This is an electronic reprint of the original article. This reprint may differ from the original in pagination and typographic detail.

A review of the foundations of systems, infrastructure and governance

Große, Christine

Published in:
Safety Science

DOI:
10.1016/j.ssci.2023.106060

Published: 01/04/2023

Document Version
Final published version

Document License
CC BY-NC-ND

Link to publication

Please cite the original version:
Große, C. (2023). A review of the foundations of systems, infrastructure and governance. *Safety Science*, *160*, Article 106060. https://doi.org/10.1016/j.ssci.2023.106060

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

This document is downloaded from the Research Information Portal of ÅAU: 30. Apr. 2024

Safety Science 160 (2023) 106060

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

A review of the foundations of systems, infrastructure and governance

Christine Große *

Risk & Crisis Research Centre, Department of Communication, Quality Management and Information Systems, Mid Sweden University, 851 70 Sundsvall, Sweden
Faculty of Social Sciences, Business and Economics, Åbo Akademi University, 20100 Turku, Finland

A R T I C L E I N F O

Keywords:
System
Critical Infrastructure
Governance
Societal Safety
Complex System Governance
Multi-level Planning

A B S T R A C T

The reliability of infrastructure that is critical to society's functionality, survival and progression has gained significance for both national security and research because of its large-scale and interdependent nature. However, the theoretical basis of the relatively new research field of critical infrastructure is incomplete and the common parlance about the underlying concepts is ambiguous. This article addresses this issue and presents the results of a substantial review of scientific literature on the concepts of systems, infrastructure and governance. The results demonstrate that the concepts encounter a common challenge in characterising their key elements, structures and processes because of their recursive nature. The multi-level character of critical infrastructure systems provokes governance to systemically address the properties of adaption, emergence and entropy which the complex system-of-systems exhibits. This article contributes with both a conceptual study of the terms system, infrastructure and governance and a detailed review of the state of the art regarding these concepts in the current scientific literature to an enhanced understanding of the theoretical foundations of the associated fields. Subsequent research could interrelate other concepts, such as vulnerability, resilience, sustainability and feedback with the provided state of the art.

1. Introduction

Infrastructure that is critical to society's functionality, survival and progression (Cohen, 2010) has been characterised as a complex 'socio-technical system-of-systems' (Gheorghe et al., 2006), implying that a system perspective is crucial to understand, develop and maintain safe and reliable infrastructure. Common criteria for classifying a system as 'complex' include interconnectedness and interdependency of system components, autonomous and adaptive behaviour of components, non-linearity of consequences and the extent of the system (Holland, 2006; Hokstad et al., 2012). Moreover, this non-linearity of cause and effect due to interconnected subsystems can evoke an emergent system behaviour, which the properties of the subsystems cannot completely explain (Bar-Yam and Kiel, 2009). Finally, the steering of any system needs to address entropy in order to maintain the system's intended function. Research on complex systems therefore also concerns governing dynamics and multidimensional problems, which invoke complex system governance to produce system viability through control, communication, co-ordination and integration (Katina et al., 2017; Keating, 2014; Keating and Bradley, 2015; Keating et al., 2014; Keating et al., 2015). The main focus is however on technical and physical systems, which excludes the socio-technical, social and political issues in the multi-level construct of the governed and governing system, its processes and the related infrastructure.

However, critical infrastructure protection (CIP) can be viewed as a common, societal concern that is located in the field of governance between governmental control and competitive market dynamics as well as the private sphere of citizens (Offe et al., 2008). According to Ashby, the governing system is similarly complex as the governed system (Ashby, 1956); which implies that the governance of CIP could be considered a similarly complex system as that of the whole society's infrastructure. Thus, this paper argues that a system perspective would be a valuable theoretical focus to understand and develop not only societies' critical infrastructure but also the steering approach necessary to ensure its safe and reliable function. Previous research has both recognised an immaturity of the research field of critical infrastructure (Seager et al., 2017; Katina and Keating, 2015) and suggested a holistic view of the system-of-systems (SoS) of critical infrastructure. Since the theoretical basis of the relatively new research field of critical infrastructure is incomplete and the common parlance about the underlying

* Address: Risk & Crisis Research Centre, Department of Communication, Quality Management and Information Systems, Mid Sweden University, 851 70 Sundsvall, Sweden.
E-mail address: christine.grosse@miun.se.

https://doi.org/10.1016/j.ssci.2023.106060
Received 11 October 2021; Received in revised form 27 June 2022; Accepted 2 January 2023
Available online 12 January 2023
0925-7535/© 2023 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

concepts is ambiguous, improvements of the conceptual base are necessary. Contributions could advance the interdisciplinary research field and facilitate communication at the intersection of infrastructure engineering and public administration in order to harmonise the perceptions of the various decision-makers who are entrusted with planning, policy-making and realisation in the context of CIP (Pescaroli and Alexander, 2016) both within a national system and across country borders (Masera et al., 2006).

This paper aims therefore to clarify the state of the art of the critical infrastructure field with regard to the multi-faceted concepts of systems, infrastructure and governance. The goal of this study is to provide a comprehensive overview about relevant theoretical foundations and properties of systems, infrastructure and governance and their applications in current research in the CIP field. To this end, this study reviews current scientific articles and papers on CIP and focuses on how recent literature communicates and applies the mentioned concepts. In addition, the investigation analyses contrary understandings or problems related to certain system properties, such as adaption, emergence and entropy, which can be of particular interest for research and practice. This article contributes with both a solid theoretical foundation with respect to the terms system, infrastructure and governance and an understanding of the state of the art regarding these concepts in the current scientific literature to propel the theoretical progression of the CIP field. Therefore, this study's findings are of interest to related fields concerned with system analysis, resilience engineering, governance, societal safety and security.

Following the outline of the basic terms and properties of systems, infrastructure and governance, the method section details the collection and analysis of recent scientific literature. The result section conveys the essence of the literature review and presents the findings regarding inherent and articulated meanings, common elements and properties. After a brief discussion of remaining gaps and implications for future research, the conclusion section completes the article.

2. Theoretical background

2.1. A brief review of system theories and key properties of systems

The lowest common denominator consists of three key elements that form a 'system': some *components* that have a kind of *interaction* and are surrounded by a certain *environment*. Although this general understanding is present in earlier history, von Bertalanffy (von Bertalanffy, 1950; von Bertalanffy, 1968) first formulated the General System Theory and discussed these elements in contrasting biological and physical phenomena. These key elements of any system have specific properties, which can be used to characterise a system type. For example, the type of exchange that a system maintains with its environment defines whether the system is considered open or closed.

Science have been concerned with closed systems to examine transformation of energy or chemical elements, wherein 'closed' conveys that no element (or only energy) can enter or leave the system, and no material exchange occurs (von Bertalanffy, 1950). In this regard, Clausius' research that resulted in the concept of entropy (Clausius, 1850; Clausius, 1850; Clausius, 1865) is of particular interest. He has stated that '[t]he entropy of the world is striving towards a maximum' [*Die Entropie der Welt strebt einem Maximum zu* (Clausius, 1865), which explains the tendency towards decay or maximal disaggregation [Disgregation (ibid)) that is observable in natural and man-made systems. In short, it implies that entropy is increasing due to irreversible processes, such as friction, a pressure increase or mixing in a closed system. To lower entropy and obtain a form of restitution of the previous state, a compensation must occur, that is, exergi must enter and anergy must leave the system. In other words, a steering mechanism must address this property to ensure the system's ability to function as intended, which appears highly relevant in the CIP context. Since then, several researchers have investigated the relationship between processes within a system and an external entity that possesses the ultimate knowledge of the system [e.g. Maxwell, 1871; The Sorting Demon of Maxwell, 1879], which facilitates system control and steering. Shannon (Shannon, 1948) has coined the adoption of entropy by information theory, wherein entropy is considered a measure of uncertainty to address the lack of knowledge in a system. Ultimately, the definition of system borders can clarify the intersection between the system and its steering entity.

