Systems thinking ontology of emergent properties for complex engineering systems

M Y Nikolaev* and C Fortin
Skoltech Space Center, Skolkovo Institute of Science and Technology, Bolshoy Boulevard 30, bld. 1, Moscow, 121205, Russian Federation

mikhail.nikolaev@skoltech.ru

Abstract. This paper presents a developed ontology of emergent properties characterizing the emergent behavior of complex engineering systems, which is the emergence of greater functionality of the overall system compared to the sum of the functionalities of system components. The ontology is based on the systems thinking approach used in systems architecture, one of the key points to consider in the conceptual design of engineering systems and used to manage the complexity of systems. Firstly, in the paper, research attributes and the adaptation of the term “ontology” for systems thinking are given. Secondly, the coverage of analyzed literature sources in the description of the literature search is demonstrated. Thirdly, the developed ontology consisting of semantics and relationships of systems emergent properties is presented. The proposed ontology is followed by highlighting its possible systems engineering applications. Finally, in conclusion, the benefits of the developed ontology are mentioned. Overall, the current paper combines aspects of systems engineering with key elements of the design of complex systems.

Keywords: complex systems, engineering systems, emergence, ontology, systems thinking

1. Introduction

Systems are diverse, and different classifications of systems exist [1]. Among all classifications, the following two classifications are crucial for understanding the purpose of systems engineering: systems can be simple and complex [2], and engineering, natural, human, etc. [1] An interdisciplinary approach and means to enable the realization of successful systems, systems engineering deals with the design of complex engineering systems [3, 4]. However, for simplification, the adjective “engineering” is usually omitted. Starting now, in the paper, the term “complex systems” will be used instead of “complex engineering systems” for the same reason.

Complex systems exhibit emergent behavior, which is the emergence of greater functionality of the overall system compared to the sum of the functionalities of system elements, or entities [2]. Being a central feature of a system concept and meaning “the whole is more than the sum of its parts” [5], emergence is the goal of systems thinking, which is an approach within systems architecture, applied to manage the complexity of systems. A systems architecture is a high-level description of the system elements and the relationships between them. It relates to systems engineering, finds its implementation in the conceptual design of complex systems, and is crucial for building successful systems. Thus, understanding systems emergence via systems thinking is a critical point of consideration, at least for the conceptual design of complex systems [2].

This paper presents a developed systems thinking-based ontology of systems emergent properties aiming to enhance understanding of emergence for complex systems. Firstly, in the paper, research relevance, research methodology, and the adaptation of the term “ontology” for systems thinking are given. Secondly, the range of literature sources identified for analysis during the literature search is demonstrated. Thirdly, the developed ontology consisting of semantics and relationships of systems emergent properties is presented, which is followed by highlighting its possible systems engineering
applications. Finally, in conclusion, the benefits of the developed ontology are mentioned. Overall, the current paper combines aspects of systems engineering with key elements of the design of complex systems. For simplification, in the paper, terms “emergence/emergent properties” instead of “systems emergence/emergent properties” are used assuming the same meaning.

2. Research relevance and methodology
Notions of emergence and complex systems are closely linked. Crawley et al. clarify that system success happens if its expected properties emerge, and system failure takes place in case if expected properties fail to emerge, or the emergence of unexpected, undesirable properties appears [2]. Therefore, the knowledge and understanding of emergence are critical for building successful systems. However, firstly, the term “emergence” initially comes from philosophy, and for its practical application, it requires concise clarification in the context of systems engineering [6]. Secondly, emergent properties constitute the emergence of systems, and it is crucial to obtain the knowledge of their ontology consisting of semantics and relationships. Thirdly, it is systems thinking within systems architecture that deals with the emergence and emergent properties of complex systems, and therefore it is essential to keep the developed ontology within systems thinking [2]. Finally, no previously developed ontology of emergent properties focused on systems thinking was found in the literature sources. Thus, the development of systems thinking ontology of emergent properties for complex systems is a relevant topic nowadays and requires further profound analysis.

