by J. H. Holland (father of Genetic Algorithms), M. Gell-Mann (Physics Nobel laureate), S. Kauffman (Biologist) and K. Arrow (Economics Nobel laureate) [19–24]. As a result of efforts at the Santa Fe Institute, a "*common theoretical framework for complexity*" was developed. This framework was built based on the previous works in many different disciplines such as biology, artificial intelligence, cybernetics, neural networks, ecology, economics, and chaos theory [20]. The basic idea of CAS is believed to be introduced in 1960s by the Belgian Nobel laureate I. Prigogine who was studying self-organizing structures in the nature [20].

Apparently, complex system analysis techniques differ from those of the conventional (classical) techniques as compared in Table 12.3 [25, 26]. The left column in Table 12.3 is associated with the problems of simplicity, while the right column is associated with the problems of complexity as described in Section 12.2.1 [3].

A CAS is defined as a dynamic network of heterogeneous agents that adapt or learn as they interact [20, 27]. These agents (representing cells, species, individuals, firms, nations) act in parallel, constantly exchange information and influence each other and the environment in a conditional manner—using IF/THEN structures—based on signals they receive. They also have the ability to adapt their behavior as a result of their experience [27, 28]. The overall behavior of the system is the result of the cooperation of agents. Since the relationships between causes and effects are nonlinear and actions of some parts affect actions of other parts, the system as a whole shows emergent properties which cannot be understood referring to the individual behaviors of the agents [20, 29, 30].

TABLE 12.3 Classical Versus Complex System Analysis Techniques [26]

Classical problems	Complex problems
Mechanistic, linear, separate parts, events, moments	Holistic, nonlinear, integrated
Whole is defined as sum of parts	Whole is greater than sum of parts
Reality is predictable; laws determine the outcome	Reality is full of possibility; nothing is predetermined
Work with building blocks; those in control dictate what is done.	Work with networks; system is emergent and self-referencing.
Chaos is suppressed; structures are taken apart to examine and control	Natural order emerges from chaos; self-organization
Science is objective; what is not observed does not exist	No objective reality; our observation evolves—we cannot avoid having an impact

The entire system never reaches equilibrium, due to continuous interaction of the agents [29]. Yoffee also mentions that "*There is no optimum state of the system performance and the system can always surprise, as when a small initial perturbation can result in a large outcome*" [29]. Gell-Mann notes that a CAS acts in the real world based on a set of regularities drawn from the information that system acquires about environment and its own interactions [22]. Dooley mentions that these schemata go through a rule discovery process in which high level schemata evolve from smaller and more basic schemata [31]. Furthermore, Dodder and Dare define CAS as a "*network of many elements gathering information, learning and acting in parallel in an environment produced by the interactions of these agents*" [32]. They also argue about the co-evolution of these agents with their environment, as well as the fact that states of agents lie between orders and anarchy at the edge of chaos.

12.3.2 Characteristics of Complex Adaptive Systems

Different authors have counted various numbers of (4–13) characteristics for CASs. For instance, Holland enumerates four characteristics of nonlinearity, aggregation, flows, and diversity for CASs [21], in 1995. In 2006, he himself mentions parallelism, conditional action, modularity, adaptation, and evolution as main characteristics for CASs. Wildberger also names the following four characteristics for CASs: emergence, strategic learning and adaptation, nonlinearity (and a potential for chaotic behavior), and feedback [33]. On the other hand, Grus *et al.* listed 13 characteristics for CASs as: openness, components, nonlinearity, feedback, emergence, adaptability, multi-understanding, self-organization, dynamism, unpredictability, sensitivity to initial condition, and fractal building [25].

Some of the mentioned characteristics are almost identical, for example, emergence and aggregate behavior sound to indicate the same behavior of the CASs [33]. Schema and internal model also seem to be conceptually identical [22].

In the following part, some of the most cited characteristics of a CAS are briefly introduced.

12.3.2.1 Emergence/Aggregate Behavior *Emergence* and *aggregate* behavior are interchangeably used to point out the same concept [33]. Merriam Webster Dictionary defines aggregation as "*formed by the collection of units or particles into a body*" [19]. In a CAS, the systematic behavior of the whole system emerges from the interdependent activities of the agents, that is, it is not simply the sum of the behaviors of its agents [34]. This property results in unexpected patterns in the whole system which cannot be produced by the components individually [35, 36]. The emergent behavior in CAS is reverted to the interconnections between the components rather than being originated from the inherent characteristics of the components [37]. Rotmans recalls this characteristic as *spontaneous* growth of patterns from inside the system [38].

This aggregate behavior can hardly be predicted by thoroughly knowing each component. *Organized complexity* is the name Weaver gave to a system with a *significant* emergent behavior (Section 12.2.1) [3]. If the emergent behavior is not *significant*, then the system does not exhibit organized complexity [3, 4].

Emergence, however, like any other feature can have both good and bad effects. Despotou *et al.* state that because of its dynamic reconfiguration character, the CAS can lead to beneficial emergence, increasing the robustness of the system [4]. Decentralized control and collaboration, on the other hand, harden system behavior prediction, since the number of internal interactions in the system has been increased.

Weijnen *et al.* exemplify electricity and IT infrastructures as CASs which were not firstly designed to form integrated systems, though they have emerged over time to become so [39]. Emergent behavior of these systems is due to the unpredictable consequences of system operators' actions and disturbances. For instance, cascading blackouts are a result of emergence occurred due to the operator's inability in directing the flows over the network. As another instance of emergent behavior, Epstein notes the neural system of human memory: "*people can have happy memories of childhood while, presumably, individual neurons cannot*" [40].

Emergence can be viewed from two philosophical aspects: Epistemological view, concerning the original nature of the subject–the study of knowledge—and Ontological view, discussing on reality or existence of emergence and its qualities [41]. O'Connor and Wong define the epistemological emergence as "*systemic features of complex systems which could not be predicted (practically speaking; or for any finite knower; or for even an ideal knower) from the standpoint of a pre-emergent stage, despite a thorough knowledge of the features of, and laws governing, their parts*" [42]. On the other hand, they introduce the ontological emergence as: "*see the physical world as entirely constituted by physical structures, simple or composite. But composites are not (always) mere aggregates of the simples. There are layered strata, or levels, of objects, based on increasing complexity*" [42].

12.3.2.2 Complexity The concept of complexity is discussed in Section 12.2.1. Here, we present some definitions of complexity regarding CAS. Waldrop believes that the complexity of CAS arises from the simultaneous interactions of many simple agents within the system [20]. From the *control* point of view, the complexity of CAS leads to a distributed control system in which there is no single governing rule that controls the whole system and each of the interacting parts is governed by its own rules. These rules may influence the outcome of the system or the actions of other parts [21, 33, 43].

An immediate consequence of complexity is dynamism. The only definite trait of the CASs is change: equilibrium and stasis are equivalent to death for CAS [8, 9, 44–46]. This is because of the number of agents, their interdependence, and their openness to external influence, that is, the system learns and explores its environment to create new structures and new patterns of the relationships [20, 47].

12.3.2.3 Adaptability The future behavior of a CAS is based on its past and current interactions with the environment, that is, it adjusts itself to deal with the changes in the environment. As an instance, the language structure adapts itself during its emergence of interrelated patterns of experience, social interaction, and cognitive mechanism [48]. Besides, changes in the environment bring the need for adaptation inside the CAS, that is, the agents' behavior changes during the adaptation process which leads to changes in the overall behavior of the system [49, 50].

Holland mentions that for a system to adapt, it should be able to change its rules which bring up two computational procedures: credit assignment and rule discovery. The former procedure includes *rewarding* those parts of the system which lead to a better situation. In a rule-based system, rules with good contributions to the system's aggregate performance are assigned credit, meaning that these rules will have more influence in future. That is "*rules with good outcome in some situations in past are more likely to be used in similar situations in future*" [46]. A rule discovery procedure is for dealing with new situations in which the system needs new rules where the credit assignment procedure cannot work properly. For the newly discovered rules to be plausible, the rules are thought to be made up of building blocks and strong rules identified via the credit assignment procedure [46].

Wildberger mentions two types of adaptation for CAS: passive and active [33]. In a passive adaptation the CAS only responds to the environmental changes; while, in an active adaptation the CAS influences the environment, trying to improve its adaptation power by modifying the environment.

Moreover, it is worth knowing that adaptability is about being adapted to the environment; while self-organization (another characteristic of the CASs) is about adaptation without being influenced by the environment (internal adaptation).

12.3.2.4 Nonlinearity The CASs show nonlinear dynamism due to the nonlinear interactions within the system components. The nonlinear behavior of the CASs makes the future of the system unpredictable. Cilliers mentions that although the interactions between the components are known (even well defined), their strengths change over time [37].

12.3.2.5 Unpredictability As stated in Section 12.2.1, the behavior of a complex system is unpredictable; while, this unpredictability can either root back to the nonlinearity of the interconnections between the system components (organized complexity), or to the unsizeable number of components (disorganized complexity) [3].

In order to predict the output of a CAS, we must know its mechanism and component interactions, while the system changes constantly and these changes do not follow constant patterns, thus it may bring surprising outcomes at any point in time [20]. Since interactions and operations in a CAS are neither linear nor fixed, there is no agreed upon pattern that governs them [32]. The unpredictability of CASs does not imply the randomness of its output; for instance, the weather pattern, as a CAS, is very difficult to predict in detail; however, the weather does not change randomly [21, 25, 29, 37, 44, 51].

12.3.2.6 Sensitivity to Initial Conditions Sensitivity to initial condition, also known as *butterfly effect*, was discovered by Lorenz in 1961 [52, 53]. It states that an infinitesimal change in an initial action may cause large unpredictable consequences in the future. Weather changes can explain this concept: "*slight changes in wind velocity or minor difference in temperature could produce sunshine one day or rain the next*" [52]. As seen in Figure 12.9, the same system with two slightly different initial conditions lead to a highly different final position.

12.3.2.7 Openness The openness property of CASs has two aspects: first, a CAS is open to external influences in a way that CAS and its environment constantly exchange influence; second, the boundaries between CAS and environment are hard to determine [20, 21, 25, 30, 37, 38, 51].

It should be noted that openness is different from adaptability. Openness of a CAS states that the CAS and its environment exchange influence; while the property of adaptability provides the CAS with the ability to adapt itself to changes in the environment. In other words, for the system to be adaptable, it should be open [21, 25, 37, 38, 43, 46].

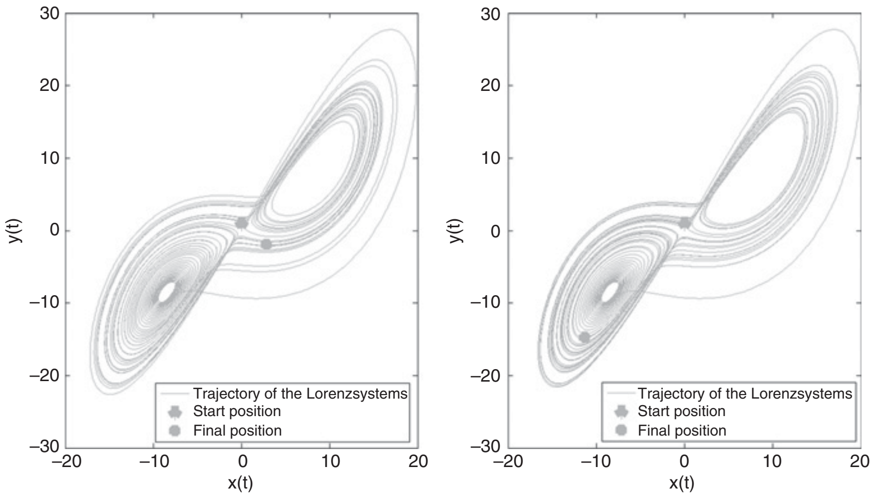

FIGURE 12.9 Sensitivity to initial condition: the initial conditions are very similar, while the future behavior of the system differs drastically.

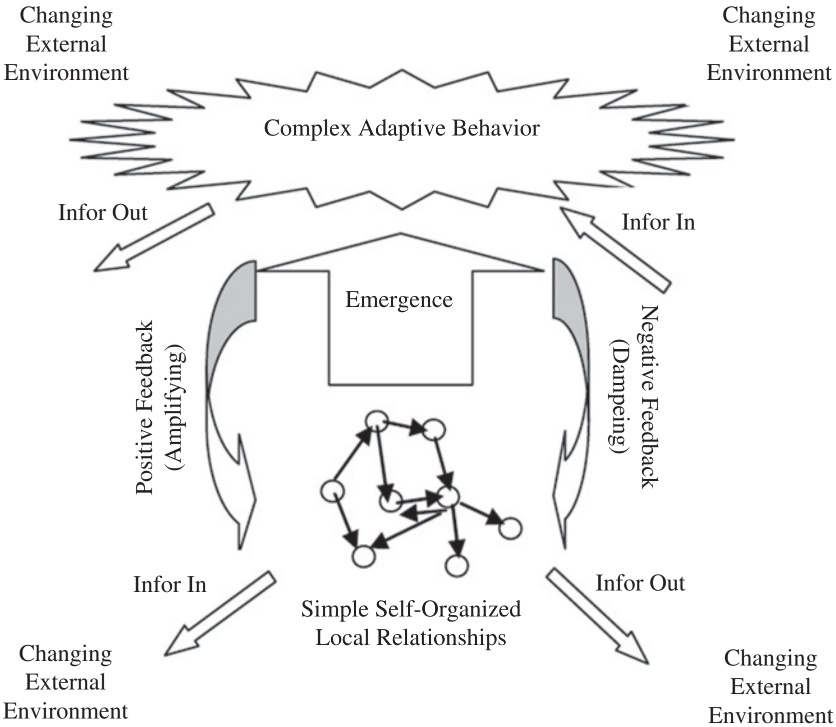

FIGURE 12.10 An illustration of the feedback mechanisms in a CAS [54].

12.3.2.8 Feedback Loops Feedback means feeding the output to input; thus, feedback loops give the CAS the ability of using the output of the previous process as the input of the next. From one point of view, the feedback loops are categorized into internal and external. Internal feedback loops connect agents within the CAS and exchange resources (materials, information, and energy) between them. These transforming feedback loops provide CAS with stability and changeability [20]. The external feedback loops help system to adapt; while the CAS and environment influence on each other.

From another point of view, feedbacks in a CAS are positive or negative. A positive (amplifying) feedback means that the CAS is learning, while a negative (damping) feedback means that the CAS is discouraging the process in order to regulate or damp the output, as shown in Figure 12.10. [25, 32–34, 51, 54].

FIGURE 12.11 Self-organization of leaf structure as a CAS.

