INTERNATIONAL STANDARD

# ISO/IEC/IEEE 21841

First edition
2019-07

Corrected version
2019-09

# Systems and software engineering — Taxonomy of systems of systems

*Ingénierie système et logiciel — Taxonomie des systèmes de systèmes*



Reference number
ISO/IEC/IEEE 21841:2019(E)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

Institute of Electrical and Electronics Engineers, Inc
3 Park Avenue, New York
NY 10016-5997, USA

Email: stds.ipr@ieee.org
Website: www.ieee.org

Published in Switzerland

# Contents

Page

# Foreword

ISO (the International Organization for Standardization) and IEC (the International Electrotechnical Commission) form the specialized system for worldwide standardization. National bodies that are members of ISO or IEC participate in the development of International Standards through technical committees established by the respective organization to deal with particular fields of technical activity. ISO and IEC technical committees collaborate in fields of mutual interest. Other international organizations, governmental and non-governmental, in liaison with ISO and IEC, also take part in the work.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the rules given in the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE-SA) Standards Board. The IEEE develops its standards through a consensus development process, approved by the American National Standards Institute, which brings together volunteers representing varied viewpoints and interests to achieve the final product. Volunteers are not necessarily members of the Institute and serve without compensation. While the IEEE administers the process and establishes rules to promote fairness in the consensus development process, the IEEE does not independently evaluate, test, or verify the accuracy of any of the information contained in its standards.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO and IEC shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents) or the IEC list of patent declarations received (see http://patents.iec.ch).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Joint Technical Committee ISO/IEC JTC 1, *Information technology*, Subcommittee SC 7, *Systems and software engineering*, in cooperation with the Systems and Software Engineering Standards Committee of IEEE Computer Society, under the Partner Standards Development Organization cooperation agreement between ISO and IEEE.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

This corrected version of ISO/IEC/IEEE 21841:2019 incorporates the following correction:

— The publication date on the cover page has been corrected.

# Introduction

Systems of systems engineering (SoSE) is a concept that is increasingly thought of as a discipline important for the realization and sustainability of large and persistent sociotechnical systems in areas as diverse as healthcare, transportation, energy, defense, corporations, cities and government.

While SoSE applies broadly to hardware, software, middle-ware as well as embedded, cyber-physical and digital systems, the importance of SoSE has been heightened in the last fifteen years by the rapid increase in the pervasiveness of information technology (IT), illustrated by new technologies and paradigms such as Sensor Networks, Cloud Computing, the Internet of Things, Big Data, Smart Devices and Artificial Intelligence. It is, for instance, the application of these technologies to cities that transform them into “smarter” cities.

This pervasiveness of IT was not only driven by the availability of these technologies, but also more importantly by the requirements in our resource and environmentally-constrained world for increased and sustainable economic development and, ultimately, personal well-being.

SoSE goes well beyond IT and potentially applies to all types of systems, including hardware and cyber physical systems where IT is an enabler. SoSE addresses functionality, performance and interdependencies of the systems as well as their connectivity. The interconnectivity of systems has become pervasive in large command and control systems, defense systems, communications systems, transportation systems and medical/health systems, among others. The accelerating need to share information and leverage capabilities from other systems has changed how systems need to be viewed and engineered.

Taxonomies provide a means in many fields to classify and describe the relationships among the relevant elements being studied. The elements of a taxonomy, or taxa, form a partitioning or means of classification within that body of knowledge. In the context of systems of systems (SoS), the relevant elements of the system of interest are, by definition, systems themselves. Using essential characteristics to partition the various types of SoS provides an abbreviated nomenclature for thinking about SoS. Based on taxonomies, different approaches to the engineering of systems of systems are possible, improving the efficiency and effectiveness of systems of systems engineering.

# Systems and software engineering — Taxonomy of systems of systems

## 1 Scope

This document defines a normalized taxonomy for systems of systems (SoS) to facilitate communications among stakeholders. It also briefly explains what a taxonomy is and how it applies to the SoS to aid in understanding and communication.

## 2 Normative references

There are no normative references in this document.

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

NOTE For additional terms and definitions in the field of systems and software engineering, see ISO/IEC/IEEE 24765, which is published periodically as a "snapshot" of the SEVOCAB (Systems and software Engineering Vocabulary) database and is publicly accessible at www.computer.org/sevocab.

ISO, IEC, and IEEE maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

— IEEE Standards Dictionary Online: available at http://dictionary.ieee.org

### 3.1 General terms

**3.1.1**
**constituent system**
**CS**
independent system that forms part of a *system of systems (SoS)* (3.1.4)

Note 1 to entry: Constituent systems can be part of one or more SoS. Each constituent system is a useful system by itself, having its own development, *management* (3.1.3), utilization, goals, and resources, but interacts within the SoS to provide the unique capability of the SoS.