To address entropy, systems can be considered open to interact across and beyond system boundaries with other systems or with a larger, surrounding environment (von Bertalanffy, 1950; von Bertalanffy, 1968). The open system concept has also been viewed as appropriate for surmounting the limiting perspectives of closed technical systems and approaching enterprises as open socio-technical systems (Emery and Trist, 1960). According to Mumford (Mumford, 2006), the technical part covers 'technology and its associated work structure', and the social part encompasses 'grouping of individuals into teams, coordination, control and boundary management' as well as 'the delegation of responsibility to the work group and a reliance on its judgement for many operational decisions'. In addition, 'the social and the technical should, whenever possible, be given equal weight'(Mumford, 2006).

Interactions are viewed as a key element of systems, particularly in sociological systems theory. Scholars have approached interactions between individuals within small groups, for example in communication processes (Neidhardt, 2017; Bräuer, 2005; Kelley et al., 2003; Kelley and Thibaut, 1978). The focus is on, among others factors, the understanding and acceptance of messages and the concept of mutual dependence and interference of the interaction partners (Bräuer, 2005; Bierhoff and Frey, 2017; Becker-Beck, 1997). In addition, Luhman has explicated an understanding of a social system that completely abstracts from humans in an all-comprehending media system (Luhmann, 1984). His perspective has been criticised for several reasons; for example, it projects a radical renunciation of social aspects in societies, and it obscures the human capacity for deliberating and pursuing rational interests (Habermas, 1981). However, this view of a social system starkly differs from the understanding within that of a socio-technical system.

Moreover, complex and adaptive systems feature components that interact in parallel, base actions on conditional reasoning, build subroutines and use adaption to improve performance. The components (agents) reside and act within a space, wherein they interact and influence each other. Therefore, the system emerges as a set of agents and their interactions that fit together optimally in a joint environment, which is called a fitness landscape [see e.g. Onik et al., 2016]. This emergent system interacts competitively with other complex adaptive systems, called landscapes, which, however, makes it difficult to clearly distinguish between the internal and external environment of the system (s) and each agent. The interactions with other systems yield information that, consistent with the previous statements, can be interpreted as an exchange that reduces a system's entropy and allows for further progress. Consequently, the complex adaptive system reorganises its network structure among the constituting and available agents to improve its key process. This adaptive reorganisation initiates further changes in both the agents' cognitive model and the number of interactions in the fitness landscape by adapting to the returning information through the layers of the system (Ellis and Herbert, 2011). These adaptions at several levels induce further interferences back and forth through the system(s) and environment(s). The consequence is a set of effects that are spontaneous, uncertain and highly difficult to predict; such effects are collectively referred to as 'emergence'.

To develop an understanding of systems that comprise systems, Ackoff (Ackoff, 1971) has compiled some key concepts, which stresses the subjectivity of a particular system configuration. In particular, he has differentiated between organisations and organisms as concepts for approaching an SoS with the aid of the label 'purposeful', which signifies the ability of a system to choose both goals and means. In this sense, an organisation is an SoS which consists of at least two systems that 'have and can exercise their own wills' for a common purpose, wherein 'at least one subsystem has a system-control function' (Ackoff, 1971). This definition implies that an organisation can be comprised of two persons (i.e. organisms) or of several organisations. Furthermore, by claiming that 'in an organism only the whole can display will, none of the parts can', Ackoff (Ackoff, 1971) has rejected the treatment of organisations as organisms in both research and practice. Nevertheless, such anthropomorphic perception of systems is evident in complex adaptive systems, wherein agents use reasoning to organise themselves in systems. The rule-based reasoning of these agents is realised by algorithms, which can, to some extent, be called artificial intelligence. Still, the extent to which a technical system in combination with a reasoning artificial 'demon' can be viewed as an 'organism' remains uncertain. One application of such organism/organisation perspective can be found in Beer's Viable System Model [see e.g. Beer, 1995; Espejo and Harnden, 1992], which approaches a system as a set of systems that, as a unit, is autonomous and capable of surviving. Although the Viable System Model conceptually enables an analyst to model an SoS, which recursively involves the SoS itself, the interrelations between the subsystems and their individual 'parent' systems, the interrelations between the latter and the various environmental settings, and the inherent complexity of such attempt reasonably necessitates a deliberate limitation of its application.

According to Maier (Maier, 1998), a system that has operational and managerial independence of its elements is a SoS. This assertion stresses the deliberate decision of systems to collaborate in an SoS for a common purpose. In this sense, Maier's perception of an SoS is similar to Ackoff's view of an organisation and the agents in a complex adaptive system. The main argument is that a system which is a component of an SoS is simultaneously a subsystem of another system, which necessitates collaboration among the latter to align strategic objectives in policies, common standards for technical interfaces, and specific goals and means for operations and development. Hence, an SoS is a system of subsystems of other SoS (Große, 2020). This term is analogically cumbersome, as it illustrates the entangled nature of SoS, which involves differences in environmental conditions and a diminished opportunity for the parent system to exercise control over its subsystems that are also part of another SoS. This conceptual construct is likewise applicable to organisations, political and social systems of societies and socio-technical systems.

2.2. The infrastructure system and its function

The term 'infrastructure' stems from the Latin words *infra*, meaning 'underlying', and *structura*, meaning'assemblage'. Therefore, infrastructure is defined as an underlying base or framework, which include material or fixed assets, service processes, formal rules and information flows [e.g. Große, 2020; European Commission, 2004]. Using a system perspective can assist in defining infrastructure in a certain context. For example, transport infrastructure can be viewed as comprising the different underlying fixed assets, such as roads, railways, train stations, ports and airports, the service processes that build the physical assets and perform transportation, and the manifestation of societal concerns regarding mobility and the supply of goods. Thus, infrastructure provides a structure or tool upon which a user acts, which confirms that the user's perspective determines the critical process that infrastructure as a system executes and the product of the process which emerges as a precondition for a particular user.

Defining infrastructure in a comprehensive manner is challenging, which official descriptions illustrate. For example, the European Commission has defined critical infrastructure as structures that 'consist of those physical and information technology facilities, networks, services and assets which, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of citizens or the effective functioning of governments in the Member States. […] Some critical elements in these sectors are not strictly speaking 'infrastructure', but are in fact, networks or supply chains that support the delivery of an essential product or service. For example the supply of food […] is dependent on some key facilities, but also a complex network of producers, processors, manufacturers, distributors and retailers' (European Commission, 2004).

Thus, reliable functionality of infrastructure depends on not only fixed or physical assets but also multi-level systems that perform interrelated processes, such as operation, maintenance and development, and decision-making regarding operational, managerial and strategic objectives. Applying a systemic view on critical infrastructure appears therefore useful for research and development. The growing interconnectedness of modern societies has increased their dependency on vital societal functions, such as transportation, healthcare, electricity and information and communication technology (ICT). Hence, the critical infrastructure system's functionality or key process that provides essential goods and services for public well-being (Katina et al., 2017) warrant further conceptual clarification.