12.3.2.9 Self-Organization The self-organization is the ability of a CAS to develop new structures, as shown in Figure 12.11 as leaf structure development. [38, 55–58] or as Levin mentions "*system assumes shape through a process of self-organization*" [55]. For instance, in human systems, spontaneous group activity, dissenting factions or clique are examples of self-organization [25]. Note that the difference between adaptability and self-organization is that self-organization is the development of new structures in the internal architectures of the system; while adaptability is the response to the changes in the environment.

Note that three characteristics of adaptability, feedback loops, and self-organization provide the system with the ability of evolution.

12.3.2.10 Scale Independence According to Merriam Webster Dictionary, scale independence or fractal structure or self-similarity means: "*any of various extremely irregular curves or shapes for which any suitably chosen part is similar in shape to a given larger or smaller part when magnified or reduced to the same size*" [19]. A well-known example of scale independence can be seen in plants: the same structure of angles exists between veins in leaves, twigs, branches, and roots [51].

12.3.2.11 Flows All CASs have nodes connected to each other by connectors. The resources within a CAS move from one node to another through connector (actions between agents involving the exchange of information and resources); this phenomenon is known as flow. For instance, in a financial system banks are nodes, electronic transfers are connectors, and money is the resource; hence, the movement of money by electronic transfers between banks is flow [21, 31, 52]. Simon uses ecosystems as an example of CAS to mention that flows provide the interconnections between agents and make it possible for the system to evolve from random collection of species into an integral whole [55].

CAS characteristics extracted out of different texts and the authors mentioning them are listed in Table 12.4.

12.4 SYSTEM OF SYSTEMS

12.4.1 Necessity and Definition

An SoS, as the name implies, is a system whose components are systems as well. Apparently, an SoS is developed only if the required application is not performable by a single system alone [41, 71, 72].

The notion of SoS has recently found its way through many application fields[4] (Figures 12.5 and 12.6); thus, converging to a unique definition for an SoS, or

[4] As Lane and Valerdi state: "In the business domain, an SoS is the enterprise-wide integration and sharing of core business information across functional and geographical areas . . . In the military domain, an SoS is a dynamic communications infrastructure to support operations in a constantly changing, sometimes adversarial environment . . . For some, an SoS may be a multi-system architecture that is planned up-front by a Lead System Integrator (LSI) . . . For others, an SoS is an architecture that evolves over time, often driven by organization needs, new technologies appearing on the horizon, and available budget and schedule . . . " [83].

TABLE 12.4 CAS Characteristics and Authors Who Have Mentioned Them

Characteristic	Explanation	References
Emergence/aggregate behavior	Behavior of the whole system emerges from the interdependent activities of the agents, i.e., it is not simply the summation of the behavior of the agents	21, 22, 24, 25, 29, 33–38, 40, 44, 46, 52, 59–63
Complexity	Simultaneous interaction of many simple agents within the system results in complexity which is the reason why the overall behavior of system differs from sum of its parts	21, 22, 25, 28, 33, 51, 64–67
Adaptability	Changes in the environment brings the need for adaptation for CAS, i.e., the behavior of agents changes during the process of adaptation to the environmental changes leading to changes in the overall behavior of the system	25, 27, 33, 37, 38, 43, 46, 48–50
Nonlinearity	The CASs show nonlinear dynamic systems due to the nonlinear interactions within the system. This nonlinear behavior of CAS makes the future of the system unpredictable	20, 21, 25, 33, 34, 37, 44, 51
Unpredictability	The system changes constantly and these changes does not follow constant pattern and may bring surprising outcomes at every point in time	20, 21, 25, 29, 33, 37, 44, 51
Sensitivity to initial conditions	An infinitesimal change in an initial action may cause large unpredictable consequences in future	25, 29, 34, 51, 52, 68
Openness	CAS and its environment constantly exchange influence in a way that the bounding between CAS and the environment is hard for determining	20–22, 25, 30, 37, 38, 51
Feedback loops	Feedback loops give CAS the ability to use the previous process's output as the input of the next	20, 25, 29, 32–34, 51
Self-organization	The self-organization is the ability of CAS to develop new structures	21, 24, 25, 29, 38, 44, 46, 55, 69, 70
Scale independence	Repeated irregular shapes in the system in different levels	25, 51
Flows	Movement of resources within the CAS from one node to another through connector actions between agents involving the exchange of information and resources	21, 31, 35, 52, 55

according to Reference 73 a "*multiple integrated complex system*" seems scarcely achievable [74–77].

An SoS is defined as a large-scale system composed of heterogeneous, independent, and self-organizing systems, each providing useful services in its own right [78, 79]. These component systems, together as a whole (SoS), are managed for a common goal and show various characteristics of emergence, complexity, evolutionary development, and synergy [78–80].

SoS itself is subjected to controversies regarding its distinction against *systems*. D. K. Hitchins, as it appears from his writings, may not accord with the current usage of the term SoS [81]. Describing SoS as "*an open set of complementary, interacting systems with properties, capabilities and behaviours [behaviors] of the whole SoS emerging both from the systems and from their interaction*", and system as "*an open set of complementary, interacting parts with properties, capabilities and behaviours [behaviors] of the whole set emerging both from the parts and from their interactions*", he deduces that these two terms, SoS and System, sound to be identical with a "*simple hierarchy shift*" [82].

Another important issue is that whether all SoSs are human made or natural—or specifically speaking, biological. Bar-Yam regards a living organism as an SoS for the following reasons: firstly, each of its constituent cells consists of a reproducing system in order to pass along their DNA information to survive, which is due to their operational and managerial independence. Secondly, as a result of environmental needs, higher effectiveness of survival is achieved for this living organism by evolutionary development, emergent behavior of the whole system, and a location distribution of the cells along the body. This representation of living organisms satisfies the expected characteristics of an SoS according to Bar-Yam's own definition of SoS [80].

Sheard and Mostashari, on the other hand, assert that a biological system is complex but cannot be considered as an SoS: "*Complex systems that consist of a large number of elementary particles or are biological systems not related to engineering would not be considered systems-of-systems*" [43].

12.4.2 Characteristics of System of Systems

As it appears from the definitions in section 12.4.1, most experts in the field define SoS in terms of its characteristics or applications. Here, a survey is performed on all of the founded definitions and some of the more cited characteristics are extracted out of them. Some of these characteristics seem to be almost identical or subset of one another.

12.4.2.1 Geographical Distribution Constituent systems of an SoS are often located widely dispersed. Therefore, one of the most challenging characteristics of SoS is the communication capability in order to secure the collaboration toward their common goal. Eisner, Maier, Kotov, Clare, Sage and Cuppan, DeLaurentis and Callaway, DeLaurentis, Purdue, and Jolly and Muirhead have enumerated geographical distribution as an SoS characteristic, and Shenhar has mentioned this characteristic as being largely widespread [71, 74, 84–91]. Samad and Parisini have exemplified Smart Grid as a geographically distributed system [92].

12.4.2.2 Complexity To define complexity, some tend to emphasize on the behavior of the system while others define it via the system components' intricate interconnections [93, 94]. Complexity in SoS, therefore, has two sides: It is either based on each constituent system's inherent behavior, or the number of entangled interconnections and information contained in those interconnections among constituent systems. As Bouwmans *et al.* assert, increasing interconnectedness between infrastructures can lead to "*new vulnerabilities, as changes or failures in one infrastructure may affect other infrastructures as well*" [5].

Despotou *et al.* [4], on the other hand, elaborate that complexity is actually a combination of three properties of autonomy, decentralized control, and collaboration among the constituent systems.

Gell-Mann, Kotov, Clare, Anderson *et al.*, Parks *et al.*, Bar-Yam, and Stevens have pointed to complexity as a major characteristic of SoS [21, 80, 86, 87, 95–97].

12.4.2.3 Emergence As stated in Section 12.3.2.1, emergence can be viewed from two philosophical aspects: epistemological view, concerning the original nature of the subject and ontological view, discussing on reality or existence of emergence and its qualities [41].

In the SoS field, emergence is regarded mostly from an ontological point of view: This behavior is an overall result of interactions among system components and cannot necessarily be predicted by just knowing each component thoroughly. *Organized complexity* is the name Weaver gives to a system with *significant* emergent behavior [3]. If the emergent behavior is not *significant*, then the system does not exhibit organized complexity [4].

Emergence seems to be the most important characteristic of an SoS, since Stoudt claims the name system-of-systems was coined "*to describe the emergent behavior of new mega-systems created by the tight integration of previously distinct and independent systems*" [98]. He also mentions that emergence cannot be seen when the constituent systems are separate [98].

Maier, Sage and Cuppan, Periorellis and Dobson, Stoudt, Despotou *et al.*, Bar-Yam, Purdue, and Sauser and Boardman have counted emergent behavior as one of SoS's characteristics [4, 72, 74, 80, 89, 98–100].

12.4.2.4 Heterogeneity/Diversity SoS is considered to have the ability to work with heterogeneous constituent systems; that is, the constituent systems may be designed and used in different contexts and be made from distinct elements and qualities. Since heterogeneity compels the SoS to have standardized protocols and interfaces for communication among its constituent systems, the immediate consequence of heterogeneity is for constituent systems to be open. That is, the constituent systems of SoS, as Azani states, must be able to exchange *energy, material, and information with outside world* and with each other [101]. As a consequence, reinforcing a new system into SoS would not be a problem [4]. This is important because is the only way for an SoS to "*achieve higher purpose(s) by leveraging the diversity of its constituent systems*" [72].

Keating *et al.*, Despotou *et al.*, DeLaurentis and Callaway, DeLaurentis, Purdue, Sauser and Boardman, and Jamshidi have listed heterogeneity/diversity as one of SoS's characteristics [4, 71, 72, 78, 88, 89, 102].

12.4.2.5 Connectivity Connectivity is a key concept in SoS, since all of the constituent systems require to exchange information or even substantial qualities of mass or energy [85]. Sauser and Boardman have defined this characteristic as the ability of a system to link with other systems, which is regarded as an important issue due to the fact that constituent systems may be highly heterogeneous and diverse [72]. Connectivity takes place via networking.

Shenhar, Purdue, DeLaurentis, Sauser and Boardman, and Jamshidi have mentioned connectivity as a characteristic of SoS [72, 78, 88, 89, 91].

12.4.2.6 Synergy Synergism, according to Reference 101, is the collaborative interaction among constituent parts of a system, while their combined effect is greater than the sum of their individual effects. In the SoS approaches, synergy between independent constituent systems is desirable in order to achieve the desired overall performance [103].

Boardman and Sauser, Bar-Yam, and Saunders *et al.* have stated synergy as SoS characteristics [79, 80, 104].

12.4.2.7 Large Scale McGraw-Hill Encyclopedia of Science and Technology presents three commonly accepted definitions of a large-scale system based on concepts of decomposition, complexity, and centrality [105]. It notes that a system is large scale if it is (i) decomposable into small-scale subsystems, (ii) complex, or (iii) geographically distributed. It also mentions that geographical distribution may be due to "*a lack of either centralized computing capability or a centralized information structure*", so the conventional control systems including "*components and information grouped in one geographical location or center*" are not applicable.

Jamshidi, Kotov, and Stevens have stated that an SoS must be large scale while all the three notions by which large scale is defined have already been regarded as SoS characteristics independently [78, 86, 97]. Thus, the *large-scale* feature of SoS can be viewed as a dependent characteristic.

12.4.2.8 Operational Independence Maier was the first to notice independency in SoS [99]. As he states, each constituent system of a SoS has its own purpose in its own right and is capable of operating independently to fulfill that purpose if separated from other constituent systems of the SoS [85].

Sage and Cuppan, Crossley, and DeLaurentis have also stated operational independence as one of SoS characteristics [74, 88, 106].

12.4.2.9 Managerial Independence Constituent systems of an SoS operate independently and "*are separately acquired and integrated but maintain a continuing* *operational existence independent of the SoS, i.e., they are managed partly for their own purposes*" [85].

Sage and Cuppan and DeLaurentis have also stated managerial independence as one of SoS characteristics [74, 88].

12.4.2.10 Autonomy Autonomy means "*the ability to act and make decisions without being controlled by anyone else*" [107]. Samad and Parisini state that the word *independence* in operational and managerial independence implies inherent autonomy in SoS [92]. Thus, operational and managerial independence are autonomy feature's subsets and may not be regarded as distinct characteristics of SoS. However, the autonomous system not only needs to have its independent operation, but also should take proper reactions against external stimuli and should make sure to accomplish the SoS purpose [73]. This characteristic leads to semi-intelligent actions of SoS.

Clough declares that the concept of autonomy resides between automation and intelligence. He illustrates that an automatic system will exactly follow a program, while an intelligent system is capable of discovering knowledge; thus, an autonomous system having "*the free will to make its own choices*" resides somewhere between two edges of automation and intelligence [108].

Despotou *et al.* (quoted from Reference 109) identify "*ten levels of autonomy, so called autonomous control levels (ACL): (1) Remotely Controlled Systems (conventional 'dull' systems), (2) Real time health diagnosis (self-awareness), (3) Adaptation to failures/weather (data loss tolerance), (4) Execution replanning (e.g. route for UAVs, intelligence), (5) Group coordination (emergent behavior), (6) Group tactical replanning (shared awareness state), (7) Group tactical goals, (8) Distributed control, (9) Group strategic goals, (10) Fully autonomous systems*" [4].

It is good to note that the above mentioned *ten levels of autonomy* differ from Sheridan's *ten levels of automation* (LOA) introduced in References 110–112 which will be described in Section 12.6.4. Periorellis and Dobson, Keating *et al.*, and Despotou *et al.* have stated autonomy as an SoS characteristic [4, 100, 102].

12.4.2.11 Self-Organization Self-organization is the process by which the system finds its way through planning without being imposed by outside stimuli or inside central authority. Although Bjelkemyr *et al.* claim that self-organization can be decomposed into operational and managerial independence—which by definition seems to be true [113]. Bar-Yam has counted self-organization as one of SoS characteristics [80].

12.4.2.12 Adaptability Adaptability pertains to the ability of a system to make changes in itself to deal with changes in its environment. It involves environmental change recognition, realization of the proper modifications inside the system toward the environmental change, and the ability to make the decided modification happen [114].

Despotou *et al.*, Holland, Bar-Yam, and Carney *et al.* state adaptability as a characteristic of SoS [4, 21, 80, 115].

12.4.2.13 Dynamic Reconfiguration In order to improve the reliability of the SoS, it should have the ability to reconfigure itself if any of its constituent systems or elements become faulty. SoS must find new resources to compensate for the loss. This process is called graceful degradation [4]. Adaptability should not be confused with dynamic reconfiguration. Adaptability is the changes in the system in response to the environment; while, dynamic reconfiguration is a reflection to a loss or failure inside the system [114].