[SOURCE: ISO/IEC/IEEE 21839:2019, 3.1.1, modified — The abbreviated term "CS" has been added.]

**3.1.2**
**governance**
process of establishing and enforcing strategic goals and objectives, organizational policies and performance parameters

Note 1 to entry: This definition is adapted from Reference [8].

**3.1.3**
**management**
system of controls and processes required to achieve the strategic objectives set by the organization's governing body

Note 1 to entry: Management is subject to the policy guidance and monitoring set through corporate *governance* (3.1.2).

[SOURCE: ISO/IEC/IEEE 24765:2017, 3.2338]

**3.1.4**
**system of systems**
**SoS**
set of systems or system elements that interact to provide a unique capability that none of the *constituent systems* (3.1.1) can accomplish on its own

Note 1 to entry: System elements can be necessary to facilitate interaction of the constituent systems in the system of systems.

[SOURCE: ISO/IEC/IEEE 21839:2019, 3.1.4]

**3.1.5**
**systems of systems engineering**
**SoSE**
process of planning, analyzing, organizing, developing and integrating the capabilities of a mix of existing and new systems, including inter-system infrastructure, facilities, and overarching processes into a system-of-systems capability that is greater than the sum of the capabilities of the *constituent systems* (3.1.1)

Note 1 to entry: This definition is adapted from Reference [9].

Note 2 to entry: SoSE also includes testing, modification, maintenance and other post-integration activities.

**3.1.6**
**taxonomy**
scheme that partitions a body of knowledge and defines the relationships among the pieces

[SOURCE: ISO/IEC/IEEE 24765:2017, 3.4167, modified — Definition 2 has been removed; Note 1 to entry has been removed.]

## 3.2 SoS types

**3.2.1**
**acknowledged system of systems**
**acknowledged SoS**
*SoS* (3.1.4) with recognized objectives, a designated manager, and resources for the SoS

Note 1 to entry: *Constituent systems* (3.1.1) retain their independent ownership, objectives, funding, and development and sustainment approaches. Changes in the systems are based on cooperative agreements between the SoS and the system.

Note 2 to entry: This definition is adapted from Reference [7].

**3.2.2**
**collaborative system of systems**
**collaborative SoS**
*SoS* (3.1.4) in which component systems interact more or less voluntarily to fulfill agreed-upon central purposes

Note 1 to entry: *Constituent systems* (3.1.1) collectively decide how to provide or deny service, thereby providing means of enforcing and maintaining consistency.

Note 2 to entry: This definition is adapted from Reference [7].

**3.2.3**
**directed system of systems**
**directed SoS**
*SoS* (3.1.4) created and managed to fulfill specific purposes and the *constituent systems* (3.1.1) are subordinated to the SoS

Note 1 to entry: Component systems maintain an ability to operate independently; however, their normal operational mode is subordinated to the central managed purpose.

Note 2 to entry: This definition is adapted from Reference [7].

**3.2.4**
**virtual system of systems**
**virtual SoS**
*SoS* (3.1.4) that lacks a central *management* (3.1.3) authority and a centrally-agreed-upon purpose for the SoS

Note 1 to entry: Large-scale behavior emerges—and can be desirable—but this type of SoS relies on relatively invisible mechanisms to maintain it.

Note 2 to entry: Virtual SoS are typically self-organizing.

Note 3 to entry: This definition is adapted from Reference [7].

# 4 Concepts and application

## 4.1 Overview

Taxonomies provide a means in many fields to classify and describe the relationships between the relevant elements being studied. The elements of a taxonomy, or taxa, form a partitioning or means of classification within that body of knowledge. Partitioning based on essential characteristics provides an abbreviated nomenclature to refer to a larger composite of characteristics, facilitating discussion about the partitions (taxa) without having to refer to each of the characteristics.

## 4.2 Importance of taxonomies to SoS

In systems engineering (SE), the relevant pieces of the system of interest can be called subsystems, elements or components. In the context of SoS, the relevant pieces of the system of interest are, by definition, systems themselves. These are called constituent systems (CS) throughout this document. That is, an SoS consists of some number of CS, plus any inter-system infrastructure, facilities and processes necessary to enable the CS to integrate or interoperate. Relationships between CS affect the SoS. Using essential characteristics to partition the various types of SoS provides an abbreviated nomenclature for thinking about SoS. While Clause 5 elaborates one mature SoS taxonomy, Annex A provides a list of SoS less-mature taxonomies. Based on taxonomies, different approaches to the engineering of systems of systems are possible, improving the efficiency and effectiveness of SoSE.

NOTE 1 Taxonomies can have some overlap in their definition and need not be orthogonal to each other to be useful. An SoS can be considered as belonging to several taxonomies as long as its characteristics meet the definitions of the taxonomies.