Whereas the existence of a system in general can be independent of the process that it was intended to facilitate, the process itself relies on an executing system. Furthermore, a process has a determined start and end, which can in turn relate to the determination of a system, though this consequence is not mandatory. A process, such as transportation, is a content-related and self-contained sequence of timely and logically consistent events and activities that processes a central, process-characterising object [see e.g. Becker and Schütte, 2004; Davenport, 2017; Davenport and Short, 1990; Scheer, 1991]. A process can be performed in parallel instances or rapid succession, which may feign continuity. Aside from demanding a trigger, each process iteration differs from previous and subsequent ones because of several changes regarding, for example, the process object, the properties of materials or the state of the executing system. The term 'process' can have two interpretations. In the first, it relates to a blueprint of such sequence, which is often referred to as a reference process (vom Brocke, 2003). In the second, it can concern a particular execution of a reference process.

With the entangled nature of infrastructure in mind, the establishment of physical infrastructure, such as roads or cars, can be considered a preceding process that is performed by another system, which also underlines the dependency of the subsequent processes, such as car-driving, on the preceding ones. Such interdependency refers to the inherent uncertainty about mutual dependencies that emerge from the intertwined character of infrastructure in society. A classification of infrastructure interdependencies states four types (Rinaldi et al., 2001): physical (exchange of goods), cyber (exchange of information), geographic (effects that emerge from close spatial proximity) and logical ('if the state of each infrastructure depends on the state of the other via a mechanism that is not a physical, cyber, or geographic connection'). Such interdependencies necessitate proper attention and management to develop and maintain safe and reliable infrastructure systems. Hence, infrastructure can be considered the system to be governed for ensuring its intended functionality for society.

2.3. Governance

As indicated, complexity challenges not only the analysis of infrastructure but also its governance since a multitude of factors can contribute to the problem. First, critical infrastructure and its protection can be seen a matter of concern for the political system, which, in accordance with Easton (Easton, 1965), can be envisioned as a 'black box' that encompasses institutions, processes and actors that yield binding decisions for society. It involves questions of who possesses authority and which influences impact its society and economy. In this sense, a political system is mainly associated with government but can also be applied to another kind of organisation, multi-stakeholder group or multi-level system that involves man-made steering mechanisms and power relations.

The governing system in the context of critical infrastructure can be related to the concept of governance, since critical infrastructure is often established, operated and maintained by private actors, whereas the steering seeks to address societal objectives beyond the individual providers' goals. However, scholars have noted that governance is an 'elusive and much debated concept' (Griffin, 2010) and a 'significant expansion, broader than management' of society (Ison et al., 2018). The lowest common denominator characterises governance as a departure from traditional ruling and top-down control, which are associated with government, towards participative forms of policy-making, in which, according to Rhodes (Rhodes, 1996), 'self-organizing, interorganizational networks' […] complement markets and hierarchies as governing structures for authoritatively allocating resources and exercising control and co-ordination'. This characterisation positions governance at the intersection of governmental control, competitive market dynamics and the private sphere of citizens (Offe et al., 2008; Grzeszczak, 2015). In this space, an interorganisational network, which corresponds to the concept of an SoS, governs (public) service delivery of, for example, transportation or undisturbed power supply. In addition, governance is perceived as a peculiarly subject-less phenomenon (Offe et al., 2008). Whereas the term 'government' clarifies the mode and body that governs society, the term 'governance' nebulises the governing actor, which can explain the popularity of the term in a variety of contexts even beyond the public sphere. Since the ambiguity of the term tends to complicate analyses in the social sciences, it has been questioned whether governance marks the contraposition (*Gegenbegriff*) or the *genus proximum* (*Oberbegriff*) to government (Offe et al., 2008; Colebatch, 2014). However, practicing decentralised governance as the opposite approach to centralised government has revealed deficit symptoms, such as dysfunctionality and loss of institutional memory about 'how things have come about, and, more importantly perhaps, why they did' (Tingle, 2015).

Research has emphasised that large-scale problems, such as climate change and an increasing dependency on critical infrastructure, challenge society and governments because they transcend political domains (Griffin, 2010; Ison et al., 2018). In view of this, Ison et al. (Ison et al., 2018) have recalled the cybernetics of Wiener (Wiener, 1948) to contend with complexity in society and introduced the concept of cybersystemic governance. This approach stresses the dynamic and systemic relationships among stakeholder groups in society and common concerns regarding, for example, the biosphere and the technosphere. The authors have particularly highlighted the relevance of negotiating and pursuing social purpose as it develops within an unfolding context. In addition, McIntyre-Mills (McIntyre-Mills, 2006) has applied a shift in thinking to characterise systemic governance as a bottom-up approach that starts at the local level and, through adaption to circumstances and the emergence of new forms, is able to span multiple areas. This perspective is *Gegenbegriff* to traditional forms of government; however, it struggles with the systemic perspective, which would also encompass larger concerns from the local perspective, and vice versa.

The representation of the governing system as network is an important phenomenon in both governance and public policy theory [e.g. Petridou, 2014; Henry, 2011]. For example, public–private collaborations that target the development and maintenance of critical infrastructure to ensure reliable service provision can be recognised as governance networks. By participating in such networks, organisations can reduce transactions costs and information asymmetries, which also has a positive effect on legitimacy and the acceptance of public policies (Ahrens and Rudolph, 2006). Although governance networks are often created and co-ordinated by the state, self-organisation is seen as the ideal steering mechanism within such networks. Central to all types of networks is the interests that dominate them, for example economic or societal purposes. Governance networks thus vary in both the degree of internal influence and the properties that ultimately characterises the individual nature of such network that performs the policy process. The generic policy process consists of five phases: agenda-setting, policy formulation, decision-making, implementation and evaluation. The first phase can be further divided into the stage of problem identification and definition and the stage of agenda-setting (Jann nd Wegrich, 2007; Rinfret et al., 2018). The last phase can also lead to the termination of a policy (Hill and Varone, 2017; Lasswell, 1948).

Thus, governance networks must be studied empirically to be characterised and analysed (Rhodes, 1997), which also applies to the CIP context. To facilitate the development of understandings regarding critical infrastructure, its governance and the related policy process, a system-theoretical perspective seems relevant in studying the structure of the governed and governing systems, represented in networks, and the functions and properties that relate to particular implementations in practice.

3. Material and methods for data collection and analysis

This section details the systematic literature review (Paré et al., 2015) that consisted of a search for relevant scientific articles (vom Brocke et al., 2009) and a qualitative content analysis of a selection of articles (Maxwell, 1992).

During the initial phase, the structured process of the literature search and selection applied broad and general search terms in various databases to identify the most comprehensive option. The initial search returned a vast range of hits in various databases, including 1,370 in ProQuest Social Sciences, 5,646 in Ebsco, 9,114 in Scopus and 3,662 in World of Science. Based on this initial assessment, Scopus was selected for the subsequent literature search.

During the search process, the initial search term was varied to reduce the number of results and, thereby, to obtain a selection that suitably represents current research in the field of complex systems, CIP and governance. Table 1 displays key words, search terms and results in a chronological order; the search process stopped after applying the term in row nine.

The literature selection process applied a four-step refinement:

1. Examining titles, keywords and abstracts on their relevance for this review
2. Reviewing the content to confirm the relevance
3. Identifying the article's focus and perspective for mapping them to the main analysis categories; and
4. Analysing the complete content.

The final selection included 30 carefully selected scientific articles and book chapters that were identified by the final search term (see Table 1, row nine); five matches that targeted entire books were excluded. This body of literature formed the basis for the analysis to substantiate the understanding of systems, infrastructure and governance.

Table 1
Key Words, Modified Search Terms and Hits in Scopus.