12.4.2.14 Evolutionary Development SoS is not fully designed and formed at the beginning. It runs an evolutionary development via adding, removing and modifying its functions and purposes [85]. Electric power systems can be regarded as an example of evolutionary development. Power systems deliver the electric power to the end consumers, using interconnections which must evolve "*over time to meet the needs of an ever growing demand for electricity.*" [116]

Maier, Sage and Cuppan, Bar-Yam, Purdue, Stoudt, and Carney *et al.* have enumerated evolutionary development as a characteristic of SoS [74, 80, 85, 89, 98, 99, 115].

Characteristics extracted out of the SoS definitions and the authors mentioning them are listed in Table 12.5.

12.4.3 System of Systems Types

Maier assumes that systems of systems with similar complexity and extent should not be regarded as equivalent; and based on managerial control, he suggests three types of SoS: Directed, Collaborative, and Virtual [99]. Moreover, from system architecture point of view, Chen and Clothier classify SoS into two types: Dedicated and Virtual [118]. Recently, Dahmann and Baldwin have introduced a new type of SoS, Acknowledged SoS, which is mostly growing in military context [119]. Different types of SoS and their initiatives' definition are described in Table 12.6.

Note that due to the *specific* purposes which *directed* SoSs are designed to serve—perhaps for a long term—and their centrally managed control system, these SoSs may not be distinguished from a system per se [120].

12.4.4 A Taxonomy of Systems Family

12.4.4.1 SoS versus Complex Systems Determining the type of a system is essential in system analysis and design. Nevertheless, Sage and Cuppan have asserted that "*What distinguishes a system of systems from other systems does not, at this point, have a definitive answer*" [74]. They continued with an example: most of the systems today are made up of systems but can we really call them all systems of systems? A PC for example is composed of several systems but monolithic in its purpose; Internet, on the other hand, serves several purposes and makes wider communications possible. Converging to a clear distinction between systems requires first bringing a definition of each system and then comparing them with SoS characteristics, context, and applications.

TABLE 12.5 SoS Characteristics and Authors Who Have Mentioned Them

SoS Characteristics	Explanation	References
Geographical distribution	Wide dispersion of component systems regarding geographical locations	71, 74, 84, 86–90, 99
Complexity	Combination of autonomy (inherent behavior of component systems), decentralized control, and collaboration of systems (intricate interconnections)	4, 21, 80, 86, 87, 95–97
Emergence	The overall behavior of the system cannot be predicted by knowing each component thoroughly due to complicated and nonlinear interactions among components	4, 72, 74, 80, 89, 99, 100
Heterogeneity/diversity	Constituent systems may be designed and used in different contexts, and be made from distinct elements and qualities	4, 71, 78, 88, 89
Connectivity	The ability of system to link with other systems	72, 78, 88, 89, 91
Synergy	The combined effect of component systems is greater than the sum of their individual effects	79, 80, 104, 117
Large scale	A system which is decomposable into small-scale subsystems, complex, or geographically distributed	78, 86, 97
Operational independence	Each constituent system of an SoS has its own purpose in its own right and is capable of operating independently	74, 85, 88, 99, 106
Managerial independence	Each constituent system of an SoS is managed to fulfill its own purpose	74, 85, 88, 99
Autonomy	*“The ability to act and make decisions without being controlled by anyone else*” [107]	4, 72, 100, 102
Self-organization	The process in which the system finds its way through planning, without being imposed by outside stimuli or inside central authority	80
Adaptability	The changes system make in itself to deal with changes in the environment	4, 21, 80, 115
Dynamic reconfiguration	The ability to reconfigure if any of constituent systems or elements becomes faulty	4
Evolutionary development	SoS runs an evolutionary development via adding, removing, and modifying its functions and purposes	74, 80, 89, 98, 99, 115

TABLE 12.6 Different Types of SoS and Their Examples

	Definition—exact quotation
Directed	"*Directed systems are those in which the integrated system-of-systems is built and managed to fulfill specific purposes. It is centrally managed during long term operation to continue to fulfill those purposes*" [99] "*If the system is developed through formal organizations to fulfill a common purpose, it is a directed SoS*" [121]
Collaborative	"*Collaborative systems are distinct from directed systems in that they do not have coercive power to run the system. The component systems must, more or less, voluntarily collaborate to fulfill the agreed upon central purposes*" [99] "*If the system is developed through the collaboration of its participants, it is a collaborative SoS*" [121]
Dedicated	"*These SoS are consciously engineered and operated to fulfill an evolving need, term them dedicated SoS. Examples of such dedicated SoS are air traffic control systems and the Internet*" [122] "*If the component systems are architected so that they can be integrated to work together to fulfill a goal, it is a dedicated SoS*" [121].
Virtual	"*Virtual systems lack a central management authority. Indeed, they lack a centrally agreed upon purpose for the system-of-systems. Large scale behavior emerges, and may be desirable, but the supersystem must rely upon relatively invisible mechanisms to maintain it*" [99] "*Virtual SoSs take forms that are rarely envisaged at design time and that they frequently comprise elements that were never designed to be integrated*" [122] (quoted from References 123 and 124) "*If subsystems are previously existing architectures that are integrated to meet an immediate mission requirement, it is a virtual SoS*" [121]
Acknowledged	"*Acknowledged SoS, like directed ones, has recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches. And like collaborative SoS, changes in the systems are based on collaboration between the SoS and the system*" [119] "*In acknowledged SoS an organization is responsible for the SoS and supporting SoS systems engineering while independent organizations and SE teams are responsible for the constituent systems that support the SoS capability objectives*" [125]

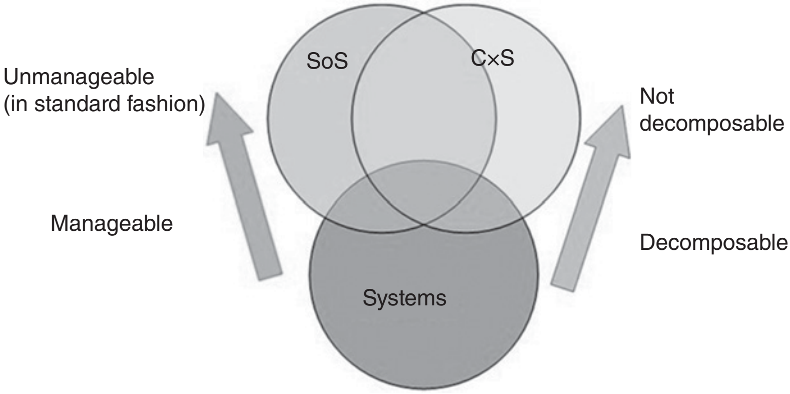

FIGURE 12.12 An illustration of complex systems and systems of systems in terms of decomposability and manageability [43].

Not all systems of systems are considered as CxS. Sheard and Mostashari compare these two as shown in Figure 12.12. They state that systems of systems are related to "*program acquisition context*" and "*unmanageable using standard top-town systems engineering*"; while, CxS are related to "*analytical or scientific context*" and "*described as being not decomposable*" [43].

12.4.4.2 Monolithic Systems Mostafavi *et al.* have recognized differences between a monolithic system and an SoS. These differences are mentioned in Table 12.7 [126].

12.4.4.3 Families of Systems We suggest the Von diagram of Figure 12.13, to represent the interrelation of families of systems, followed by a short explanation of each member of the families of systems, including: family of systems (FoS), SoS, federation of systems, and coalition of systems.

TABLE 12.7 Comparing Monolithic Systems and System of Systems [126]

	Monolithic system analysis	System of systems analysis
Focus	Single system	Integrated systems
Boundaries	Static	Dynamic
Problem	Defined	Emergent
Structure	Hierarchical	Network
Goals	Unitary	Pluralistic
Approach	Process	Methodology
Timeframe	System lifecycle	Continuous
Centricity	Platform	Network

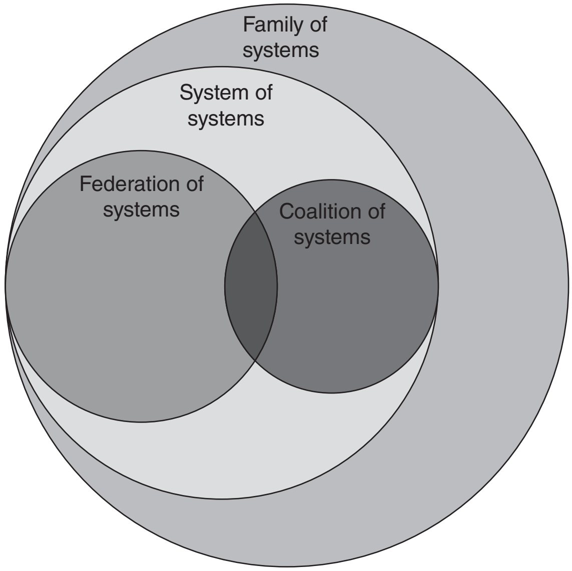

FIGURE 12.13 Von diagram rendering interrelation of taxonomy of systems family.

12.4.4.4 Family of Systems An FoS is said to be a set of systems and "*not considered to be a system per se*" [120]. To distinguish it from SoS, Clark has mentioned some differences: While SoS's constituent systems have been integrated and it is their interconnections that create a capability beyond the sum of each individual's capabilities, FoS's constituent systems are not integrated and therefore, there is no synergism among them [127]. The same deduction could be made about emergence behavior of SoS causing new and unpredictable properties that FoS cannot achieve. Furthermore, one of the main characteristics of SoS is heterogeneity, but considering the mentioned definition, FoS's constituent systems should possess some common characteristics, such as being in the same domain or product line. In other word, "*the member systems may not be connected into a whole*" [120].

12.4.4.5 Federations of Systems To distinguish federation of systems from systems, Krygiel introduces three aspects to be investigated: autonomy, heterogeneity, and dispersion [128]. Federations of systems, as Wells and Sage assert, are more diverse (this diversity especially addresses to the *transcultural and transnational sociopolitical* aspects) and therefore, managed autonomously in a way that each component system fulfills its own objectives, and are geographically more distributed [129].

12.4.4.6 Coalition of Systems Coalitions of systems are "*a class of system similar to systems-of-systems but they differ in that they interact to further overlapping self-interests rather than an overarching mission*" [130]. Shared interests and continuing operation dependence may be coalition of systems' Achilles heel, since there always is the possibility that "*coalition partners renege on their responsibilities to provision parts of a service or application*" [130]. Consequently, a proactive risk management is essential.

12.4.4.7 Other Types of Systems' Relations *Composite systems*: Karcanias and Hessami recognize SoS "*as an evolution of the standard notion in engineering of Composite Systems (CoS)*" [131]. However, they have mentioned that SoS and CoS are different regarding independence and autonomy of their constitute systems; while subsystems of SoS are autonomous and satisfy their own goals, in a CoS, subsystems are subjected to "*the rules of the interconnection topology*" and do not have independent goals [131].

Cyber physical systems (CPS): CPS are composed of systems with tightly combined and conjoined computational and physical elements. Their "*ability to interact with and expand the capabilities of the physical world through computation, communication, and control is a key enabler for future technology developments*" [132].

These systems, according to Reference 133, are developed to achieve "*systems that:*

(a) *respond more quickly (e.g., autonomous collision avoidance),*
(b) *are more precise (e.g., robotic surgery and nano-tolerance manufacturing),*
(c) *work in dangerous or inaccessible environments (e.g., autonomous systems for search and rescue, firefighting, and exploration),*
(d) *provide large-scale, distributed coordination (e.g., automated traffic control),*
(e) *are highly efficient (e.g., zero-net energy buildings),*
(f) *augment human capabilities, and enhance societal wellbeing (e.g., assistive technologies and ubiquitous healthcare monitoring and delivery).*"

Samad and Parisini have mentioned two differences between CPS and SoS. Firstly, considering that CPS totally interacts with physical world while SoS does not *"necessarily require closing the loop in the real world"*; for instance, applications that are purely in the information space are not necessarily outside SoS realm and secondly, a CPS does not necessarily require distributed and hierarchal systems; even a Single Input–Single Output Proportional–Integral–Derivative Controller (SISO PID) could be regarded as CPS [92]. Security of CPSs is of a great concern nowadays, due to recent cyber-attacks and cyber-intrusion trials [134, 135].

12.5 COMPLEX ADAPTIVE SYSTEM OF SYSTEMS

Holland claims that "*it is feasible to understand any System of Systems as an artificial complex adaptive system. It is manufactured to achieve a predefined mission and will involve a large number of interacting entities with persistent movement* *and reconfiguration, changing based on changes in context, ordered through self-organization, with local governing rules for entities and increasing complexity as those rules become more sophisticated"* [21].

CASoS—firstly defined in the Sandia National Laboratories—are systems which exhibit four qualities: (1) be a system; a system consists of some interacting components placed in an environment which is its context of use; (2) be an SoS; since the overall operation is not achievable by a single system; (3) be complex; both inherent complexity in each constituent system and interconnections between them. They are large and irreducible, so "*interpretation, modification, and quantifying the impacts of modification are difficult*," and (4) be adaptive; behavior of component systems change during connection to the environment [136, 137].

Sandia researchers have stated some examples of CASoS including tropical rain forests, agro-ecosystems, cities and megacities (and their network on the planet), interdependent infrastructures (local to regional to national to global), government and political systems, educational systems, health care systems, financial systems, economic systems and their supply networks (local to regional to national to global), the global energy system, and global climate [138].

12.6 HUMAN–AUTOMATION INTERACTION

12.6.1 Automation

The term *automation* was first used in the meaning as is now accepted in industry by Ford Motor Company's VP, *D. S. Harder* around 1946 [139]; while, in academia, E. Nagel used it for the first time in a *Scientic American* article [140].

Automation is defined in Britannica Encyclopedia as: "*a wide variety of systems in which there is a significant substitution of mechanical, electrical, or computerized action for human effort and intelligence*" [139]. In a narrower sense of industrial context, automation can be described as: "*the application of sensors, control systems, and information technologies to reduce the need for human work in the production and delivery of goods and service*" [141].

Historically, mechanical machines were the first automation tools that substituted the human labor; whereas, computers and IT (information technology) systems were widely used then to assist humans in information and decision tasks. Therefore, in this chapter, the terms *automation*, *computer*, *machine* and *IT*, are interchangeably used as a general instance for the automation system or agent "*who executes the function, task or job previously performed or conceivably could be accomplished by a human"* [142]. The latter is our adopted definition of automation. Machines, especially computers, are now capable of accomplishing many functions that at one time could only be performed by humans. Machine execution of such functions (automation) has also been extended to functions that humans do not wish to perform, or cannot perform as accurately or reliably as machines do [110].[5]

[5]Due to the centrality of Reference 110 in our approach to human–automation interaction, we write this reference in its complete form, to stress on the role of all of its authors.