This research paper aims to achieve the following goals:
• to adapt the term “ontology” for systems thinking;
• to perform an extensive literature search and identify appropriate publications;
• to analyze chosen publications and develop systems thinking ontology of emergent properties;
• to highlight possible systems engineering applications of the developed ontology.

The formulation of a research question is as follows: “How can semantics and relationships of emergent properties be organized to define a system’s thinking ontology?” This paper’s research, according to general design research methodology, consists of research clarification, primary descriptive, and prescriptive studies [7]. Research clarification is made up of the adaptation of the term “ontology” for systems thinking and literature search. Analysis of the literature sources, identification of semantics, and relationships refer to the primary descriptive study. Uniting semantics and relationships and highlighting its possible systems engineering applications constitute the prescriptive study. Overall, the presented paper’s research is based on a literature survey and results in creating an ontology.

3. Adaptation of the term “ontology” for systems thinking
The term “ontology” occurred for the first time in the work Ogdoas scholastica (1606) by the Calvinist Jakob Lorhard and found its final endorsement in Philosophia prima sive ontologia (1730) by Christian Wolff. The term comes from philosophical works, where it had the general meaning of metaphysics, or the science of being. Initially, the term “ontology” was used to describe several metaphysical models, but later its use was narrowed to the description of a single model [8]. During the 20th century, the idea of ontology was adopted by scientists from natural, technical, and other scientific domains, including systems engineering and design.

In systems engineering, an ontology is described as the combination of concepts, relationships, and rules that govern how these concepts are linked to each other [9]. In design, specific “design ontologies” are developed, and they are defined as sets of hierarchically structured terms aimed to serve as foundations for knowledge bases [10]. Both cases are similar, and include the following [9]:
• semantics: identification of objects and entities in the domain;
• relationships: use of objects and entities inside and outside the boundary of the domain, rules that govern the existence of entities and behavior.
Unifying terms “semantics” and “relationships” were added to the list above by the authors of this paper in order to add versatility to the explanation of the components that systems engineering and design ontologies include. As ontology is a model of reality, and the concepts of the ontology tend to reflect this reality, there is no one single correct way to do that [10]. Added versatility allows to increase the degree of freedom in the development of systems engineering and design ontologies.

Systems thinking is both a matter of systems architecture and the conceptual design of complex systems. Hence, the systems thinking ontology of emergent properties belongs both to systems engineering and design ontologies. The term “systems thinking” was used to emphasize the concrete relevance of the developed ontology to the particular systems architecture approach, on which it is based. It is useful to remember that an ontology is still a documentation of the terminology used to describe objects, properties, and associations in a particular domain [10]. And the developed systems thinking ontology of emergent properties also tends to be the same type of documentation. As ontology is a model of reality, the developed ontology can be called “an ontological model.”

4. Literature search
Over 45 publications out of more than 1200 considered books and papers were selected for further analysis. The dynamics of their publishing by the years is demonstrated in figure 1.

![Figure 1](image_url)

**Figure 1.** The dynamics of publishing on the emergence and emergent properties in systems engineering, systems architecture, and design.

The scope of the literature search included Scopus and Web of Science abstract/citation databases, Design Society, IEEE, and OnePetro articles and conference papers. The authors also conducted an additional search to identify appropriate books using the Google Scholar database. The search area was narrowed by using the keywords. Having tried several options, combinations of “system” and “emergent properties” or “emergence” were finally chosen as the most appropriate variants. Although emergence and emergent properties were sporadically mentioned in the literature sources before 1990, the authors decided to start analysis using the sources since 1990, as it was a meaningful year for contemporary systems engineering. In 1990 International Council on Systems Engineering was founded [11]. As illustrated in figure 1, the interest of researchers in the subject of systems emergence and emergent properties grew, starting with one publication per each 5-year period in the 1990s, increasing in the 2000s, and reaching its peak in 2005-2009, then maintaining a high level of interest with some deviations in the number of publications for analyzed 5-year periods in the 2010s. No appropriate publications for analysis were currently identified in 2020. However, the subject of emergence and emergent properties
remain to be popular in different disciplines. Systems thinking ontology of emergent properties is based on the analysis of publications identified during the described literature search.