N	*Search Term*	*Hits*
0	(TITLE-ABS-KEY ("system* governance*")) OR (TITLE-ABS-KEY ("critical infrastructure*"))	9 114
1	TITLE-ABS-KEY ("complex system*")	62 997
2	TITLE-ABS-KEY ("critical infrastructure")	8 711
3	(TITLE-ABS-KEY ("critical infrastructure")) AND (protection)	3 936
4	(TITLE-ABS-KEY ("critical infrastructure")) AND (protection) OR (governance)	4 141
5	(((TITLE-ABS-KEY ("critical infrastructure*")) AND (protection) OR (governance)) AND (system*))	3 796
6	(((TITLE-ABS-KEY ("critical infrastructure*")) AND (protection) OR (governance)) AND (system*)) AND (complex*)	1 441
7	(((TITLE-ABS-KEY ("critical infrastructure*")) AND (protection)) AND (system*)) AND (governance)	288
8	(((TITLE-ABS-KEY ("critical infrastructure*")) AND (protection)) AND (system*)) AND (governance)AND (complex*)	155
9	(((TITLE-ABS-KEY ("critical infrastructure*")) AND (protection)) AND ("complex system*")) AND (governance)	35

Table 2
Sources of Journal Articles and Serial Publications Included in the Literature Review.

Source of publication	*n*
International Journal of Critical Infrastructures	6
Energy Policy	2
Journal of Contingencies and Crisis Management	2
Nato Science For Pease And Security (Series C: Environmental Security)	2
Reliability Engineering And System Safety	2
ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering	1
Cognition, Technology & Work	1
IFIP Advances in Information and Communication Technology	1
International Journal of Disaster Resilience in the Built Environment	1
International Journal of Disaster Risk Science	1
Safety Science	1

In pursuit of a solid point of departure for the academic community that is interested in systems and their reliability (Paré et al., 2015; Pfeffer and Sutton, 2006), the literature analysis started already alongside the selection process by assessing the type of literature, the year and place of publication, the number of authors and other available *meta*-information.

As Table 2 indicates, the final selection consisted of two chapters of a serial publication and 18 journal articles, of which two provided literature reviews. Furthermore, the selection included 10 conference articles, of which the majority had been published in or after 2016.

Research designs that use qualitative, semi-qualitative or mixed-method approaches are useful to expand understanding and to enrich insights (Johnson et al., 2007). The in-depth review of the selected literature applied therefore a qualitative content analysis that assists with analysing and interpreting texts to find patterns in their content. The analysis followed an iterative process. First, the key words from the literature search directed the initial reading in which the results were highlighted manually in the material. Then, a close textual analysis was conducted that adapted the kaleidoscope for integrative system analysis—KISA (Große, 2021) to extract the understandings provided in the selected articles. This conceptual frame aligns with the outlined theoretical background and includes four perspectives: system, infrastructure, governance and related processes. After gaining an initial understanding of the articles, detailed categorising and coding was performed.

In particular, the analysis concentrated on the following representations:

- Systems: What constitutes the system of interest and how is it defined? What are the theoretical foundations and key concepts? How is the nature of the system characterised?
- Infrastructure: What is the provided definition of infrastructure? What types are described? What is the conveyed understanding of its purpose, function and structure?
- Governance: How is governance described and interpreted? What tasks and properties are associated?

Definitions, examples and certain aspects that the authors have emphasised were extracted from each article. The qualitative content analysis was also attentive to patterns and issues that emerged from the texts, such as contrary understandings, common usage of concepts and problems of particular interest for this review. The analysis of articles from the outlined theoretical perspectives and main categories both broadened and deepened the understanding of the content until saturation was reached, that means, no further details could be uncovered to enrich the gained understanding with respect to the analysis questions. To this end, the data analysis applied a hermeneutic approach to the selected articles, which necessitated deliberate, reflected subjectivity of the analyst to interpret data and results that could yield novel insights (Breuer et al., 2002; Reichertz, 2015). One observation is that about three-quarters of the reviewed articles contain no description of the actual research process or epistemological position, which can relate to the mentioned immaturity of the relatively new research field of CIP (Seager et al., 2017; Katina and Keating, 2015), its strong anchorage in engineering or its preference for multi-disciplinary approaches in the interplay between solution-orientation and theory development. However, excerpts from the articles substantiate the analysis of the state of the art in Section 4.

4. State of the art: System, infrastructure and governance

This section presents the results of the literature review and elaborates on the concepts and theories that connect the corner stones of the triangle of systems, infrastructure and governance. It concentrates on definitions, common elements and emerging issues that are explicitly articulated or implicitly incorporated in the articles.

4.1. The spectrum of system concepts

Considering the initial assumption of this study that a system perspective is a valuable theoretical lens to understand and develop critical infrastructure and its governance, condensed into the search term for this literature review, it is surprising that none of the reviewed articles contains a definition that derives from original research of any system theory. Furthermore, less than one-third of them makes any reference to previous research in this context when describing the elements of a system (Katina and Keating, 2015; Große and Olausson, 2019; Coaffee and Clarke, 2017; Liu et al., 2017; Lykou et al., 2017; Gonzva et al., 2016; Normandin and Therrien, 2016; Ouyang, 2014; Sajeva and Masera, 2006). Apart from the possibility that such absence stems from the immaturity of the research field of CIP, as Seager et al. (Seager et al., 2017) and Katina et al. (Katina and Keating, 2015) have recognised, the insufficient anchoring in theory can relate to either a tendency of scholars to exclusively connect to recent research in the field (e.g. mainly published within the recent five years) or a belief of the authors that the inherent meaning of the term 'system' constitutes common knowledge. Closer textual analysis refutes this belief and reveals that the articles incorporate a broad spectrum of meanings. Descriptions of properties dominate the usage of the system concept in the reviewed articles; however, the type of the system of interest remains often unclear. The abstraction level in the articles covers systems ranging widely from those of an all-encompassing character (Prelipcean, 2010) or global impact (Schaberreiter et al., 2016) to purely technical systems, which, for example, have been considered in the modelling and simulation of a small gas-power-distribution network (Liu et al., 2017).

To label specific systems, the articles use a vast number of aspects, such as a focus on the key elements of a system, particular system behaviours or properties, or the main purpose of a system of interest. The analysis following Table 3 considers some labels of the former two types, namely technical/technological, socio-technical, social, political, complex adaptive and SoS labels as well as open, closed and interdependent labels. Those of the latter type, which regard the systems' key functions, recur in Section 4.2.

The majority of the articles rather vaguely characterise the system under investigation, which radiates confidence—intended or not—that the *Weltanschauung* of the authors is similar to that of a reader regarding the interpretation of the distinct system constituents. Based on the literature review, six main types can be deduced: technical/technological, socio-technical, social, political, complex adaptive and SoS.

4.1.1. Technical and technological systems

System characterisations in the investigated context are merely oriented towards physical components and technical constructions wherein humans mainly appear in the role of output recipients (i.e. users) or are addressed as an environmental factor (e.g. operator or manager of the technical system). Such type of system bears several additional labels

Table 3
Appearance of System as Concept (* C: Components, I: Interrelations, E: Environment).