Etymologically, the term automation roots back to Greek word *automatos* [143]; thus, full automation (i.e., complete substitution of humans by machines) might be taken for granted for the term automation. Nof, for instance, argues: "*automation, in general, implies operating or acting or self-regulating, independently, without human intervention*" [143]. Whereas, automation, in a wider sense, can be regarded within a spectrum of no automation (manual) to full automatic (automate), since practically many tasks are performed in a collaboration of humans and automation systems, that is, partial automation or semi-automation [111, 143].

The main reasons to apply automation systems in industry are higher efficiency, avoiding human from hard/hazardous situations, assisting human as a(n) (intelligence/analysis/decision/action) supporting agent and succeeding in critical tasks [110, 144–147].

12.6.2 HAI: Where Humans Interact with Automation

Humans might passively utilize the automation (or its products); however, this can hardly be regarded as an instance for human interaction with automation. Instead, Sheridan and Parasuraman confine the HAI concept to the situations in which humans "*(a) specify to the automation the task goals and constraints (do X but avoid doing Y) and trade-offs between the goals and constraints; (b) control the automation to start or stop or modify the automatic task execution; and (c) receive from the automation information, energy, physical objects, or substances*" [111].

The *automate-as-possible* philosophy, which is the traditional approach to automation systems design, mostly rely on Paul M. Fitts' list [148], in which, a human operator is ironically expected to be responsible for the weaknesses of automation, which itself has been developed for covering human operators' pitfalls: "*functions better performed by automation are automated and the operator remains responsible for the rest, and for compensating for the limits of the automation*" [149].

On the contrary, human-centered automation (HCA) approach promises the notion of more humane automation systems [150, 151], although there might be a controversy on different interpretations of its meaning [152]. HCA seeks the optimum function allocation between the humans and the computers instead of the older attitude of substituting human by computer, and consequently, leaving the un-automatable jobs for humans [153]. The idea of "*eliminating the human to eliminate the human errors*" now appears obsolete amongst most of the automation and computer engineers, and of course, within the human factors engineers as well [111]. Research shows that the moderate combination of job sharing between the humans and the computers might provide better performance and situation awareness (SA) than that of extremist *automate-as-possible* philosophy [154–156].

Bainbridge articulated the ironies of automation to stress on the lack of attention to the role of human in automation [153], and Sheridan ruminated on automation, linking the human decision-making to his well-known taxonomy of automation levels [112, 157]. Moreover, Billings popularized the phrase *human-centered automation (HCA)*, highlighting the importance of human–computer collaboration in the automation system design [111, 150–152, 157]. The term *human-centered computing (HCC)* is also used to demonstrate the significant contribution of human factors to the computer system development [158].

12.6.3 HAI and Function Allocation

A well-crafted automation solution is expected to consider a *manifesto* in which the job sharing between the humans and the machines is completely clarified. This job sharing could aim to optimize the total system performance, mitigate risks, minimize costs, maximize return, and eliminate the operational errors.

The human–machine function allocation has been considered as a classic problem since the early days of very basic automation. The Fitts' list of MABA-MABA, that is, "*men are better at - machines are better at*" is amongst the most well-known solution methodologies [110, 111]. Fitts' MABA-MABA slogan is furthered by T.J. Watson, as IBM Pollyanna principle by "*machines should work- people should think*". Table 12.8 shows an exemplary list of MABA-MABA.

Fitts' list supports automation system designers with a basic idea for static allocation of functions to humans and machines; however, some weaknesses are attributed to that objective. One major drawback of the list, as Dekker and Woods declare, is the false idea of fixed strengths and weaknesses of humans and machines [159]. Whereas, Fitts writes: "*the performance capacity of the human motor system plus its associated visual and proprioceptive feedback mechanisms, when measured in information units, is relatively constant over a considerable range of task conditions*" [148, 160]. In fact, the performance of both humans and machines varies in different situations which implies that the function allocation can scarcely be static, as the MABA-MABA list changes over time. Sheridan also enumerated seven problems of Fitts' approach to function allocation; specifically, he argues that increased autonomy causes function allocation (FA) to be much different from anything Fitts could have imagined [161].

Being a classic problem, function allocation is still a matter of controversy among the scientists and engineers; even on the definitions, concepts and its practical solvability as an either scientific or artistic design problem [152, 161–166]. Moreover, the introduction of intelligent computerized machines and software agents has raised the need for more sophisticated HAI models, capable of providing human–automation

TABLE 12.8 An Exemplary List of MABA-MABA [148]

Men are better at (MABA)	Machines are better at (MABA)
Perceiving patterns	Responding quickly to control tasks
Improvising and using flexible procedures	Repetitive and routine tasks
Recalling relevant facts at the appropriate time	Handling simultaneous complex tasks
Reasoning inductively	Reasoning deductively
Exercising judgment	Fast and accurate computation

collaborative environments rather than simple models that perform a straightforward job allocation. As Proud *et al.* declared: *"The question, 'How autonomous should the system be?' is of primary importance to the designers of the next generation human spaceflight vehicle*" [167]. Endsley and Kaber wrote "*very little experimental work has been conducted to examine the benefits of applying the intermediate LOA (levels of automation) in complex tasks*" [154].

The HCI and HAI methods are developed either by introducing various models and approaches [110–112, 154, 168–175], or by performing practical experiments on implementation of the pre-introduced HAI models [155, 156, 167, 176–188]. Moreover, ergonomists, cognitive engineers, and applied psychologists presented valuable works on the human side of the human–computer systems [142, 185, 187, 189–191].

12.6.4 Evolution of HAI Models: Dimensions

Figure 12.14 reveals the chronological evolution of the HAI models, indicating four breakthroughs in 1951, 1978, 1999/2000, and 2006. The first milestone belongs to Fitts' manual or automate model. P. M. Fitts' list of MABA-MABA can be regarded as one of the first models of HAI [148].

As for the second milestone, the concept of 10 autonomy levels for human–computer (or human–automation) systems is initially proposed by Sheridan and Verplank for teleoperation applications, which Sheridan himself modestly states "*was taken more seriously than were expected*" [112, 157]. However, the considerable

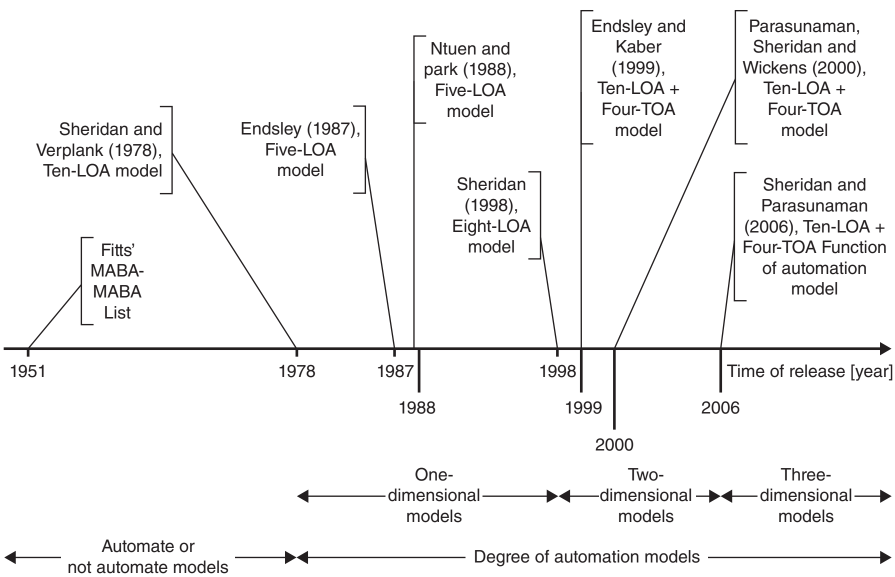

FIGURE 12.14 The chronological evolution of human–computer interaction models.

number of citations to their presented taxonomy shows that it deserves to be taken seriously [155–167, 174, 178, 182, 188]. (LOAs represent degrees or grades of automation for an automatable task, ranging from the lowest (manual) to the highest (full automatic) LOA. We refer to this 10-level model as one-dimensional (1D) model of LOAs in this chapter which is shown as the vertical axis of Table 12.9.

Albeit Endsley introduced an LOA taxonomy for decision support applications; and, Ntuen and Park presented another hierarchy of LOAs for teleoperation applications as well [154, 192]. Although many researchers develop HAI (HCI) models after Sheridan, the 10-level taxonomy was named after Sheridan, as Sheridan's LOA or Sheridan's model of HAI (HCI), since he has initially introduced the idea of degrees of automation in Reference 112, instead of Fitts' automate or non-automate notion.

Subsequently, Endsley and Kaber and Parasuraman, Sheridan and Wickens expanded the 1D LOA model to a 2D model by offering another dimension as type (or stage) of automation (TOA) [110, 154]. TOAs are presented as four types (or stages) for performing a single task, as in horizontal axis of Table 12.9. We refer to this model as 2D model of HAI in this chapter. Table 12.9 compares the 2D HAI models, based on the contributions of Endsley and Kaber and Parasuraman, Sheridan and Wickens [110, 154]. The other dimension of this model (TOA) roots back to the idea that "*proper function allocation differs by process stage*" [161]. It is not clearly stated in their publications which group of authors firstly introduced the second dimension (TOA); however, with respect to both groups of authors, we call the four-stage classification (the second dimension) as "*type of automation (TOA)*" in this chapter. Fereidunian *et al.* discussed on TOAs, questioning it as it is actually *stages of automation* or rather *types of automation* [193, 194].

Another milestone in HAI model development is the introduction of a three-dimensional model by Sheridan and Parasuraman [111]. They added another dimension to the former 2D model as *functions of automation* to make a more comprehensive model.

12.6.5 Evolution of HAI Models: Dynamism

Figure 12.15 shows another aspect of HAI model evolution, in terms of function allocation dynamism, in a chronological order from up to down. As mentioned in the previous section, the first stage in HAI modeling was Fitts' list of MABA-MABA in which a fixed model is considered for manual or automatic function allocation between humans and automation systems as shown in the upper part picture in Figure 12.15 [148].

A step ahead, Sheridan and Verplank furthered the Fitts' two-level—either manual or automatic—model to a 10-degree LOA taxonomy, asserting that an automating job should be considered as incremental degrees of automation, shown in the middle picture in Figure 12.15 [112]. The LOA of HAI model is still a static one, that is, the functions (tasks) are once divided between human and automation in more or less 10 LOAs. This approach was called *static automation* by Parasuraman *et al.* [195].

The performance of human–automation systems is affected by environmental conditions; therefore, the fixed determination of LOA fails to maintain full advantages

TABLE 12.9 The TOA–LOA Model of HAI

LOA	Description [110]↓		Name of the LOA given by Endsley and Kaber [154]↓		
10	The computer decides everything, acts autonomously, ignoring the human		Full automation (FA)		
9	Informs the human only if it, the computer, decides to		Supervisory control (SC)		
8	Informs the human only if asked, or		Automated decision-making (ADM)		
7	Executes automatically, then necessarily informs the human, and		Rigid system (RS)		
6	Allows the human a restricted time to veto before automatic execution, or		Blended decision-making (BDM)		
5	Executes that suggestion if the human approves, or		Decision support (DS)		
4	Suggests one alternative		Shared control (SC)		
3	Narrows the selection down to a few		Batch processing (BP)		
2	The computer offers a complete set of decision/action alternatives, or		Action support (AS)		
1	The computer offers no assistance: human must take all decisions and actions		Manual control (MC)		
	Stages (or types) of automation (TOA) (Parasuraman, Sheridan and Wickens [110]**):** →	I: Information acquisition	II: Information analysis	III: Decision selection	IV: Decision Action
	Stages (or types) of automation (TOA) (Endsley and Kaber [154])→	Monitoring	Generating	Selecting	Implementing

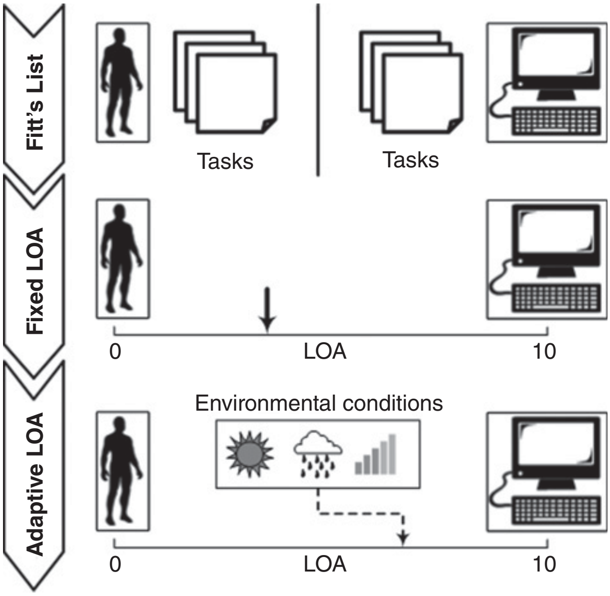

FIGURE 12.15 Development of the HAI in the literature from up to down: Fitts' list (fixed manual or automatic function allocation), fixed LOA (static LOA or fixed 10-level LAO) and adaptive LOA (AA or dynamic LOA).

of the basic idea of automation degrees. As a result, LOAs should be adapted to the environmental conditions. This adaptation necessity paves the way toward further development of the HAI, which according to Sheridan and Parasuraman in Reference 111, is a concept rooting back to Rouse [197]; however, its practical model has been introduced as *adaptive automation* (AA) in References 110 and 155, *adjustable automation* in Reference 169, *dynamic automation* in Reference 111, or *adaptive autonomy* in References 194, 196, and 198, as shown in the lower part picture of Figure 12.15. Improvement of HAI system performance has been reported, as a result of implementing adaptive autonomy, comparing to that of static LOAs [155, 192, 199].

12.6.6 Adaptive Autonomy Implementation

Although the notion of adaptive autonomy is simple, plausible, understandable, and even old (197), it can scarcely be implemented straightforwardly [110, 111, 196, 166]. Parasuraman *et al.* categorized the adaptive autonomy implementing techniques as: "*critical events, operator performance measurement, operator physiological assessment, modeling, and hybrid methods combining one or more of these techniques*" [195] (quoted in Reference 111). These five classes of adaptive autonomy

TABLE 12.10 Summary of Comparisons of Adaptive Autonomy Implementation Methods

Class of adaptive autonomy implementation method	Advantages	Disadvantages
Environment monitoring	• Responsive to the unpredicted changes in environmental conditions	• Ignoring the unpredicted changes in humans' performance and physiological conditions • Sensitivity to the environmental monitoring system
Human monitoring	• Responsive to the unpredicted changes in humans' condition	• Ignoring the unpredicted changes in environmental conditions • Sensitivity to the human performance or physiological monitoring system
Human–automation interaction modeling adaptive autonomy (model based)	• Implementable as an offline adaptive autonomy expert system (AAES) • Less dependence on online monitoring systems	• Dependent on correctness, preciseness and complexity of the models • Delayed response to the changes in environmental or human conditions, due to lack of online monitoring

Source: Taken and Summarized with adaptation from References 111 and 195

implementation methods can be summarized as the three classes of environment monitoring methods, human monitoring methods and HAI modeling (model-based) methods, as shown and compared in Table 12.10.