5. The development of systems thinking ontology of emergent properties
Emergent properties are the object of the developed ontology. To develop the systems thinking ontology of emergent properties, initially, the semantics of emergent properties and associated terms were defined. Then the authors decomposed the object on entities using existing classifications of emergent properties. By analyzing the classifications, the semantics of entities and relationships were described. Additionally, the schematic representation of the developed ontology was proposed.

5.1. The semantics of emergent properties and associated terms
Emergent properties are the properties of a complex system that characterize its emergence. In other words, these are discovered behaviors of a system that emerge spontaneously [12]. Emergent properties reveal themselves when the entities of a system are put together [2]. Therefore, they are systemic as only a system possesses them but not its separate parts [13]. These properties can also be considered as “unforeseen consequences” of a system [14]. Emergent properties play a key role in complex systems analysis. Hitchins in 1992 even put the concept of emergent properties as the primary task of systems engineering [15]. The term “emergent properties” is associated with the relative terms “emergence,” “emergent behavior,” and “synergy.”

The term “emergent properties” is very close to the term “emergence.” Emergence means “the whole is more than the sum of its parts” and is the goal of systems thinking [2, 5]. It is the central feature of any complex system. One of the earliest sources to mention the term “emergence” is Hume’s Dialogues Concerning Natural Religion in 1779 [13]. In the 20th century, this term appeared in the works related to the engineering disciplines. Both emergence and emergent properties found their application in the description of complex systems. Systems engineering and design researchers frequently equate these two terms. For instance, Kopetz et al. directly give the definition of emergence built upon the definition of an emergent property [16]. It can be concluded that emergence and emergent properties are fungible terms, and can be equated. Equating singular “emergence” with plural “emergent properties” proves that emergent properties constitute the emergence.

Another close term is “emergent behavior.” Generally, emergent behavior assumes a behavior of the system that cannot be understood only considering the behavior of the separate system entities [3]. However, there is no single definition existing for this term. Pomorova and Hovorushenko identified 14 different sources giving the definitions to both emergent behavior and emergent properties in systems engineering. By analyzing their list, it can be concluded that emergent properties are the attributes of a complex system that result from its emergent behavior and characterize it.

The last relative term, “synergy,” is defined as properties or behaviors that exist only because distinct elements can interact [12]. It is the type of emergence related to enhancing existing functions of systems entities instead of being oriented on the appearance of new functions [17]. However, it is still part of emergence. Therefore, the term “synergy” can also be equated with the term “emergent properties,” but only for cases of enhancing existing systems functions.

The decomposition of the object of ontology on entities, together with the description of relationships, is given in the subsection below.

5.2. The semantics of entities and relationships through classifications
The semantics of entities and relationships were analyzed by using existing classifications of emergent properties and emergence (as these terms can be equated). The classifications found in the analyzed literature sources are united in table 1. They serve as the decomposition of the analyzed object (emergent properties and emergence) on its entities (types). Following table 1, the semantics of entities and the rules that govern their existence and behavior, or relationships, is given. The presented list of emergent properties/emergence types is basic and essential. However, it provides an opportunity for further
extension, as new types of emergence or emergent properties are regularly established by researchers from different fields in application to the design of new systems.

Table 1. Classifications of emergence/emergent properties.

| #  | Classification          | Types                                          | Citations |
|----|------------------------|------------------------------------------------|-----------|
| 1  | Strength-based         | Weak, strong                                   | [6, 16]   |
|    |                        | Weak, strong, dynamic                          | [18]      |
|    |                        | Weak, synchronic, diachronic                   | [13]      |
|    |                        | Simple, weak, strong, spooky                   | [19]      |
| 2  | Complexity-based       | Simple, complex                                | [20]      |
| 3  | Anticipation-based     | Expected (desirable/undesirable),              | [2, 21]   |
|    |                        | unexpected (desirable/undesirable)             |           |
| 4  | Impact-based           | Positive, negative                             | [22]      |
| 5  | Systems thinking-based | Immediate value: function, performance         | [2]       |
|    |                        | Life-cycle value: ilities                      | [2, 23]   |
|    |                        | Undesirable: emergency                         | [2]       |
|    |                        | Safety                                          | [2, 24, 25]|
| 6  | Strategy-based         | Elegance                                       | [2, 26]   |
|    |                        | Knowledge                                       | [27, 28]  |
| 7  | Various                | Program accountability, road congestion,       | [29, 30]  |
|    |                        | fault and adversary tolerance, salience, etc.  |           |