NOTE 2 It is possible that inter-system infrastructure, facilities and processes do not meet the criteria for being systems in their own right. From the perspective of the SoS, these could be system elements (or SoS elements).

## 4.3 Use of SoS taxonomies

There are many characteristics such as scale and scope, around which taxonomies can be derived. The SoS taxonomy in Clause 5 organizes the relevant aspects or essential characteristics of SoS, providing specific viewpoints that align with stakeholder concerns. This organization facilitates communications between the various stakeholders that are involved with activities like governance, engineering, operation and management of these SoS, and provides a reference for other related standards. The taxonomy in Clause 5 meets the following criteria.

— External references are publicly available.

— The taxa are stable with evidence of having been applied in multiple systems.

Annex A lists additional SoS taxonomies that do not meet all of the above criteria. These developing taxonomies can still be useful, but they lack sufficient maturity to be included in Clause 5. As the discipline matures, it is likely that more taxonomies will evolve.



# 5 Taxonomies for systems of systems

## 5.1 General

SoS taxonomies organize the relevant aspects or essential characteristics of SoS, providing specific viewpoints that align with stakeholder concerns. Taxonomies can have some overlap in their construction, but the lack of orthogonality does not inhibit their application.

Since most of the taxonomies are not explicitly named, they are most often referenced in practice by the author's names or the names of the taxa. Consequently, the taxonomies are presented using the taxa names themselves, using the author's order.

## 5.2 Taxa: directed, acknowledged, collaborative and virtual

### 5.2.1 Overview

In this taxonomy, SoS are classified according to the degree of managerial and operational independence. Four types are defined: directed, acknowledged, collaborative and virtual.

This taxonomy is mature, originating in the work of Maier (1998)[6], expanded by Dahmann and Baldwin (2008)[9] and published as an informative annex in ISO/IEC/IEEE 15288. Maier's observation was that SoS are not simply systems in which the constituents are also systems. One essential characteristic is that constituent systems within the SoS are operationally independent. Operational independence means that the CS are able to usefully operate independently, that is, fulfil customer purposes on their own. Consequently, SoS deal with multiple consumers that can have different priorities and expectations. Unlike a system, which has been designed to fulfill a purpose and an expected quality of service, the quality of service within an SoS can be subject to additional variation.

Another essential characteristic is that the CS within the SoS are managerially independent. The CS operate with each other to produce the SoS capabilities; however, managerial independence means that the CS also not only can but do operate independently from each other. This suggests that the CS are managed independently, and that these organizations can have different goals and objectives for the CS. If so, the degree of independence of governance can be more appropriate than the degree of independence of management. Regardless of the means of managing the organizations, alignment (or lack thereof) in the goals and objectives affect the system of systems.

### 5.2.2 Description of the taxa

#### 5.2.2.1 Directed

The strongest governance relations apply to directed SoS, where an SoS organization has authority over all of the CS even though the CS were not originally engineered to support the SoS. All aspects of the CS of the SoS fall under that authority from the point at which they become an element of the SoS. In a directed SoS, CS are very strongly aligned managerially and operationally.

#### 5.2.2.2 Acknowledged

Somewhat less control is afforded for acknowledged SoS, where allocated authority between the CS and the SoS has an impact on the application of some of the SE processes. For the acknowledged SoS, although the authority for the CS is distributed, there are agreements to work together under a designated management structure to have an SoS authority and manage the SoS. In an acknowledged SoS, CS are less strongly aligned managerially and operationally than in a directed SoS and can fulfill additional customer-operator purposes on their own.

#### 5.2.2.3 Collaborative

Collaborative SoS do not have centralized management. Instead, CS interact voluntarily to fulfil agreed-upon purposes, collectively deciding how to interoperate, as well as how to enforce and maintain standards. In a collaborative SoS, CS are less strongly aligned managerially and operationally than in an acknowledged or directed SoS and fulfill additional customer-operator purposes on their own. The degree of alignment affects the potential quality of service as CS have greater autonomy to prefer goals and objectives outside the SoS.

#### 5.2.2.4 Virtual

Virtual systems of systems lack a central management authority and lack a centrally-agreed-upon purpose. Managerial and operational alignment is the weakest in virtual SoS because CS are managerially and operationally very independent. Consequently, SoS behaviors and capabilities rely upon relatively invisible mechanisms rather than explicit governance to maintain them.

### 5.2.3 Examples of potential application of the taxa

The following list provides explanations of how the taxa apply to some examples.

— An intelligent transportation SoS links various information sources to provide enhanced capabilities. Examples include route planning applications that use data from vehicles to leverage real-time speed information to improve routing. Without a central management authority or a centrally-agreed-upon purpose, such systems could be considered virtual SoS.