In the class of environment monitoring adaptive autonomy methods, the external environment (including the under-control plant and other influential factors) is continuously monitored to identify a certain event, like a fault or an abnormal condition in the operation. The automation system intervenes in a human task if those specific events occur, according to some predetermined signs. Parasuraman *et al.* explain the critical event technique (applicable to its general form: environment monitoring) as "*automation is invoked if certain external events occur, but not otherwise*" [195]. Automatic safety management and emergency shutdown (ESD) systems are examples of this class of methods: the safety management system intervenes if certain events occur. For example, consider a safety management system in a robotic manufacturing line; if an operator's hand or head would be recognized entering the operation area of the material handling or welding robots by light guards or other presence sensors, the safety management system will shutdown the manufacturing process, followed by the safety restoration process in an automatic way. Electrical protection and relaying systems and automatic autopilot mechanisms are also good examples for the environmental monitoring adaptive autonomy methods. As Sheridan and Parasuraman argue, the possible insensitivity to actual systems and human operator performance is a disadvantage of the environmental monitoring methods [111]. For instance, in the environment monitoring AA methods, the emergency shutdown system will shutdown the whole process in any prospective recognition of emergency signatures which can be false or not as critical as making the system shutdown.

Class of human monitoring adaptive autonomy methods, on the contrary, continuously monitors the human operator or supervisor of the system to identify any changes in mental workload, fatigue or even improper intention [111]. This can be achieved by assessing operators' performance or measuring operators' physiological condition. If the human performance decrease exceeds a certain limit, more tasks shall be assigned to the automation system, that is, migrating to a higher LOA. For example, Kaber and Riley utilize a measurement technique to determine operator workload in a complex control system. Sheridan and Parasuraman suggest that measuring physiological signals, such as EEG, could potentially prevent operators' extreme fatigue or workload to provide computer aiding to considerably alleviate the potential danger [111]. EEG signals, event-related potentials (ERPs) and eye scanning could be mentioned as examples of human monitoring in the class of AA methods reported in the literature [111, 189, 195, 200–202].

Class of HAI modeling adaptive autonomy (model-based) methods consider both human and automation sides of the interaction. The privileges of model-based methods include its potential for offline implementation, as it could easily be modeled by expert systems. On the other hand, necessity of validation, consideration of all aspect of human operator performance, and divergence of different model results are accepted to be the limitations of this class of methods [111]. Consequently, hybrid methods are introduced to overcome the limitations [111].

12.7 HAI IN SMART GRID AS A CASOS

12.7.1 Smart Grid

Smart Grid, as the future vision of electric power systems, is expected to be intelligent, reliable, optimized, self-healing, and adaptive. This vision leads to significant extension prior to the traditional power system's features. Decentralization of generation, high penetration of renewable energies resources, high contribution of information technologies, power flows from all conceivable places, possibility of anyone to control connections, and adaptive behavior of the Smart Grid feature main differences from the traditional grid [203, 204].

Electric power delivery is a complex phenomenon, due to technical difficulties of storing electric energy. In fact, power distribution system is a collective system, rather than being a delivery system: collecting the power demands from the customers, and distributing the requested energy. This scheme can be considered as a signaling system. Thus, the information availability and quality is one of the most important factors in success of an electric utility company. Electric utilities are committed to perform their delivery job successfully, in terms of legal, technical, and ethical devotions. Any unbalance condition between demand and delivery may cause severe technical issues, which in turn causes economic hazards.

Electric power systems have been subject to many changes in the last two decades. They have emerged from a regulated governmentally owned infrastructure, to a privatized market in capitalized economies. Power systems have migrated from making large power generation plants to encouraging the private sector to contribute in power generation as distributed generations.

Information technology (IT), on the other hand, has become one of the most considerable features of the twenty-first century. All industries devote an effort to adapt themselves to this rapid growing field, to gain more and more from its capabilities. Information technology not only provides an infrastructure to help the industries to overcome their shortages and solve their problems in a more efficient way, but also enables them to do businesses in innovative ways. These industries will be called IT enabled. In power systems, information technology is extensively used to support supervisory control and data acquisition (SCADA), automated operations and *maneuvers* within the network, asset management/facility management (AM/FM), automated meter readings (AMRs) and billings, customer relation management (CRM), and customer information systems (CIS). This extensive use of IT can shift the whole paradigm in electric power utilities, on both technical and managerial sides.

The Smart Grid notion is the fruit of such a paradigm shift: gaining from IT leverages for managing the grid, as well as using the market mechanism for a better demand response, mixed up with the most recent innovations in distributed energy resources (DERs), especially the renewable ones.

Figure 12.16 shows the major subsystems of a Smart Grid scheme. As shown in Figure 12.16, it consists of the following subsystems: power system, automation, and control system, IT infrastructure, operational human (operator, supervisor, controller, or manager), consumer human, HAI system, adaptive AAES, and the surrounding environment.

As the core technology of the Smart Grid, the power system is responsible for electric energy processing and its delivery to the end consumer. The automation and control system manages the operation of the power system. The IT infrastructure provides the data processing and communication between the different nodes and hubs of the system, that is, the interconnections among automation and control, power system, and human [203, 205–212].

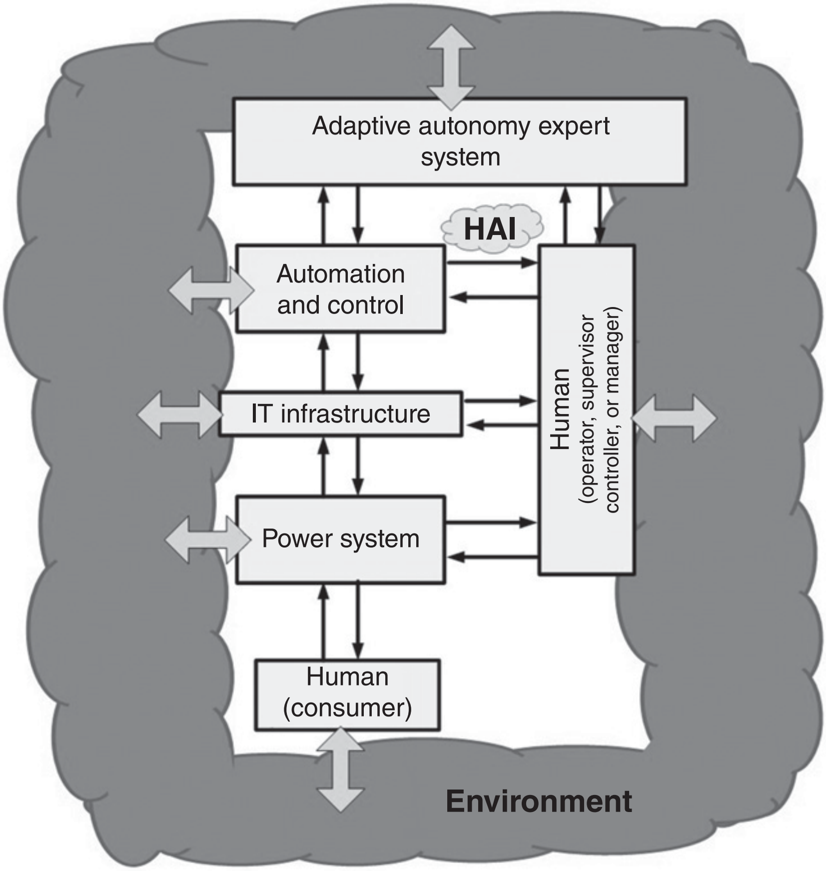

FIGURE 12.16 Smart Grid and its constituent subsystems.

As in Figure 12.16, human participation in Smart Grid is considered as playing two roles: consumption and operation. The consumer human deals with the Smart Grid by consuming the electric energy. Whereas, the operational human is involved in operation, supervision, control or management of the power system, by interacting with the power system, IT infrastructure, and automation and control system with the purpose of design, decision-making, operation, and maintenance.

The HAI system is the sphere in which the operational humans and the automation system collaborate in operation and management of the power system. Finally, the AAES (the up-most block in Figure 12.16) regulates the collaboration of the operational human and the automation system, that is, it adapts the autonomy level (LOA) of the humans and the automation system to the environmental changes. The surrounding environment (the surrounding cloud in Figure 12.16) is the external and internal environment that encompasses the whole Smart Grid system.

In the succeeding subsections the concepts and definitions from previous sections—CAS and SoS—are utilized to investigate the HAI as a CASoS.

12.7.2 HAI in Smart Grid as a CAS

Systems are natural or artificial (human made[6] or engineered) [64]. An artificial system is usually designed and engineered to achieve some specific objectives and to behave according to a predetermined scheme. A conventional control system, a computer program, and a building are examples of artificial systems. Artificial systems are expected to express deterministic behavior, thus, some do not normally regard them asCxS. Unpredictable behaviors may occur in artificial systems—like instability in the control system, divergence in the computer program, or dynamic instability in the building—however, these behaviors are exceptions to regular norms.

The power system, automation and control, and IT infrastructure subsystems of the Smart Grid are artificial systems that are engineered to serve specific goals. Some researchers regard these systems as Information/Decision/Action systems (IDA systems). IDA systems are abstractions of systems that all involve human decision-making, like: individuals and groups of humans, piloted vehicles, companies, governments, air traffic control, finance and banking, management information, command and control information [13, 213]. All of these systems include sensing, communication, assessment of the sensed information (Information), humanistic decision-making (Decision), and consequent controlled action (Action) [13]. IDA systems are claimed to not necessarily be categorized as CASs, since "*a feature missing from some of these IDA systems, for instance, is a degree of regulation and control which tries to prevent them from self-organizing*" [13].

Natural systems, on the other hand, are not engineered by humans. The natural systems evolve during the time from different systems, as they may evolve to other different systems. A lake may evolve to a desert and a tree may evolve to a garbage wood. Science might predict futures for the natural systems based on the empirical experiences from the similar systems. Nevertheless, humans are not personally aware of the goal and target of the natural systems, thus the natural systems are unpredictable in their behavior.

However, between these two extremes, there are systems that are artificial, yet they are larger and older than to be engineered by a team of humans. Infrastructures are one of the most crystal instances of such systems. Weijnen *et al.* exemplify electricity and IT infrastructures as CASs which were not firstly designed to form integrated systems, though they have emerged over time to become so [39, 214]. Emergent behavior of these systems is due to the unpredictable consequences of system operators' actions and disturbances. For instance, cascading blackouts are a result of emergence occurred due to the operator's inability in directing the flows over the network.

[6] In accordance with gender neutrality, here we call the man-made systems as human-made systems.

Now let us apply the above discussion to our Smart Grid case:

> As a holistic view, in a Smart Grid system, although the behavior of each component, for instance a bus-bar, a data link, or a measuring device within different sub-systems is known, the overall behavior of the system is unpredictable. That is, the summation of behaviors of the agents does not simply lead us to the aggregated behavior of the system's components. In other words, the overall behavior of the system is the result of cooperation of its agents. Furthermore, since the relationships between causes and effects are nonlinear, and the action of some parts always affects the action of other parts; the system as a whole shows emergent properties. This nonlinear quality exists both within different subsystems (power system and human operators/consumers) and in the interconnections between them. Moreover, one of the most important qualities of Smart Grid is its ability to adapt to the environmental changes. Furthermore, the subsystems within the Smart Grid system adapt themselves to the changes in the context provided by other subsystems. This internal adaptation is called self-organization (See Section 12.3).

Due to the above discussion, and according to the definitions and characteristics of CASs given in Section 12.3, humans—both operational humans and consumer humans—are obviously CASs, as natural systems. The same applies to the surrounding environment, as it is unpredictable and adaptive.

Power systems are artificial systems that are initially engineered by humans to behave in a deterministic manner; however, they express complex, emergent, adaptive, nonlinear, and even chaotic behavior during their lifecycle. For instance, as a clear example of emergence behavior, a single machine system (i.e., a power generator connected to the bus-bar) is designed and installed to produce electricity with a high level of static, dynamic, and transient stability. However, interconnection of a multimachine system is shown to be prone to dynamic instabilities, causing oscillations in frequency and power, leading to potential cascading trips and even blackouts [215]. As another example for adaptive behavior, consider a situation in which a load varies its consumption. In such a case, the other nodes of the electric network change their voltages and currents to meet the power flow equations [216], thus behaving adaptively.

Similar to the power system, the IT infrastructure and the automation and control subsystems of the Smart Grid are artificial, and are initially engineered by humans to behave deterministically. As stated, these IT infrastructures and automation and control systems are categorized in the class of IDA systems [213]. However, this is provided to that they are conventional ones, that is, they do not include intelligent agents. Otherwise, if the IT infrastructure and the automation and control system include artificial intelligence, the intelligent agents adapt themselves to the changes and learn from their experiences during operation. Thus, apparently, they are complex and adaptive. An example for the actions of automation and control in power systems is restoration by reconfiguration, in response to a fault in the power delivery system by the automation and control system and the employment of the proper tool by IT infrastructures [217–219]. Restoration by reconfiguration is performed while dealing with changes in environment, which can be considered as an adaptive behavior. Nevertheless, even the conventional automation and control systems (i.e., non-intelligent) they also express complex and adaptive behaviors, as discussed earlier quoting Reference 39.

The HAI system (as well as its governing AAES system) is the sphere in which the humans and the automation systems collaborate. The human side is obviously a CAS, and the automation side also behaves as a CAS, as discussed earlier. The HAI is a CAS phenomenon in two senses: firstly, the collaboratively performed tasks of humans and automation systems are complex and should be adapted to the changing environment; and secondly, the human–automation collaboration itself is a complex phenomenon and should be adapted to the changing environment. Thus, an HAI system can be regarded as a CAS.

12.7.3 HAI in Smart Grid as an SoS

HAI can also be regarded as an SoS. In addition to the above mentioned characteristics for a CAS, it is needed to be some complementary characteristics to form an SoS. These characteristics must depict the dispersion aspect of constituent systems: geographical distribution, heterogeneity, and connectivity.