Author, year	*Definitions / Descriptions*	*System of interest's nature*	*Elements** *C*	*I*	*E*
(Abedi et al., 2019)	'*Real systems consists of thousands to then thousands of components*' (p. 27)	– Known component – Mathematically modellable – Technical and measurable – Interdependent	X	X	X
(Cedergren et al., 2019)	'*the resource system represents the stock of the resource, resource units represent what users withdraw from the resource system'* (p. 2)	– Known components – Interactions with the system's environment or stakeholders – Technical and measurable – Constitutes a limited resource	X	X	X
(Große and Olausson, 2019)	*'interactions between components in a system cause system behaviour, which is not easily explained by the properties of components'* (p. 426)	– Emergent behaviour – Interdependent – Entropic and adaptable – Large and dynamic	X	X	X
(Katina et al., 2019)	'*blockchaining systems'* in which blockchain has the '*potential to revolutionise internal, external and intra systems and their transaction processes at different levels'* (p. 131)	– Based on virtual currencies (e.g. bitcoin) – Physical/information technology – Values and beliefs	X	X	X
(Große and Olausson, 2018)	*'Multilevel planning system consists of three hierarchical levels—the local, the regional and the national level'* (p. 1896) and '*co-operation between system components'* (p. 1899)	– Large number of participants – Interdependent – Unknown components and interrelations are possible – Hierarchical and reticular	X	X	X
(Tehler et al. 2018)	'*they are becoming increasingly interconnected growing into 'system of systems' and thereby increasing the risk of transboundary crises*' (p. 1865)	– Feedback loops – Interdependent – Large extent – Physical and technical	X	X	X
(Gheorghe et al., 2018)	'*space systems, mainly satellites orbiting the Earth*' (p. 555) '*are an unalienable component of high-functioning system-of-systems'* (p. 559)	– Physical/information technology – Interdependent – Functionally expansive	X	X	X
(Antonsen et al., 2017)	*'Dealing with interconnectivity requires good system descriptions'* (p. 1840)	– Interconnected – Smart – Communication	X	X	X
(Coaffee and Clarke, 2017)	*'complex adaptive systems with* […] *ability to adapt to such conditions of uncertainty and volatility' (p. 365)* and '*a near exclusion of social and human factors'* (p. 367)	– Interdependent – Large and interconnected – Uncertain and volatile – Non-linear and dynamic – Socio-technical and integrated	X	X	X
(Katina et al., 2017)	*'Physical (hard) systems such as roads* […]*, hospitals, electrical* […] *and water systems as well as soft systems,* e.g. *SCADA and ICT'* (p. 172)	– Face operational factors – Interdependent – Technical, controllable – Large and dynamic	X	X	X
(Liu et al., 2017)	Systems-of-systems '*are made by many physically and functionally heterogenous components* […] *organized in a hierarchy of subsystems that contribute to the system function'* (p. 1)	– Technical – Interdependent – Mathematically modellable – Linear-dynamic – Network structure	X	X	X
(Lykou et al., 2017)	*'fixed installations* […]*, vehicles* [and] *operations (people, institutions, laws, policies, and information systems) that convert* [the former two] *into working* […] *networks*' (p. 2)	– Mainly physical, fixed – Extensive network – Transboundary – Interconnected – Long life span and high costs	X	X	X
(Seager et al., 2017)	*'characterized by empirical relationships between and among people, objects, and other systems*' (p. 88)	– Interdependent – Interobjective – Has boundaries and purpose	X	X	X
(Gonzva et al., 2016)	*'Socio-technical systems link physical systems with actors and rules to provide a particular function'* (p. 2)	– Large number of dynamically interacting, diverse elements – Unanticipated variability	X	X	X
(Häring et al., 2016)	*'socio-technical systems like critical infrastructure'* (p. 273) that serve '*functions of critical interest'* (p. 274)	– Technical and quantifiableContext and conditions – Interdependent behaviour		X	X
(McGee et al., 2016)	*'cannot be completely understood or effectively resolved by addressing parts in isolation*' (p. 147)	– Technical and interdependent – Causal relationships – Non-linear effects	X	X	X
(Normandin and Therrien, 2016)	'*any social system* […] *is composed of a large number of parts that interact non-linearly*' (p. 110)	– Emergent behaviour (macro) – Interaction (micro) – Order/disorder (neg-/entropy)	X	X	X
(Schaberreiter et al., 2016)	'*composed of many components that are interacting to provide a service* […] *not* […] *in isolation*' (p. 672)	– Socio-technical and diverse – Interdependent and global – Technology-based and cyber	X	X	X
(Katina and Keating, 2015)	'*a set of interrelated components working together toward some common objective or purpose*' (p. 332)	– Physical (hard) and soft (ICT) – System-of-systems – Integrated and co-ordinated	X	X	X
(Di Maio, 2014)	'*not limited to the IT infrastructures, Data Base and Network but extend to facilities, utilities and support services; policies, procedures, and people*' (p. 5)	– Interoperable – Plurality of actors – Interdependent – Virtually no-boundary	X	X	X

(*continued on next page*)

Table 3 (*continued*)

Author, year	*Definitions / Descriptions*	*System of interest's nature*	*Elements**		
			C	*I*	*E*
(Ouyang, 2014)	'*hierarchical structures where each level imposes constraints on the activity of the level beneath*' (p. 55)	– Interdependent – Feedbacks and controls – Not static but evolving	X	X	X
(Spyridopoulos et al., 2014)	'*various assets, interactions with the internal and external environment*' (p. 438)	– System-of-systems – Proprietary – Having boundaries	X	X	X
(Johnsen and Veen, 2013)	'*is an international wireless communications standard for railway communication*' (p. 1)	– Technical – Distributed – Single point of failure	X	X	X
(Prelipcean, 2010)	'*social systems with* [...] *contributions to the entire global system*' (p. 220)	– Universal and all-embracing – Socio-economic	X	X	X
(van der Vleuten and Lagendijk, 2010b, a)	'*consist of interconnected yet separately managed networks*' (p. 2055)	– Mainly technical – Transnational – Feedback and causal loops	X	X	X
(Eusgeld and Kröger, 2008)	'*interdependent structures of components*' with a '*dependence on natural and operational environment*' (p. 476)	– System-of-systems – Interdependent – Dynamic and non-linear	X	X	X
(Robert et al., 2008)	'*networks are interdependent on each other. Each one uses resources that the others produce*' (p. 393)	– Dynamic – Socio-economic environment – Mainly technical	X	X	X
(Sajeva and Masera, 2006)	'*composed of multiple, heterogeneous, distributed systems, interconnected among themselves at various levels*' (p. 381)	– System-of-systems – Emergent – Chaotic (i.e. non-linear) – Socio-technological	X	X	X
(Gheorghe, 2004)	'*relations exhibited today by complex technical and societal systems*' (p. 123)	– Technically designed – Genuine uncertain and ambiguous conditions		X	X

that emphasise, for example,

- The **components**: generator (Abedi et al., 2019), real (Abedi et al., 2019), rail/railway (Seager et al., 2017; Cedergren et al., 2019), resource (Cedergren et al., 2019), computer (Große and Olausson, 2019), traditional (Katina et al., 2019), cyber-physical (Katina et al., 2017), hard (Katina et al., 2017; Katina and Keating, 2015; Lykou et al., 2017), soft (Katina et al., 2017; Katina and Keating, 2015), canal (Seager et al., 2017), sewerage (Antonsen et al., 2017), physical (Katina et al., 2017; Seager et al., 2017; Gonzva et al., 2016), storage (McGee et al., 2016), and router (Katina and Keating, 2015);
- The **interaction**: (a) among components—grid (Seager et al., 2017; Abedi et al., 2019), linear (Coaffee and Clarke, 2017), wireless (Katina and Keating, 2015), network (Cedergren et al., 2019; Coaffee and Clarke, 2017; Di Maio, 2014; Johnsen and Veen, 2013; Katina et al., 2017, 2019; Liu et al., 2017; Lykou et al., 2017; van der Vleuten and Lagendijk, 2010b,a; Gonzva et al., 2016; Robert et al., 2008; Schaberreiter et al., 2016), cyber (Katina et al., 2017; Schaberreiter et al., 2016; Abedi et al., 2019; Katina et al., 2019); or (b) with an environment—closed (Katina et al., 2019; Tehler et al., 2018);
- The location in relation to an **environment**: local, regional, national, transnational (van der Vleuten and Lagendijk, 2010b,a); distributed (Ouyang, 2014; Sajeva and Masera, 2006; Johnsen and Veen, 2013; Eusgeld and Kröger, 2008; Eusgeld and Kröger, 2008).