— The Internet could be considered a collaborative SoS because this system consists of networks that are independently owned and managed but bounded by a common set of protocols, rules and address schemes maintained by a non-profit association. CS cooperate to develop standards and voluntarily comply with standards.

— A smart city can have a wide range of potential functionality and therefore could fall into any of the classifications. If a smart city has recognized objectives, a designated manager and its own resources, it could be considered an acknowledged SoS even while CS retain their independent ownership, management and resources.

— Integrated Air Defense could be considered a directed SoS because such systems are often developed and operated to a common purpose. That common purpose is expressed through formal organizations, technical standards and the socialization of its operators.

### 5.2.4 When to use

This taxonomy can be used effectively throughout the life cycle of an SoS. Since the characteristics of an SoS can evolve over the life cycle, the SoS's characterization or alignment to the taxa can evolve as well.

### 5.2.5 How to use

Consider the degree of operational or managerial independence along a spectrum in general terms from high to low. The characteristics in the taxa can be used to facilitate the classification of a candidate SoS. Based on the classification, explore options to improve the alignment of goals and objectives.

### 5.2.6 Why to use

This taxonomy can be effective when the degree of operational or managerial independence, or the alignment between the goals and objectives of the constituent systems, can be determined.

### 5.2.7 Limitations

The following are potential limitations with this taxonomy.

— This taxonomy mixes multiple, overlapping characteristics (e.g., authority, purpose, management, operations, ownership, resources) in the taxa, making a clean distinction of the underlying characteristics more difficult.

— The term “managerial independence” can obscure the implications of the goals and objectives more clearly evident in the term “governance.”

— One of the characteristics for a collaborative SoS notes that constituents “interact voluntarily to fulfill agreed-upon purposes”, which presumes a positive outcome. One extension to this taxonomy would be to accommodate that CS collaborate in ways that are not voluntary and without agreement on purpose. CS could be utilized in ways they are not aware of (involuntary) that result in collaborative activity. For example, the products or services of one CS could be directed or used by an independent third party to support the needs of another CS.

— In some organizations, particularly those in which the existing managerial approach tends to be directive, there can be an assumption that shifting the SoS to be more directed would be beneficial.

### 5.2.8 Benefits of use

Regardless of the classification, alignment of goals and objectives (or lack thereof) is an important aspect of an SoS and SoSE. Options that improve the alignment in goals and objectives can lead to improvements in the overall quality of service and resiliency of the SoS. However, the ability to influence goals and objectives across multiple organizations depends on the type of SoS. In this regard, SoS are very different from systems.

# Annex A
(informative)

# Summary of SoS taxonomies

Table A.1 summarizes SoS taxonomies.

**Table A.1 — Summary of SoS taxonomies**

| Year of Publication | Authors | Taxa |
|---|---|---|
| 1998 | Maier | Directed, Collaborative, Virtual |
| 2005 | Gideon, Dagli, and Miller | Dedicated, Virtual |
| 2005 | Gideon, Dagli, and Miller | Chaotic, Directed, Collaborative |
| 2005 | Gideon, Dagli, and Miller | Physical, Conceptual, Social |
| 2008 | Dahmann and Baldwin | Directed, Acknowledged, Collaborative, Virtual |
| 2014 | Somerville | Organizational, Federated, Coalition |

# Bibliography


[1] ISO/IEC/IEEE 15288, *Systems and software engineering — System life cycle processes*

[2] ISO/IEC/IEEE 21839:2019, *Systems and software engineering — System of Systems (SoS) considerations in life cycle stages of a system*

[3] ISO/IEC/IEEE 24765:2017, *Systems and software engineering — Vocabulary*

[4] Gideon J, Dagli C.H. , Miller A. 2005. *Taxonomy of Systems-of-Systems*

[5] Somerville I., 2015. “Systems of Systems” included in Chapter 20 of "Software Engineering”, 10th Edition. Available at: https://www.dropbox.com/s/xo80lb1rvwtzd1e/Ch%2020%20Systems%20of%20systems.pdf

[6] Maier M.W.1998. , Architecting Principles for Systems-of-Systems. *Syst. Eng*. pp. 267–284

[7] SEBoK Authors. "Systems of Systems (SoS)." in BKCASE Editorial Board. 2017. *The Guide to the Systems Engineering Body of Knowledge (SEBoK)*, v. 1.8. R.D. Adcock (EIC). Hoboken, NJ: The Trustees of the Stevens Institute of Technology. Accessed August 8, 2017. Available at: https://www.sebokwiki.org/

[8] Software Extension to the PMBOK(R) Guide Fifth Edition

[9] DAHMANN J., BALDWIN K., 2008. US DoD Systems Engineering Guide for Systems of Systems. Available at: https://www.acq.osd.mil/se/docs/SE-Guide-for-SoS.pdf