The strength-based classification of emergence and emergent properties primarily deals with the differentiation between weak and strong emergence. Weak emergence is the one determined from the relationship of a system and its parts. Strong emergence results from the consideration of the set of possible states the system can be in or from a relationship between the system and aspects of the environment [18]. Other types of emergence within the strength-based classification are close to the division between weak and strong emergence. The level of emergence occurrence governs this classification: inside the system (weak), states of the system, or the relationships between the system and environmental aspects (strong). It finds its broad application in the description of physical systems but is very consolidated and, therefore, cannot provide detailed separation of the types of emergent properties. Very close to the strength-based classification is the complexity-based one, as the levels of emergence occurrence also govern it, and it is also very consolidated.

Anticipation-based and impact-based classifications of emergence and emergent properties are similar in rules governing their divisions. Each of these types of classification is governed by the usefulness of emergence/emergent properties. The division on positive and negative emergence is very consolidated. However, the division on expected/unexpected and desirable/undesirable emergent properties is more detailed and seems to be sufficient to consider in the development of systems thinking ontology.

Systems thinking-based and strategy-based classifications of emergence and emergent properties seem to be the most promising for the practical use in characterizing emergent behavior of complex systems. The consideration of the value of systems governs these classifications. Emergent properties, according to them, include the following types based on bringing the particular type of value [2, 27, 33]:

- immediate value: function (what a system does) and performance (how well a system executes its function or functions);
- life-cycle value: ilities (operability, maintainability, usability, durability, safety, etc.), cost;
- undesirable value: emergency (unexpected and undesirable emergence);
- strategic level values (educational, economic, overall, etc.): knowledge, benefit, elegance.
The anticipation-based classification of emergent properties can be incorporated in these classifications by the distribution of expected and desirable emergent properties among function, performance, and ilities, and the distribution of undesirable and unexpected emergent properties within the emergency. To be more precise, the emergency can be differentiated on low (unexpected, undesirable emergence) and high (severe emergence). A combination of anticipated-based, systems thinking-based, and strategy-based classifications result in the systems thinking ontology of emergent properties. The schematic representation of the developed ontology is given below. “Various” type of classification is not touched as it unites unique cases of specific types of emergent properties identified by various researchers in a broad range of engineering fields.

5.3. Schematic representation of systems thinking ontology of emergent properties and its applications

The schematic representation of the developed systems thinking ontology of emergent properties for complex systems is given in figure 2. It can also be called a schematic ontological model.

![Figure 2. Schematic representation of systems thinking ontology for complex systems.](image)

The schematic representation of the developed ontology uses types of values and is based on uniting systems thinking-based and strategy-based classifications of emergent properties, incorporation of anticipation-based classification. Knowledge, benefit, and elegance refer to the upper, strategic level of values. Function, performance, ilities, cost, and emergence refer to the lower, engineering level. They bring immediate (function, performance), life-cycle (ilities, cost), and unanticipated (emergency) values. It is the general case, but depending on a particular use case, value decomposition can be performed differently. However, the specific type of emergent property can refer to multiple value types. The schematic representation of systems thinking ontology is a useful tool that allows the characterization of emergent properties and the vivid demonstration of their semantics and relationships.