The labelling of a system as 'hard' or 'soft' is particularly interesting. Lykou et al. (Lykou et al., 2017) have referred to 'hard and extensive infrastructures', such as roads, runways and buildings. Katina et al. (Katina et al., 2017; Katina and Keating, 2015) have extended this description with, among others, 'hospitals', which raises the question of whether the 'hard' part of such a system (e.g. the building or even the medical equipment) is capable of constituting a hospital or if first the inclusion of an interrelated workforce (e.g. healthcare professionals or operational staff) would complete the system as a hospital. Spontaneously, such workforce would emerge as a complementary (i.e. soft) part of the hospital system. However, the description of 'soft' in the articles instead uncovers supervisory control and data acquisition (SCADA) systems and information and telecommunication technologies (Katina et al., 2017; Katina and Keating, 2015). In this context, such soft systems can be understood as the technical aspects of an information system, such as its hardware and software. In contrast, previous research has characterised soft systems as an interrogative concept intended to facilitate debate among concerned parties about poorly structured problems (Avison and Taylor, 1997; Checkland, 1989; Checkland, 2008). This example illustrates the ambiguity of such labels and the difficulty of articulating their inherent meanings. Nevertheless, the rapid development of ICT (information and communication technology) intertwines its components with the former technical systems, which the articles seem to reflect with the usage of the label'technological'.

Furthermore, many articles use labels such as 'linear', 'network' and 'grid', which illustrate the interactions within the technical system components. Thus, from a traditional engineering point of view, the interaction between system components in technical systems occurs via physical connections, such as cables, roads or rails (Liu et al., 2017; Lykou et al., 2017; Cedergren et al., 2019; McGee et al., 2016), which renders the border between a technical system and its environment relatively obvious and thereby enables its image as a closed system. As noted, the development of ICT (e.g. the Internet) and its global application is diminishing the visible appearance of networks and, thereby, the borders between a system and its environment. Some of the articles reference this point with labels such as 'wireless' or 'cyber', which characterise both types of interactions—within a system and between a system and its environment.

All articles recognise a type of environment that either presents constraints which the system must regard or constitutes a counterpart for interaction. Ultimately, the quality of the system borders has an impact on the system. In the literature that was reviewed, only the article by Eusgeld and Kröger (Eusgeld and Kröger, 2008) explicitly acknowledges system boundaries for analysing system vulnerabilities. All other articles imply that the boundaries are rather fluent and invisible. The label 'open' appears in relation to the mentioned ICT, such as in 'open information infrastructures' (Sajeva and Masera, 2006) and 'open, interoperable and reliable cyberspace' (Schaberreiter et al., 2016).

4.1.2. Socio-technical systems

Some of the reviewed articles acknowledge the socio-technical character of the system of interest. Table 3 presents a definition by

Gonzva et al. (Gonzva et al., 2016) that integrates the technical system, actors and rules into a joint system. The reviewed articles mainly consider the environment in the form of constraints, such as natural events, legal regulations or public values, that frame the course of action.

Whereas previous research (Emery and Trist, 1960) has argued that 'the technological component has been found to play a key mediating role'—and thus must be integrated with the social system of an enterprise into a socio-technical one—Coaffee and Clarke have recently identified a 'near exclusion of social and human factors' (Coaffee and Clarke, 2017). The article by Katina and Keating has confirmed this perception in mentioning the difficulty of including 'social-technical dimensions' in modelling and simulating technical systems, which necessitates the involvement of different worldviews (Katina and Keating, 2015). Hence, humans are seldom portrayed as a constituent part of the system as in the articles by Große and Olausson (Große and Olausson, 2019; Große and Olausson); most of the time, they are addressed as a resource in a production machinery (Di Maio, 2014; Eusgeld and Kröger, 2008), a cause of failure (Katina et al., 2017; Abedi et al., 2019; Gheorghe, 2004) or somehow included in the design or analysis or as part of a system (Seager et al., 2017; Lykou et al., 2017; Ouyang, 2014; Cedergren et al., 2019; Häring et al., 2016; Johnsen and Veen, 2013). In contrast, Schaberreiter et al. (Schaberreiter et al., 2016) have emphasised that analyses of complex relations within socio-technical systems must address organisational and human aspects as much as the technical considerations as well as the economic and legal requirements that are provided by the environment.

Nevertheless, the majority of the articles lack a clear explanation of the system of interest and its analysis. One example can be found in the article by Johnsen and Veen (Johnsen and Veen, 2013), which reports the application of 'a broad socio-technical approach to safety that builds on many knowledge areas such as relevant technical issues, psychology, organization knowledge, culture, human factors, and safety'. Still, it remains unclear whether the knowledge base that was used for the analysis can be considered socio-technical, whether the system under investigation is intended to be of a socio-technical type or whether the research system that performed the analysis has been characterised. This example illustrates the difficulties in determining not only the constituting elements but also the system borders for analysis.

As indicated in section 2, interactions are a key element of systems. Therefore, several system properties and dynamics are connected to the form and quality of interaction, which implies that studies in the context of CIP would clarify the relationships in the analysed systems. However, interactions between system components or between the system and its environment appear similarly undefined in the majority of the reviewed articles. As indicated, exchanges to manage entropy and maintain a balanced open system thus incorporates both a dependency on a substantive support, such as material, workforce and information, and a variation in the internal processes for adapting to different external constraints. While recent research has primarily focused on the latter to investigate the resilience of systems (Katina et al., 2017; Coaffee and Clarke, 2017; Lykou et al., 2017; Gonzva et al., 2016; Häring et al., 2016; McGee et al., 2016; Spyridopoulos et al., 2014; Johnsen and Veen, 2013), some of the investigated articles also reflect the former, namely the dependency of an adequate resource influx into the system (Seager et al., 2017; Große and Olausson, 2019; Tehler et al., 2018).

4.1.3. Social and political systems

Two out of the 30 articles explicitly mention the social system. One article uses the notation as a container for all types of recipients that are exposed to the effects of physical disasters, but it lacks a more detailed specification (Prelipcean, 2010). The second article employs the concept of complexity to characterise a social system as 'a large number of parts that interact nonlinearly' and further cites the examples of 'an organisation or a city' (Normandin and Therrien, 2016). This portrayal of a city as a social system is remarkable since it is subject to a broader discussion in another article within the reviewed literature. Despite acknowledged difficulties in establishing a general definition, Gonzva et al. (Gonzva et al., 2016) have argued that although cities could be understood as socio-ecological systems, which would allow for 'even include humans as components of these ecosystems', the authors perceive it 'more relevant to approach city as a technical object'. The concept of cities also re-appeared in the context of political systems.

Several of the investigated articles acknowledge the importance of political activities as drivers or constraints of the system of interest (Abedi et al., 2019; Antonsen et al., 2017; Coaffee and Clarke, 2017; Große and Olausson, 2019; Johnsen and Veen, 2013; Katina et al., 2019; McGee et al., 2016; Sajeva and Masera, 2006; van der Vleuten and Lagendijk, 2010b,a; Schaberreiter et al., 2016; Seager et al., 2017). However, the majority of the articles abstain from a more precise definition of a political system because it is considered merely an environmental factor that is not as central in these studies. Similarly to other types of system, a political system relates to borders, such as national boundaries or a common framework for action. Seager et al. (Seager et al., 2017) have exemplified such political borders with 'city, county, or state lines' or regulatory boundaries. Furthermore, Katina and Keating (Katina and Keating, 2015) have recalled the boundaries in the European Union when considering cross-border effects in the context of CIP.