Power Systems—and consequently Smart Grids—are geographically dispersed due to the geographically dispersion of their consumers of electrical power. North American power system is considered to be largest ever implemented human-made system [33].

Smart Grid consists of heterogeneous subsystems that are diverse in purpose, technologies, and context. For instance, the IT infrastructure is responsible for running the required communications among different subsystems. The power system, on the other hand, is responsible for generation, transmission, and distribution of the electrical power.

Connectivity is an inseparable characteristic of SoS, since constituent systems require to communicate with each other to gain the ability of synchronization and pursue their common goal if necessary. Connectivity in Smart Grid is implemented via the IT infrastructure subsystem.

To summarize, a Smart Grid contains a set of geographically dispersed and heterogeneous systems including a large number of agents with nonlinear interconnections—complexity—plus the ability of adaptation to changes in the context produced by other agents or the environment—adaptability. These systems are collaborating together to accomplish a common goal and therefore, Smart Grid can be regarded as a CASoS.

12.8 PETRI NETS FOR COMPLEX SYSTEMS MODELING

Petri nets, introduced in 1962 by C. A. Petri, are basically known as powerful tools for modeling and analysis of systems with concurrent, distributed, nondeterministic, and/or asynchronous behavior. Some examples of application areas of Petri nets are manufacturing systems [220–225], robot planning [226–231], financial systems

[232–234], computational biology [235–240], transportation systems [241–245], and work flow analysis [246–248].

This section is intended to briefly introduce the main concepts of Petri nets. We use notations, definitions, and properties as given by Wu and Zhou in Reference 241.

12.8.1 Definition

A Petri net is a particular kind of bipartite directed graph together with an initial marking depicting the initial state of net. The net includes *places*, *transitions*, and *directed arcs*. Directed arcs connect places to transitions or transitions to places. A *marking* is an assignment of *tokens* (nonnegative integers) to the places of the net. The dynamic behavior of a Petri net is shown by flow of tokens from some places to others by firing transitions resulting in a different marking (state).

A Petri net is formally defined as a 5-tuple $PN = \left(P, T, I, O, M_0\right)$, where

(1) $P = \left\{p_1, p_2, \dots, p_m\right\}$ is a finite set of places;
(2) $T = \left\{t_1, t_2, \dots, t_n\right\}$ is a finite set of transitions, $P \cup T \neq \emptyset$, $P \cap T = \emptyset$;
(3) $I : P \times T \rightarrow N$ is an *input function* that defines directed arcs from places to transitions where N is a set of nonnegative integers;
(4) $O : T \times P \rightarrow N$ is an *output function* that defines directed arcs from transitions to places; and
(5) $M_0 : P \rightarrow N$ is the initial marking.

12.8.2 Graph Representation of Petri Nets

A Petri net graph has two types of nodes, *circles* and *bars (boxes)* representing places and transitions, respectively. *Directed arcs (arrows)*, labeled with their multiplicity (weight), connect places and transitions. *Dots* resided in the circles represent tokens in places (as shown in Figure 12.17).

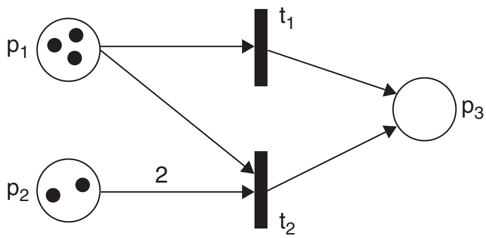

FIGURE 12.17 A simple Petri net graph.

For Petri net of Figure 12.17:

$$
\begin{aligned}
&P = \{p_1, p_2, p_3\};\\
&T = \{t_1, t_2\};\\
&I(p_1, t_1) = 1, I(p_2, t_1) = 0, I(p_1, t_2) = 1, I(p_2, t_2) = 2, I(p_3, t_i) = 0;\\
&O(t_1, p_3) = 1, O(t_2, p_3) = 1, O(t_i, p_j) = 0;\\
&M_0 = (3, 2, 0)^T;\\
&(i, j = 1, 2).
\end{aligned}
\tag{12.1}
$$

12.8.3 Transition Firing

The execution of a Petri net is controlled by the number and distribution of tokens in places. *Enabling rule* and *firing rule* of a transition which control the flow of tokens in places are as follows (see Figure 12.18):

(1) Enabling rule: A transition t is enabled if $\forall p \in P : M(p) \geq I(p, t)$.

(2) Firing rule: The firing of an enabled transition t removes from each input place p the number of tokens equal to the weight of arc (WOA) connecting p to t; and deposits in each output place the same number of tokens equal to the WOA connecting t to p.

Mathematically, firing t at M yields a new marking M' determined:

$$\forall p \in P : M'(p) = M(p) - I(p, t) + O(t, p) \tag{12.2}$$

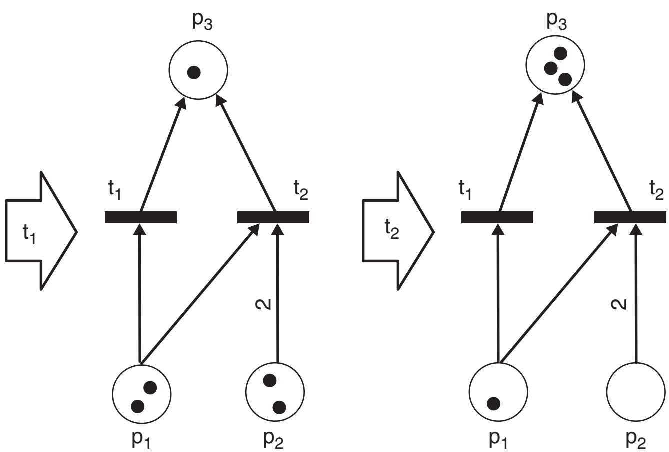

FIGURE 12.18 Transition firing and new markings.

12.8.4 Reachability

A marking M_1 is said to be *immediately reachable* from M_0 if firing an enabled transition in M_0 results in M_1. Reachability is generalized in the way that a marking M_2 is said to be reachable from M_0 if firing a sequence of transitions in T, starting from M_0, results in M_2. The set of all reachable markings of a graph Z from initial marking M_0 is denoted by $R\left(Z, M_0\right)$ [249].

12.8.5 Incidence Matrix and State Equation

The incidence matrix of a Petri net with m places and n transitions is $A = [a_{ij}]_{n\times m}$ with typical entry $a_{ij} = a_{ij}^{+} - a_{ij}^{-}$ where $a_{ij}^{+} = O(t_i, p_j)$and $a_{ij}^{-} = I(p_j, t_i)$. According to firing rule, a_{ij} represents change in the markings in place p_j when transition t_i fires once.

Suppose M_k as an $m \times 1$ column vector whose jth entry denotes the marking in place p_j immediately after the kth firing in some firing sequence, and x_k as the kth firing vector with only one nonzero entry, a 1 in the ith position for the ith transition to be fired at the kth firing. The state equation for a Petri net is as follows (250):

$$M_k = M_{k-1} + A^T.x_k; k = 1, 2, \dots . \tag{12.3}$$

Now, suppose that destination marking M_d is reachable from M_0 through a firing sequence $\{x_1, x_2, \dots, x_d\}$. The state equation can be generalized as follows [250]:

$$M_d = M_0 + A^T.\sum_{k=1}^{d} x_k. \tag{12.4}$$

12.8.6 Inhibitor Arc

An *inhibitor arc* connects an input place to a transition and changes the transition enabling condition in a way that there should be no tokens in each input place connected to the transition by the inhibitor arc (see Figure 12.19). Inhibitor arcs are used to model priority in the system.

12.8.7 IF–THEN Rules by Petri Net

An IF–THEN rule can be modeled as a transition whose input places and output places represent antecedent portion and consequence portion of the rule respectively, in a way that each proposition in the antecedent portion is modeled as an input place and each proposition in the consequence portion is modeled as an output place [251]. For instance, the following IF–THEN rule can be modeled as shown in Figure 12.20:

$$R_1 : if\ ((A\ or\ B)\ and\ C)\ then\ ((D\ or\ E)\ and\ F). \tag{12.5}$$

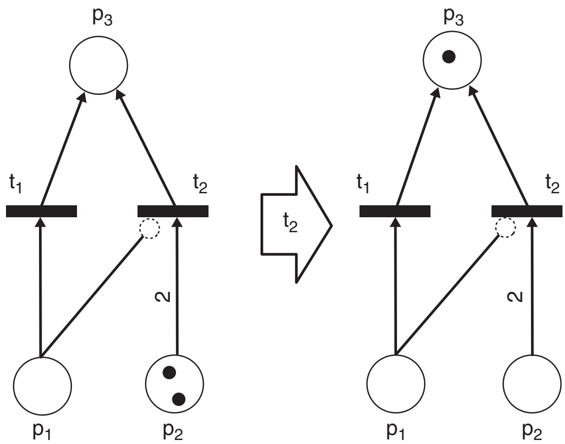

FIGURE 12.19 Inhibitor arc in Petri net graph.

12.9 MODEL-BASED IMPLEMENTATION OF ADAPTIVE AUTONOMY

12.9.1 The Implementation Framework

An implementation framework for adaptive autonomy is proposed by Fereidunian *et al.,* which belongs to the model-based class of adaptive autonomy implementation methods (see Table 12.10 for classification), as shown in Figure 12.21 [193, 194, 198]. The upper loop in Figure 12.21 sequentially checks for the changes in performance shaping factors (PSF). PSFs are used to introduce the environmental conditions to the adaptive autonomy implementation process. PSFs represent the most influential factors that shape the performance of humans and the automation system (intelligent electronic devices (IEDs)). PSFs are used in this framework to tackle the issue of quantitative representation of the SCADA system environmental conditions [193, 198].

Each time the environmental conditions change—according to the monitored field dynamic data—PSFs are updated. Afterward, the new autonomy level is determined

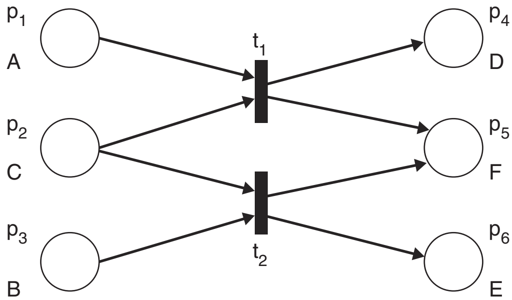

FIGURE 12.20 Petri net modeling of IF–THEN rule.

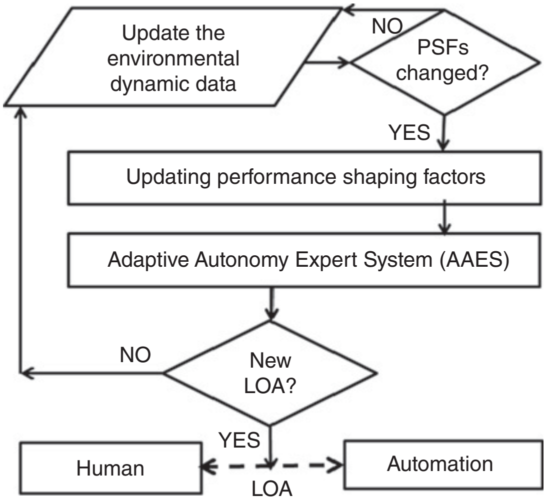

FIGURE 12.21 The proposed framework for implementation of adaptive autonomy.

by a trade-off analysis between the humans and the automation in light of the subjective knowledge of Experts' Judgment. Since the aim of the human performance evaluation is to compare it to those of automation, this research does not seek to focus on direct methods of human mental models, that is, the objective methods; instead, we referred to the subjective knowledge of the filed experts. The Experts' Judgment is gathered through interviews with the GTEDC's (Greater Tehran Electric Distribution Company) SCADA and dispatching experts, based on a standardized questionnaire, where each interview took at least 1 hour time [193, 194, 198].

An extended version of the LOA–TOA model of Parasuraman, Sheridan, and Wickens is used in our proposed method: level 1 of the original Sheridan's taxonomy is shifted down to form a new level 0*; and a new level of 1* is introduced as a new LOA [110]. Hence, our adaptive autonomy framework deals with 11 LOAs. The justification for the necessity of the new level is given in [193], and the definitions of the LOAs, TOAs, and HAI model can also be found in References 110, 193, and 194.

Up until now, this implementation framework has been realized using the following eight technologies: AAES using weighted summation fusion [196], AAFES using fuzzy systems [252], AAGLMES using generalized linear models [208], AALRES using logistic regression [253], AAHES using hybrid neural network [254], AAPNES using Petri nets [255, 256], AAHPNES using hierarchical Petri nets [257], and AAFGES using fuzzy gradient descent [258].

12.9.2 Case Study: Adaptive Autonomy in Smart Grid

Utility management automation (UMA), as a subsystem of Smart Grid, acts as a SCADA system for the electric utility in which human operators and automation systems work collaboratively. In this section, an expert system (referred to as

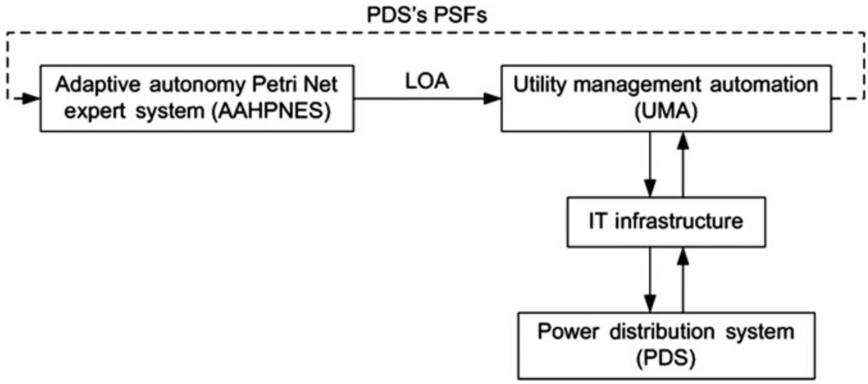

FIGURE 12.22 Position of Petri net adaptive autonomy expert system in power distribution system.

AAHPNES) is employed to adapt the autonomy level (LOA) of the UMA system to the changes in the PSFs. In other words, the AAHPNES controls the LOA of the UMA system.

AAHPNES is implemented to one of the power distribution automation functions, referred to as feeder reconfiguration function of utility management automation (UMA-FRF). The UMA-FRF system—which has been introduced in References 207, 219, 259–261—automatically restores the electric energy for the affected customers (electric power delivery load points) by reconfiguring the distribution network topology after a failure in the distribution network [217, 218, 262, 263]. Figure 12.22 shows the proposed expert system role in relation with the other subsystems of the UMA. The dashed arrow from the UMA conveys the PSFs to the AAHPNES where the other solid line arrows command the LOA recommended by AAHPNES to the UMA.