The developed ontology can find different systems engineering applications listed in table 2 below.

| #   | Application          | Application domain                                  | Close source               |
|-----|---------------------|-----------------------------------------------------|----------------------------|
| 1   | Systems architecting| Assistance in converting function to form            | [2]                        |
| 2   | Managing complexity | Use as a decomposition tool in systems analysis      | [2]                        |
| 3   | Risk assessment     | Assistance in predicting unanticipated emergence     | [21]                       |
| 4   | Verification        | Assistance in conducting verification of systems     | [34]                       |
| 5   | Decision making     | Managing the complexity of value for decisions via the use of emergent properties | Ph.D. research by Mikhail Nikolaev |
The list of possible systems engineering applications given in table 2 is not full and can be expanded during future research. However, these all can be united as “characterizing emergent behavior.”

6. Conclusion
The current paper presented the development of systems thinking ontology of emergent properties for complex engineering systems. It included a specific adaptation of the term “ontology” for systems thinking, description of the conducted literature search, development of systems thinking ontology itself, and highlighting its possible systems engineering applications. The paper answered its research question by the analysis of semantics and relationships and unifying them into the systems thinking ontology. The main benefit of the developed ontology consists of that it could be represented in a schematic way, which is comfortable to use for listed systems engineering applications: managing complexity, systems architecting, risk assessment, etc. Other benefits include possibilities to decompose systems emergence, translate customer’s needs to emergent properties, and find additional applications of the developed ontology towards other systems engineering tasks.

The developed systems thinking ontology of emergent properties for complex engineering systems is a promising tool that allows consideration of systems emergent behavior. For future research, the developed ontology will be used to create a new type of design decision-making model to be applied to making architectural decisions in the conceptual design of complex engineering systems.

7. References
[1] Magee C L and de Weck O L 2004 Complex system classification Proc. INCOSE 14th Annual Int. Symp. (Toulouse) vol 14 (Wiley Online Library) pp 471–488
[2] Crawley E, Cameron B and Selva D 2016 System Architecture: Strategy and Product Development for Complex Systems (Harlow: Pearson Education Limited)
[3] INCOSE 2015 Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities (Hoboken: John Wiley & Sons)
[4] Kossiakoff A, Seymour S J, Flanagan D A and Biemer S M 2020 Systems Engineering Principles and Practice (Hoboken: John Wiley & Sons) p 3
[5] Aslaksen E W 2013 The System Concept and Its Application to Engineering (Berlin: Springer-Verlag) p 29
[6] Johnson C W 2006 What are emergent properties and how do they affect the engineering of complex systems? Reliability Engineering and System Safety 91 1475–1481
[7] Blessing L T M and Charkabarti A 2009 DRM: A Design Research Methodology (London: Springer-Verlag) p 18
[8] Devaux M and Lamanna M 2009 The rise and early history of the term ontology (1606-1730) Quaestio 9 173–208
[9] Sarder M B and Ferreira S 2007 Developing systems engineering ontologies Proc. IEEE Int. Conf. on Systems Engineering (San Antonio) (IEEE)
[10] Sarder M B 2006 The Development of a Design Ontology for Products and Processes (PhD Thesis) (Arlington: The University of Texas at Arlington) pp 57–61
[11] Honour E C 1998 INCOSE: History of the International Council on Systems Engineering Systems Engineering 1 4–13
[12] de Weck O L, Roos D and Magee C L 2011 Engineering Systems (Cambridge: The MIT Press) p 190
[13] Damper R I 2000 Emergence and levels of abstraction International Journal of Systems Science 31 811–818
[14] Georgiou I 2003 The idea of emergent property Journal of the Operational Research Society 54 239–247
[15] Boarder J C and Laming J 1995 A system engineering framework and its evaluation Proc. 4th Int. Conf. of the United Kingdom Systems Society (Hull) (New York: Springer Science) pp 221–226

7
[16] Kopetz H, Höftberger O, Frömel B, Brancati F and Bondavalli A 2015 Towards an understanding of emergence of systems-of-systems (IEEE)

[17] Cruz I L I 2017 A Framework for Architecting Federation of Systems (PhD Thesis) (Moscow: Skolkovo Institute of Science and Technology) p 38

[18] Bar-Yam Y 2004 A mathematical theory of strong emergence using multiscale variety Complexity 9 15-24