The indistinct boundaries of an open political system are imagined in the article by Schaberreiter et al. (Schaberreiter et al., 2016), which notes that the task of preserving the openness and freedom of the Internet while improving privacy and security has become an issue for the global forum. Van der Vleuten et al. (van der Vleuten and Lagendijk, 2010b,a) have detailed how political systems have affected technical development in the context of European power distribution networks over decades as well as how technical and societal requirements can transform from local and regional to national and transnational issues and thereby stimulate evolution of the concerned systems.

4.1.4. Complex adaptive systems

Because of the search term that was used, all articles in the literature review label the system under investigation as 'complex'. Viewing a system as complex adaptive further emphasises its 'ability to adapt to such conditions of uncertainty and volatility', according to Coaffee and Clarke (Coaffee and Clarke, 2017). Spyridopoulos et al. (Spyridopoulos et al., 2014) have noted that such systems consist of 'large sets of components that interact with each other while synergies emerge through those interactions'. Among the articles, there is wide recognition that the components of complex (adaptive) systems are interconnected and autonomous agents that, due to individual adaption to interactions and particular environmental conditions, display non-linear behaviours, which can lead to emergence and unpredictable outcomes (Katina et al., 2017; Seager et al., 2017; Katina and Keating, 2015; Große and Olausson, 2019; Coaffee and Clarke, 2017; Liu et al., 2017; Normandin and Therrien, 2016; Sajeva and Masera, 2006; Abedi et al., 2019; McGee et al., 2016; Eusgeld and Kröger, 2008). The articles provide examples of emergent properties, such as resilience (Normandin and Therrien, 2016), self-organisation (Katina et al., 2017; Coaffee and Clarke, 2017; Katina et al., 2019), self-healing (Schaberreiter et al., 2016), system adaption and (co–)evolution (Katina et al., 2017; Katina and Keating, 2015; Ouyang, 2014; Sajeva and Masera, 2006; Prelipcean, 2010; Cedergren et al., 2019; Katina et al., 2019; Eusgeld and Kröger, 2008; Gheorghe, 2004). The latter further indicates that complex adaptive systems are not single systems but are often concerned with SoS. In the interest of completeness, the difference between the properties 'complicated' and 'complex' warrants acknowledgement. According to Sajeva and Masera (Sajeva and Masera, 2006), the label 'complicated' distinguishes between 'large systems [that] can be described as merely complicated' and systems that are complex. However, such distinction depends on the point of view. A system is complicated from the perspective of an observer or user, which relates to his or her level of experience and knowledge. Meanwhile, complexity is a property of the system and persists independently of a particular observer or user. The appearance of the system element 'environment' remains ambiguous in both the articles and the theory, which reflects the openness of the systems under investigation.

4.1.5. Systems of systems

Around one-third of the reviewed articles mention a specific type of system, namely SoS, in the context of CIP (Katina et al., 2017; Katina and Keating, 2015; Liu et al., 2017; Gonzva et al., 2016; Ouyang, 2014; Sajeva and Masera, 2006; Abedi et al., 2019; Tehler et al., 2018; Gheorghe et al., 2018; Spyridopoulos et al., 2014; Eusgeld and Kröger, 2008). The authors have emphasised the interconnected nature of systems, which permits the relation of SoS to the noted key elements of a system: the components (in this case, systems); interactions (relations between the systems); and an environment that surrounds the SoS and therefore must also concern the individual environments of each subsystem and the space between them. Each subsystem is considered 'open', which, as discussed above, involves a dependency of exchange with its particular environment that, in turn, somehow contains the other components (i.e. subsystems) of the system. The majority of the articles acknowledge this openness of the subsystems by labelling the components and their interactions as 'interdependent' on each other, which indicates the close relationship of SoS with complex adaptive systems.

Several concepts were prominent in the review of the articles. Ouyang (Ouyang, 2014) has referenced the definition of SoS by DeLaurentis (DeLaurentis, 2007), which asserts that SoS 'consist of multiple, heterogeneous, distributed, occasionally independently operating systems embedded in networks at multiple levels that evolve over time'. In addition, Sajeva and Masera (Sajeva and Masera, 2006) have noticed a 'high complexity, plurality of stakeholders and neither is it a clear definition of roles and responsibilities' as characteristics. Considering the aforementioned interdependencies, Tehler et al. (Tehler et al., 2018) have anticipated an increasing risk of a transboundary negative impact. Similarly, Gheorghe et al. (Gheorghe et al., 2018) have contended that negative effects (e.g. triggered in space) could easily transcend geographic or jurisdictional boundaries because of the interconnected structure of SoS. Accordingly, Eusgeld and Kröger (Eusgeld and Kröger, 2008) have argued that analyses of SoS should consider 'interdependent structures of components, which result in an often spatially distributed 'system-of-systems', [which] may show strong interdependencies, dynamic and non-linear behaviour, rippling effects, dependence on natural and operational environment, etc'.

Whereas some of the articles implicitly adopt a similar perspective of systems, the conceptual paper by Normandin and Therrien (Normandin and Therrien, 2016) reflects discernibly Ackoff's perspective, which differentiated between organisations and organisms. With reference to previous research (Maier, 1996), Katina and Keating (Katina and Keating, 2015) have presented characteristics of SoS, such as operational and managerial independence of constituent systems, evolution, emergence and geographical distribution when mapping these features to the critical infrastructure field. However, the cited author (Maier, 1998) has deviated from the latter and adjusted the focus on the former two.

Liu et al. (Liu et al., 2017) have expressed a similar perspective in considering the interconnected system of a natural gas distribution network and a power grid. While such network can, in reality, be considered an SoS—for example, if the various parts are operated by different providers—the investigated model then appears as a simplified network with linear dependencies, which may diverge excessively from the nature of the original SoS. Spyridopoulos et al. (Spyridopoulos et al., 2014) have provided another perspective that is remarkable in two respects. First, it positions an industrial control system, namely a generic SCADA system, as an SoS. In accordance with (Maier, 1998), neither the sheer complexity of such systems as a SCADA nor the connection with the Internet alone innately justifies classification as an SoS. Second, the linguistic imprecision with regard to a system of systems or a system-of-systems according to the SoS concept is apparent in the article's application of Beer's Viable System Model. In the discussed article (Spyridopoulos et al., 2014), the authors restrict the view to one organisation, which is further recognised as an 'organism' to abstract from complex interactions and adaption processes.

Katina and Keating (Katina and Keating, 2015) have thus emphasised a holistic worldview with respect to SoS that concerns 'not only the technical aspects of the domain, but also the human, social, organisational, managerial, policy and political aspects'. In addition, they have signalled 'the need to consider coordination and integration beyond individual constituent systems'. Nevertheless, the influence of the various parent systems on an SoS is still an underrepresented issue. In their article, Katina et al. (Katina et al., 2017) propose complex systems governance for a specific SoS, which consists of cyber-physical systems. Similarly to Spyridopoulos et al. (Spyridopoulos et al., 2014), they consider a cyber-physical-system as an organism wherein a software system ultimately controls a physical process in the respective technical system. The authors have argued that the emergence of this type of SoS is due to the increasing interconnectedness of subsystems that organisations comprise, and they have applied the notation of a 'metasystem' to differentiate management processes from operations, which is comparable to the scheme of Beer's Viable System Modell (Katina et al., 2017; Beer, 1995). However, the article does not succeed in maintaining a separation of the concepts; it struggles with the hierarchies of the model in terms of planning and operation and finally confuses the 'metasystem' with the SoS, which was also labelled as 'overall' [cf. Katina et al., 2017]. This article demonstrates the difficulty of preserving a distinction between the discussed concepts, especially when an investigation concerns several hierarchical levels, different types of system and components, and a broad spectrum of interrelations, interdependencies and processes.