12.10 ADAPTIVE AUTONOMY REALIZATION USING PETRI NETS

12.10.1 Implementation Methodology

Here the implementation method of the AAHPNES is presented.

12.10.1.1 IF–THEN Rules of AAHPNES IF–THEN rules and their representation in Petri net are the primary concerns in realization of the AAHPNES. In this section, the general form of the extracted rules from the experts' judgment is presented.

There are two kinds of rules that are employed in the AAHPNES: *Comparative Rules* and *Combinational Rules*. The comparative rules suggest an LOA when only *one* PSF changes from its normal condition, while combinational rules suggest an LOA when *multiple* PSFs change from their normal conditions. In other

TABLE 12.11 PSFs' Values and Their Corresponding WoAs

PSF	PSF's value (a_i)	WoA (b_i)
Time	Day*	1
	Night	2
Service area	Uncrowded urban*	1
	Crowded urban	2
	Rural	3
Customer type	Residential*	1
	Commercial/industrial	2
	VIP	3
Number of faults per 2 hours	Few*	1
	More	2
	Much more	3
Network age	New*	1
	Middle aged	2
	Old	3
Load	Low*	1
	High	2

a * denotes a basic PSF state.

words, combinational rules describe the effect of change in one PSF's value on LOA at a time, while combinational rules describe effects of changes in two or three PSFs' values on LOA together at the same time. The list of practical PSFs and their values is shown in Table 12.11. For example, according to experts' judgment for an *old* network (PSF_5 = Old), while other PSFs are normal, the LOA is 3—comparative rule; and for a *highly* loaded network with *much more* (10) faults per 2 hours ($PSF_4 = Muchmore$and$PSF_6 = High$), independent from other PSFs, the LOA is 7—combinational rule. To put it in other words, the first rule demonstrates that an *old* network, alone and in comparison with normal condition, decrease two units in LOA; while, the second rule implies that the effects of *much more* faults per 2 hours combined with high load increase two units in LOA.

12.10.1.2 Petri Net Representation of Rules In this part, rules are customized to be applied to the AAHPNES. According to GTEDC's experts, LOA depends on six main PSFs which are shown in Table 12.11 [252]. Using these PSFs, rules are represented in the following general form:

$$R_1 : if((PSF_1\ is\ a_1)\ and \ldots and\ (PSF_6\ is\ a_6))\ then\ (LOA\ is\ c). \qquad (12.6)$$

In order to model this rule by Petri net, antecedent and consequent portions of the rule have to be transformed to Weight of Arcs (WoAs) to the corresponding transition and from it, respectively (see Figure 12.23). To do so, the proposition "$PSF_i isa_i$" is transformed to a WoA (b_i), connecting the input place corresponding to PSF_i to transition corresponding to this rule. Table 12.11 shows the corresponding WOAs

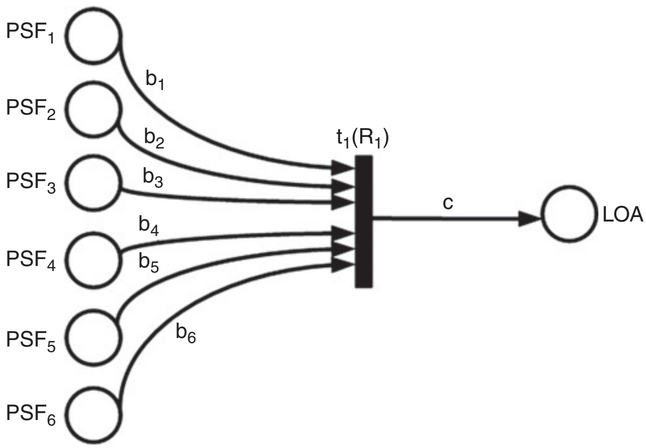

FIGURE 12.23 Petri net modeling of rule of Equation (12.6).

(b_i) for different PSFs' values (a_i) of each PSF. As shown in Table 12.11, the concept in determining WOAs is that for each PSF, the normal PSF's value (marked by * in Table 12.11) gets $WOA = 1$ and for other PSFs' value, WOA increases as the abnormality of PSF's value, relative to the normal PSF's value increases. Note that all PSFs' values are linguistic values: for the first three PSFs (Time, Service area, and Customer type) these values describe different types of the corresponding PSF considered in our modeling and for the last three PSFs (Number of faults per 2 hour, Network age, and Load) these values describe different levels of numerical values of the corresponding PSF, that is, the practical range of numerical values of each PSF is quantized into two or three levels and each quantization level, labeled with a specific linguistic value, is transformed into a nonnegative integer (WoA).

For consequent portion of the rule, "*LOAisc*," b is suggested as WOA between the corresponding transition and output place.

12.10.2 Realization of AAHPNES

AAHPNES recommends the proper LOA in the presence of different PSFs. The proposed Petri net expert system has two layers, *Comparison layer* and *Combination layer*, corresponding to two sorts of rules.

12.10.2.1 Comparison Layer This layer of the Petri net model is constructed using *11 comparative rules*. The antecedent portion of these rules is in the form of$PSF = [1, \ldots, i, \ldots, 1]\,, i \neq 1$, that is, all PSFs are normal except one of them (Table 12.11). To model these rules by a Petri net, the six PSFs are divided in three groups based on their effect on LOA [260]. These groups and their effects are:

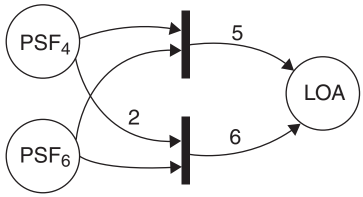

FIGURE 12.24 Simple Petri net modeling of rules of Equation (12.7), each rule is modeled by a transition.

(a) PSF_1 and PSF_2, tend to increase the LOA when their value deviates from normal;
(b) PSF_3 and PSF_5, tend to highly decrease the LOA when their value deviates from normal; and,
(c) PSF_4 and PSF_6, tend to highly increase the LOA when their value deviates from normal.

For each group, using the corresponding rules, a hierarchical Petri net model is derived. To illustrate the hierarchical method of modeling, suppose the following rules:

$$R_1 : PSF = [1, 1, 1, 1, 1, 1] \rightarrow LOA = 5$$
$$R_2 : PSF = [1, 1, 1, 2, 1, 1] \rightarrow LOA = 6. \tag{12.7}$$

These two rules can simply be modeled as shown in Figure 12.24 in which each rule is modeled by a transition using WOAs from Table 12.11; however, this simple model, since there is no priority between transitions, cannot guarantee the correct output for some combinations of inputs. Therefore, it needs a complicated analysis to determine the final LOA; for instance, suppose that PSF_4has two tokens, it can also fire the upper transition without firing the lower transition. This problem was resolved in AAPNES of Zamani *et al.* in References 255 and 256 by introducing priority to the model using deterministic timed Petri nets (DTPN). Here in AAHPNES of Fereidunian *et al.* in Reference 257, these rules are modeled in a hierarchal organized Petri net, as shown in Figure 12.25. This hierarchical modeling technique is based on experts' judgment procedure while determining the proper LOA for real input PSFs. Moreover, in the final modeling, instead of the LOA itself, its deviation from the normal condition ($LOA = 5$) is considered. Figure 12.26 shows this concept for the model of Figure 12.25. The concept of determining deviation from normal LOA as the output of the net instead of the real LOA is employed to make the judgment procedure simpler for experts.

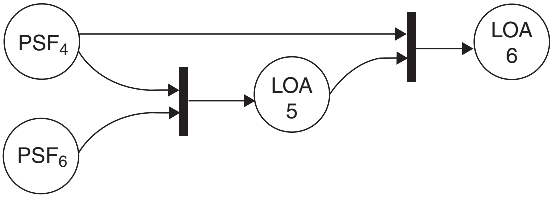

FIGURE 12.25 Hierarchical Petri net modeling of rules of Equation (12.7).

Now that the hierarchical modeling method is explained, we explain the complete procedure of deriving a Petri net model for the third PSFs group (PSF_4 and PSF_6). This model is derived from four comparative rules listed below:

$$\begin{aligned} &R_1 : PSF = [1,1,1,1,1,1] \rightarrow LOA = 5 \\ &R_2 : PSF = [1,1,1,2,1,1] \rightarrow LOA = 6 \\ &R_3 : PSF = [1,1,1,3,1,1] \rightarrow LOA = 7\,. \\ &R_4 : PSF = [1,1,1,1,1,2] \rightarrow LOA = 6 \end{aligned} \tag{12.8}$$

As stated above, the first rule indicates the normal condition, R_2 and R_3, are the comparative rules regarding $\mathrm{PSF}_4$and $\mathrm{R}_4$is the comparative rule regarding PSF_6. Nonetheless, to be able to derive a model, there is a lack of information about two other feasible conditions: $PSF = [1,1,1,2,1,2]$ and $PSF = [1,1,1,3,1,2]$. For the later one, using R_3 and the fact that the highest practical level of LOA for this application is 7, it is concluded that

$$R_5 : PSF = [1,1,1,3,1,2] \rightarrow LOA = 7. \tag{12.9}$$

For the former one, we have to use a combinational rule—which is actually derived from the nature of the system:

$$R_6 : PSF = [1,1,1,2,1,2] \rightarrow LOA = 6. \tag{12.10}$$

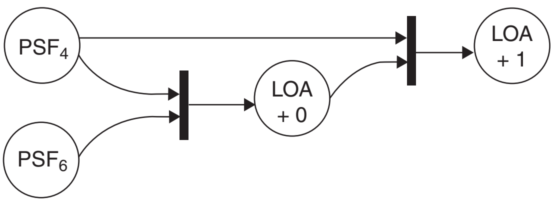

FIGURE 12.26 Hierarchical Petri net modeling of rules of Equation (12.7), output places show the change in LOA from normal condition.

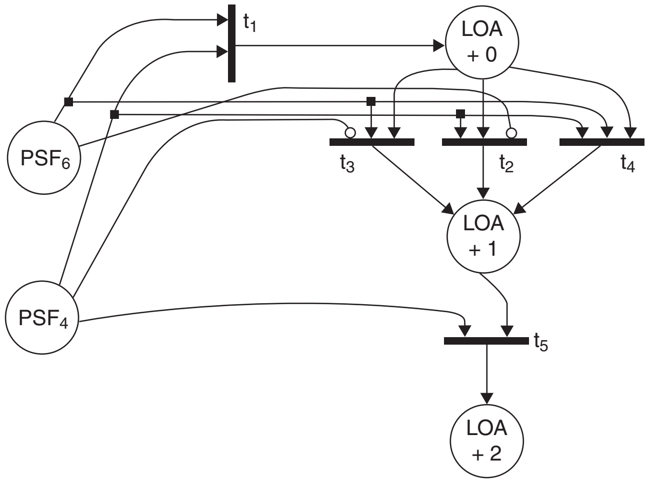

FIGURE 12.27 Hierarchical Petri net modeling of group c includes PSF_4 and PSF_6.

Note that in all of the rules above, the other PSFs (PSF_1, PSF_2, PSF_3, and PSF_5) have their normal values. Now that all needed rules are available, the hierarchical Petri net model can be derived as shown in Figure12.27. In this model t_1, t_2, t_3, and t_4 correspond to R_1, R_2, R_4, and R_6respectively; andt_5 corresponds to R_3 and R_5.

Using the same procedure, the Petri net models of the other groups of PSFs are derived as shown in Figure 12.28. Note that the notation "$\frac{1}{2}$+" in Figure 12.28a indicates that the corresponding input PSFs cannot change the LOA individually and their effect is determined in combination with other input PSFs (this task is performed by the combination layer of modeling).

12.10.2.2 Combination Layer The combination layer of the Petri net model is constructed using *11 combinational rules*. In order to apply these rules, the antecedent portions of them are translated to make them applicable to the outputs of the comparison layer. For instance, the rule

$$R_{12} :, \mathrm{PSF}_4 = 3, \mathrm{PSF}_6 = 2 \rightarrow LOA = 7 \tag{12.11}$$

is translated to

$$R_{12} : (\mathrm{LOA2+})\,\&\,(LOA2+) \rightarrow LOA = 7. \tag{12.12}$$

The modeling method for these rules is transforming each rule to a transition; like the method applied in Figure 12.24 for modeling the rules of Equation (12.7). These rules determine the final LOA (Figure 12.30).

In addition, during the execution of the overall Petri net, in order to give priority to the comparison layer over the combination layer, a transition is added as

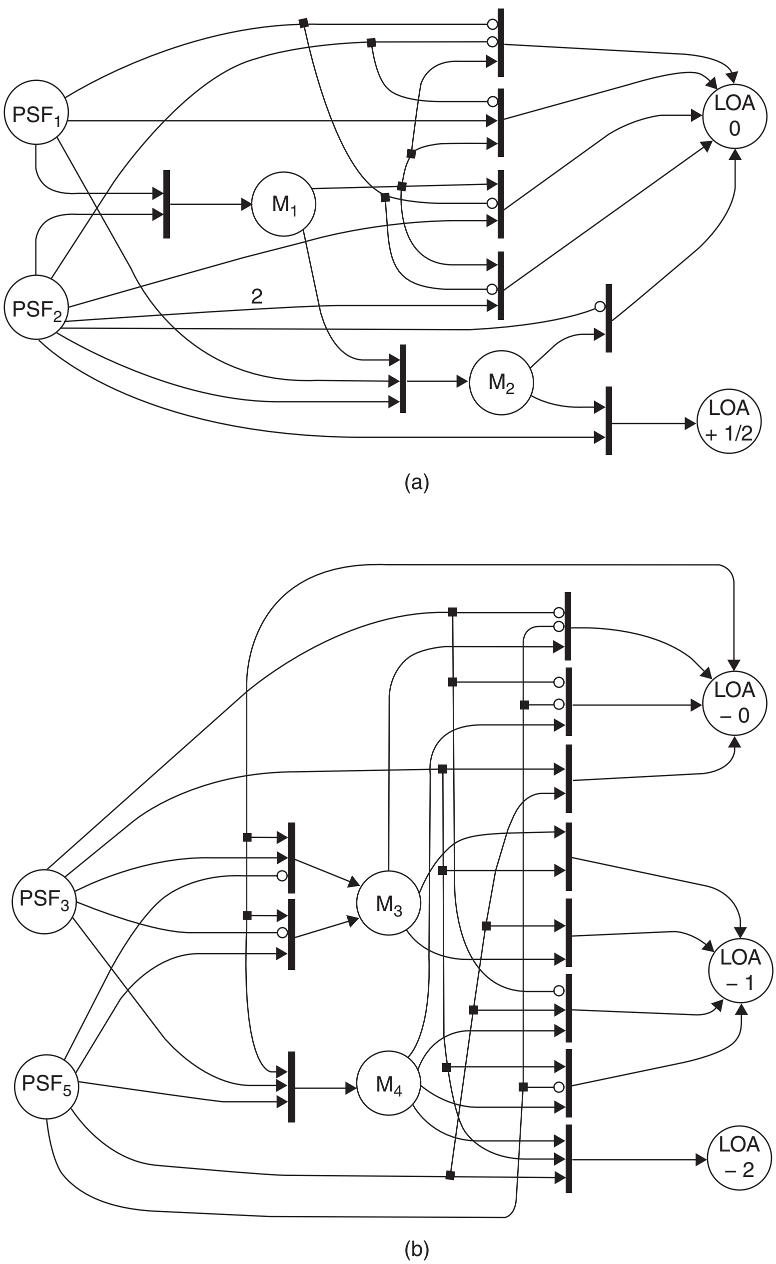

FIGURE 12.28 Hierarchical Petri net modeling of: (a) group a includes PSF_1 and PSF_2, (b) group b includes PSF_3 and PSF_5.