[19] Tolk A, Koehler M T K and Norman M D 2018 Epistemological constraints when evaluating ontological emergence with computational complex adaptive systems Proc. 9th Int. Conf. on Complex Systems (Cambridge) (Cham: Springer Nature Switzerland AG) pp 1–10

[20] Halley J D and Winkler D A 2008 Classification of emergence and its relation to self-organization Complexity 13 10–15

[21] Ferreira S, Faezipour M and Corley H W 2013 Defining and addressing the risk of undesirable emergent properties Proc. IEEE Int. Systems Conf. (Orlando) (IEEE)

[22] Giammarco K 2017 Practical modeling concepts for engineering emergence in systems of systems Proc. 12th System of Systems Engineering Conf. (Waikoloa) (IEEE)

[23] Sullivan B P, Rossi M and Terzia S. 2018 A review of changeability in complex engineering systems IFAC-PapersOnLine 51 1567–1572

[24] Yang Q, Tian J and Zhao T 2016 Safety is an emergent property: Illustrating functional resonance in air traffic management with formal verification Safety Science 93 162–177

[25] Mitropoulos P and Cupido G 2009 Safety as an emergent property: Investigation into the work practices of high-reliability framing crews Journal of Construction Engineering and Management 135 407–415

[26] Salado A and Nilchiani R 2013 Using Maslow's hierarchy of needs to define elegance in system architecture Procedia Computer Science 16 927–936

[27] Alaba O 2010 Knowledge capital: An emergent property of a complex system Proc. Int. Conf. on Management of Emergent Digital EcoSystems (Bangkok) (New York: Association for Computing Machinery)

[28] Biggiero L 2007 Organizations as cognitive systems. Is knowledge an emergent property of information networks? Proc. 4th National Conf. of the Italian Systems Society (Castel Ivano) (Singapore: World Scientific Publishing) pp 697–712

[29] O’Connell L 2005 Program accountability as an emergent property Public Administration Review 65 85–93

[30] Manley E and Cheng T 2010 Understanding road congestion as an emergent property of traffic networks Proc. 14th World Multi-Conference on Systemics, Cybernetics and Informatics (Orlando) (Winter Garden: International Institute of Informatics and Systemics)

[31] Brun Y and Medvidovic N 2007 Fault and adversary tolerance as an emergent property of distributed systems’ software architectures Proc. 2007 Workshop on Engineering Fault Tolerant Systems (Dubrovnik) (Design Society)

[32] Alberti F, Sugden R and Tsutsui K 2011 Salience as an emergent property Journal of Economic Behavior & Organization 82 379–394

[33] Petetin F 2012 Decision-Making in Disruptive Technological Innovation Projects: A Value Approach Based on Technical and Strategic Aspects (PhD Thesis) (Paris: Ecole Centrale Paris) pp 107–109

[34] Rouff C, Truszkowski W and Hinchey M 2004 Verification of NASA emergent systems Proc. 9th IEEE Int. Conf. on Engineering Complex Computer Systems Navigating Complexity in the e-Engineering Age (Florence) (IEEE)

Acknowledgments

Mikhail Nikolaev acknowledges the Skolkovo Institute of Science and Technology (Skoltech) for providing the Ph.D. scholarship. The authors thank Dr. Pavel Dorozhkin (Skoltech, Russian Railways) and Dr. Andrey Kazak (Skoltech) for fruitful discussions on the subject of emergence in complex
systems. Also, we want to express our gratitude to Dr. Alessandro Golkar (Skoltech) and Dr. Dimitry Pissarenko (Skoltech, Total S.A.) for their constructive comments on the earlier version of the model.

**Authors’ background**

| Name               | Prefix                  | Research Field          | Email                               |
|--------------------|-------------------------|-------------------------|-------------------------------------|
| Mikhail Y. Nikolaev | PhD Student             | Systems Engineering     | Mikhail.Nikolaev@skoltech.ru        |
| Clement Fortin     | Professor of the Practice | Systems Engineering     | c.fortin@skoltech.ru                |