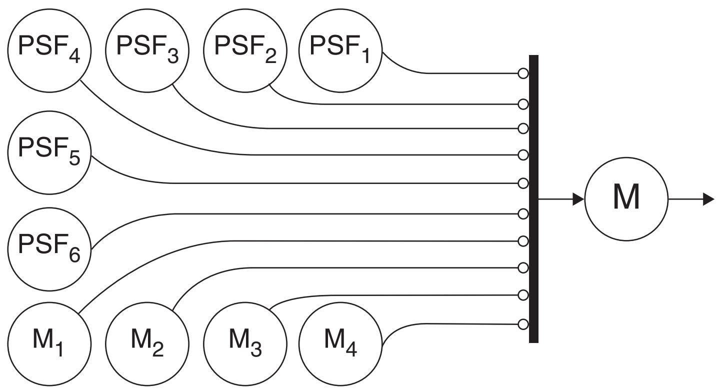

FIGURE 12.29 Trigger for giving propagation priority to comparison layer over combination layer.

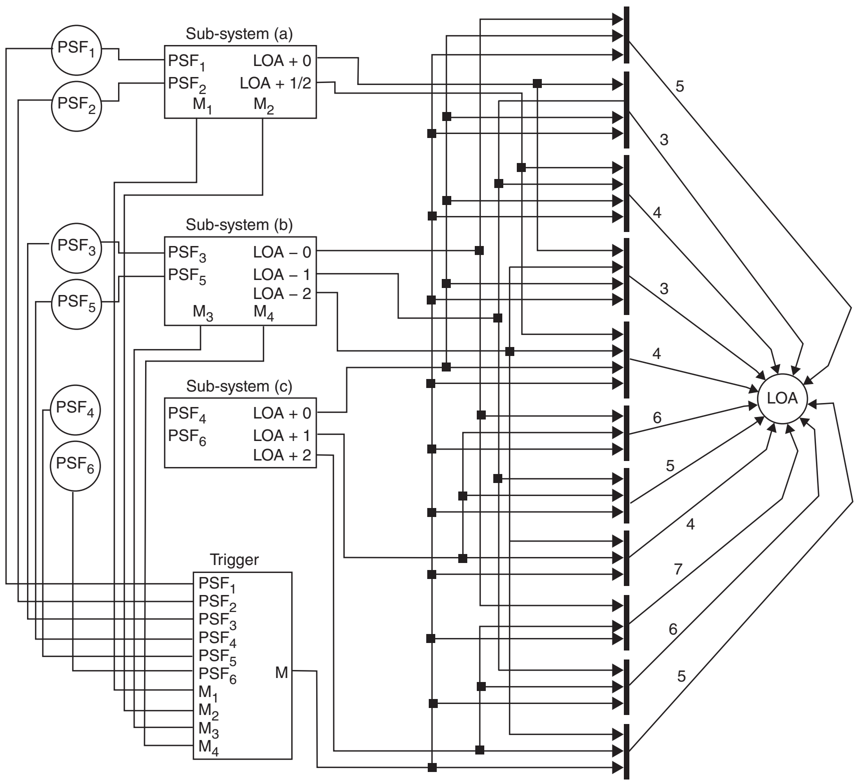

FIGURE 12.30 The overall Petri net expert system.

a trigger. Figure 12.29 shows the structure of the trigger. As shown, the transition will be enabled when all the input and medium places of the comparison layer are empty, that is, the execution of the comparison layer is finished. The output place of this transition (M) is added as an input place to all transitions of the combination layer; thus, the combination layer's transitions would not be enabled, unless the process of the comparison layer is finished.

Figure 12.30 shows the overall Petri net expert system. As can be seen, the hierarchical Petri net modeling of grouped PSFs in elementary layer and the trigger are shown as blocks (subsystems); while, the secondary layer of the modeling is shown in detail.

To apply the Petri net model, the input condition (PSF vector) is transformed to an initial marking according to Table 12.11, that is, the same mechanism for determining WOAs from rules holds for determining the initial marking from the input PSF vector. Afterward, using reachability analysis, the dead-end marking from a firing sequence, in which there is no repeated transition, is calculated.

Note that all of the reachable markings from any initial marking (in which only input places,PSF_{1-6}, include a nonzero number of tokens) lead to a dead-end marking. To understand this, note that in the overall Petri net of Figure 12.30, tokens only propagate from the left-hand side of the net to the right-hand side. Based on the modeling method, there is only one such marking and only this marking can be used for determining LOA, because other dead-end markings, even with a nonzero number of tokens in the place "LOA," are not reasonable due to firing some transition(s) more than once. In this dead-end marking, number of tokens is the place "LOA" demonstrates the final LOA. To illustrate, consider the subsystem (a) of Figure 12.30, which is shown in detail in Figure 12.27. As shown in Figure 12.27, for any initial marking (number of tokens in places PSF_4 and PSF_6), only transition t_1, is enabled at first, since other places has no token. Thus, t_1 is the first transition to be fired. Subsequently, since t_1 cannot be fired anymore and regarding the number of tokens remained in $PSF_4$and PSF_6, only one of the transitions t_2, t_3, or t_4 is enabled and it is the next entity of the firing sequence. Finally, if still a token remains in PSF_4, since none of the transitions t_1, t_2, t_3, and t_4 can be fired, even if they are enabled, t_5 will be enabled and fired. Figure 12.31 shows all of the feasible initial markings and corresponding firing sequences. As you can see, they all end in a marking with only one place with nonzero (one) number of tokens—this place is one of the three output places of "LOA + 0," "LOA + 1," and "LOA + 2."

Using the same procedure, we can also show that for the Petri nets in Figure 12.28 (subsystems b and c of Figure12.30), any feasible initial marking leads to a dead-end marking in which there is only one place with nonzero (one) number of tokens and that place is one of their output places. Now that one of the output places of each subsystem is set (has only one token) and all other places within the subsystems are empty, the combination layer is triggered. Based on the distribution of tokens in output places of subsystems, only one transition among 14 transitions of combination layer will be enabled. Firing this transition deposits in place "LOA" a number of tokens equal to the final LOA—note that each distribution of tokens in output places of subsystems of comparison layer corresponds to only one of the

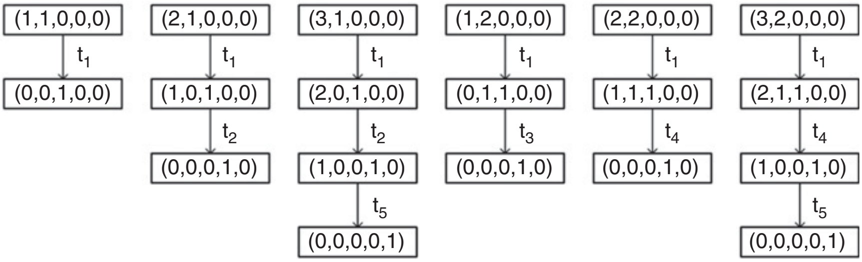

FIGURE 12.31 Firing sequences and corresponding markings for all feasible initial markings for Petri net of Figure 12.27 (the order of places in given markings is PSF_4, PSF_6, LOA + 0, LOA + 1, and LOA + 2).

transitions in the combination layer and only one transition can be fired since output places of subsystems of comparison layer include only one token.

To summarize, AAHPNES paves the steps shown in Figure 12.32, to determine LOA for a HAI system.

12.10.3 Results and Discussions

The intelligence of an expert system intensively relies on including appropriate rules. Furthermore, to evaluate the performance of the expert system, it is needed to verify whether the system can simulate an expert opinion or not. Therefore, both rule set and test set are asked from a superior expert in various PSFs combinations. The superior experts are experts whose superiority (in higher and more reliable expertise) has been verified according to consistency for their expert judgments [252]. All feasible conditions include 324 states which are used to determine correct classification rate (CCR) of the system.

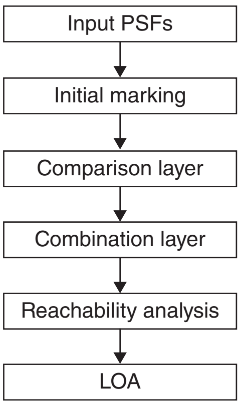

FIGURE 12.32 Steps of expert system in determining hybrid LOA from input PSFs.

The CCR of the proposed AAHPNES is 78% which indicates the high overall performance of the expert system. Moreover, the CCR of the proposed expert system for $LOA = 3\, or 7$ is 94% which demonstrates that the system almost exactly simulates an expert opinion in critical situations. This illustrates higher performance of proposed AAHPNES, both generally and in critical situations, in comparison with its ancestor, AAPNES, introduced in References 255 and 256.

In comparison with the other model-driven systems of References 196 and 252, AAHPNES not only shows a higher CCR—especially in complicated situations, but also employs a systematic method that is more like a humanistic decision-making in terms of hierarchical reasoning. To illustrate, while expert systems of References 196 and 252 apply all extracted rules from the experts' judgment at once, the presented AAHPNES first determines the effect of PSFs separately, then combines them to determine to proper LOA. This method is based on experts' attitude during interviews. Moreover, the introduced AAHPNES, like its ancestor AAPNES of References 255 and 256 has the unique quality of employing the priority introduced in experts' judgments in modeling. This priority is used in the second level of modeling in the process of combining outputs of the first level. Although the expert systems of References 208, 253, and 261 may show higher performance regarding CCR, they are all data driven and require a large amount of data to be able to determine a proper LOA, while the proposed AAPNES is based on 22 general rules.

12.11 CONCLUSIONS

After introducing the systems-related concepts of complexity, CASs and SoS, different views regarding these concepts were compared. Especially, the characteristics of the CASs and SoSs were enumerated and explained. Subsequently, the automation-related notions of automation and HAIs were described, and then, evolution of HAI models from both viewpoints of dimensions and dynamism were investigated. Furthermore, the idea of adaptive autonomy (AA) was introduced as a dynamic HAI scheme, followed by a classification of AA implementation methods. Afterward, the HAI system was studied as a CAS and an SoS. Petri nets were introduced as powerful tools for modeling CxS. Finally, the Petri net realization of AAES was expressed and its performance was evaluated.

Besides introducing and explaining the topic itself, a couple of open questions were elaborated in this chapter. One of the most important questions is the source of complexity: either the complex entity itself or the observer (Section 12.2.1). The complexity that is sourced back to the complex entity is referred to as innate complexity, and described as a state of world. Whereas, the complexity that is sourced by the observer is referred to as cognitive complexity or complicatedness (i.e., making confused), and described as a state of mind when responding to complexity [2]. This is a controversial issue, as some argue that if there was no human (as observer), we could not regard any entity as complex. Others, on the other hand, believe that complex entities are inherently complex, regardless of the human observer. An interesting advocate for the innate complexity is that the human mind is a complex phenomenon itself. Thus when talking about cognitive complexity, one should remember that the observer's mind evolve, as a complex entity. This controversy needs more discussions in a proper situation and more investigation on this issue might be furthered in future research.

The 2D classification of Table 12.1 (Section 12.2.2), or as we called it source–problem representation of CxS, has been introduced in this chapter for the first time. Thus it needs more investigation, and perhaps more development.

Definitions of complexity are qualitative ones, while, we can talk about degrees of complexity: two systems might be complex; nevertheless, one of the two could be much more complex than the other one. Many complexity measures have been introduced for different types of complexity (in Section 12.2.3); however, a unified measure of complexity is needed. Moreover, more quantitative work on complexity needs to be performed. Although fuzziness of the complexity concept is acknowledged, little research has been conducted on this, to the best of our knowledge.

We enumerated 11 characteristics for CASs, out of the almost 20 found in the literature (Section 12.3.2). This can be reduced to fewer characteristics by extracting the most principal characteristics. If it is not theoretically possible, a practical list of minimum requirement for CAS' characteristics can be agreed upon. For example, it can be said that a system is a CAS, if and only if it exposes the four principal characters of emergent behavior, complexity, adaptability, and nonlinearity. It is quite plausible that the other characteristics can be deduced from those principal characteristics. Similarly, 14 characteristics were counted for SoSs, out of many (in Section 12.4.2). This can also be reduced to fewer by extracting the most principal ones or by agreeing upon a criteria list for SoS characteristics. The latter two studies—that is, criteria of systems for being CAS and SoS—are more expected from the professional organizations and standardization bodies like IEEE.

A preliminary taxonomy of systems family was developed in this chapter (Section 12.4.4.3) and depicted in Figure 12.13. Some other members of the systems family should be added to it and perhaps some editions required, which can be done in future works.

In this chapter, the qualitative HAI model of Parasuraman, Sheridan, and Wickens in Reference 110 (see Section 12.6.4) was engineered according to the model-based adaptive autonomy framework of Fereidunian *et al.,* in Reference 198 (see Sections 12.6.6, 12.9.1 and 12.9.2), and then realized using a hierarchical Petri net expert system (Sections 12.10.1 and 12.10.2), referred to as AAHPNES [257]. The HAI model of Reference 110 may be implemented by different methods and the adaptive autonomy framework of Figure 12.21 can be improved. Both models can also be implemented to different automation application domains, to compare the context-specific results with our results in Smart Grid.

Furthermore, according to Fereidunian *et al.,* in Reference 194, implementation of the HAI model faces to the following challenges: quantification of a qualitative model, type or stage, the lost LOA, and independency or interdependency of the TOA and LOA. The latter challenge is still an important open question and is a niche in the future research.

Moreover, the performance of the proposed AAHPNES system can be improved by applying additional rules; however, the issue is that a large number of rules (transitions) are needed to provide noticeable improvement. In other words, there is a trade-off between system performance and number of rules. A colored Petri net might show better performance compared to that of the hierarchical Petri net presented in this chapter.

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