4.2. Critical infrastructure and protection

Generally, the reviewed articles commonly perceive infrastructure as a common good that already and forever exists. In the majority of the articles, infrastructure has a physical nature and long durability. Table 4 presents typical examples, such as roads, railways, power grids and buildings (Antonsen et al., 2017; Cedergren et al., 2019; Große and Olausson, 2019; Johnsen and Veen, 2013; Katina et al., 2017; Katina and Keating, 2015; Liu et al., 2017; Lykou et al., 2017; McGee et al., 2016; van der Vleuten and Lagendijk, 2010b,a; Große and Olausson; Prelipcean, 2010). Research has also identified emerging infrastructures in space, under the sea and below the ground (Gheorghe et al., 2018; Gheorghe et al., 2018). Sometimes, the term infrastructure involves established organisational structures and collective knowledge (Seager et al., 2017; Coaffee and Clarke, 2017; Katina et al., 2019). Developments in ICT and their entanglement with industrial processes have forced a perception of ICT as either a particular type of infrastructure or as infrastructure that is incorporated into other types of infrastructure (Schaberreiter et al., 2016; Katina et al., 2019; Di Maio, 2014; Spyridopoulos et al., 2014; Johnsen and Veen, 2013). However, the unconscious assumption that these physical assets are permanent involves a certain level of abstraction, which implies that there is no need to wonder where they came from or how they came into being. Although this perspective may be helpful for assessing a particular system level or process by abstracting from certain details, the specific applications of the concept of infrastructure often remain ambiguous in the articles. Moreover, some authors have explained 'infrastructure' by the concept of 'infrastructure' (Lykou et al., 2017) or the aid of several system concepts (Katina et al., 2017; Katina and Keating, 2015; Häring et al., 2016; Spyridopoulos et al., 2014), which highlights that infrastructure should be approached as a system but does not necessarily bring more clarity due to complex system characteristics, such as adaption, emergence and entropy. Thus, two questions remain: which

Table 4
Characterisations and Examples of Infrastructure and its Criticality.

Author, year	*Definitions / Descriptions*	*Critical Infrastructures*
(Abedi et al., 2019)	'*large-scale man-made systems that operate interdependently to provide and deliver essential goods and services. Failure or destruction affects the safety, security, economy, health, and well-being of a community*' (p. 2)	– Energy and communication networks – Transportation systems – Water and gas distribution systems
(Cedergren et al., 2019)	'*Many of society's essential functions and services are provided by critical infrastructures*' (p. 1)	– Electrical power supply – Communication systems – Rail infrastructure
(Große and Olausson, 2019)	'*their continuity during disturbances is crucial for the survival and progress of a depending society*' (p. 424)	– Power supply – Railway – Electric vehicles
(Katina et al., 2019)	'*systems serving the welfare of the public and their services*'' (p. 122)	– Blockchain – Financial transactions
(Große and Olausson, 2018)	'*important users in society [that are] crucial for private households, businesses, and public operations to function and survive*' (p. 1893)	– Power supply – Railway – Electric vehicles
(Tehler et al., 2018)	'*functioning of modern societies is dependent on the services provided by an interconnected web of critical infrastructures*' (p. 1865)	– Telecommunication – Electric power supply – Transportation – Water supply
(Gheorghe et al., 2018)	'*capacity for the provision of unique services or of services that are difficult to substitute sustainably through* […] *alternatives*' (p. 555)	– Space systems – Global navigation satellite system
(Antonsen et al., 2017)	'*modern critical infrastructures are becoming increasingly 'smarter*'' (p. 1837) *and are 'required to meet the population and society's basic needs such as food, water, heating, security and the like*' (p. 1840)	– Harbour / cargo port – Industries – Fuel supply – Societal functions
(Coaffee and Clarke, 2017)	'*a larger, more complex and an increasingly interconnected amalgamation of social, technical and economic networks*' (p. 365)	– Physical / informational – Energy, water, transport
(Katina et al., 2017)	'*system of systems that provides essential goods and services necessary for public well-being with the aid of control systems in the form of information and telecommunications*' (p. 173)	– Roads, highways, hospitals – Electrical systems – Water systems – SCADA and ICT systems
(Liu et al., 2017)	'*engineered systems which provide continuous flows of goods (*e.g. *energy, water, gas) and services (*e.g. *transportation, information), that are used for industrial productions and people living [and] are interconnected to each other*' (p. 1f)	– Power grids – Energy/gas/water supply systems – Telecommunication networks
(Lykou et al., 2017)	'*greatly supports the smooth functioning of society's prosperity and viability of economies worldwide; services that are vital for business and for the quality of life of citizens*' (p. 1)	– Fixed installations (e.g. roads, railways, terminals [airports, railway and bus stations, seaports])
(Seager et al., 2017)	'*those* [services] *which are vital for protecting or providing essential human capabilities*' (p. 91)	– Organisations – Physical equipment
(Gonzva et al., 2016)	'*complex socio-technical systems in which the components are particularly interdependent* [and] *constitute the backbone of modern societies*' (p. 1)	– Physical structures – Transportation – Rail transport network
(Häring et al., 2016)	'*complex and interdependent* […] *socio technical systems*' (p. 272f)	– Technical and societal
(McGee et al., 2016)	'*risk relationships and resultant cascading effects*' (p. 146) and '*some may potentially be more "critical" than others*' (p. 151)	– Electric power – Communication network – Transportation systems – Water systems – SCADA and ICT systems
(Normandin and Therrien, 2016)	'*access to networks of resources; diverse components; skills and infrastructure in communication*' (p. 116)	– Housing/shelter – Medical capacity – Access/evacuation
(Schaberreiter et al., 2016)	'*provide services that are at the core of our modern society and a disruption or destruction of these services would have severe consequences for society and the economy*' (p. 668)	– Energy – Telecommunication – Information systems
(Katina and Keating, 2015)	'*provide goods and services that enable the maintenance and sustainment of public wellbeing including public safety, economic vitality, and security*' (p. 317)	– Roads, highways, hospitals – Electrical systems – Water systems – SCADA and ICT systems
(Di Maio, 2014)	'*aircraft (airborne or on the ground), airports – considered "soft targets" – and in general the infrastructures serving civil aviation*' (p. 1)	– Air traffic management – Air navigation service – Air transport
(Ouyang, 2014)	'*network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services*' (p. 44)	– Telecommunications – Electric power systems – Natural gas and oil – Banking and finance – Transportation – Water supply systems – Government services Emergency services
(Spyridopoulos et al., 2014)	'*interconnected networks* [whose] *essential service provision* [is] *of critical importance*' (p. 438f)	– Power production – Telecoms
(Johnsen and Veen, 2013)	'*railway tracks and signaling equipment [and] key communication infrastructure* "(p. 2f)	– Communication system – Railway
(Prelipcean, 2010)	'*deliver special services to clients*' (p. 220) "*assets* […] *critical to household's welfare*' (p. 223)	– Town halls, roads – Border police offices – Civil protection facilities
(van der Vleuten and Lagendijk, 2010b,a)	'*electric power grids count among the most 'critical' of all modern infrastructure*' (p. 2053) due to '*the massive societal and economic dependency on uninterrupted energy infrastructure services*' (p. 2042)	– Electric power grid – Gas supply networks
(Eusgeld and Kröger, 2008)	'*highly integrated and interdependent* […] *large scale interconnected* […] *system-of-systems (or meta-infrastructure system* […] *supplying goods and services* […] *perceived as common good*' (p. 1–2)	- Electric power supply – Telecom system

(*continued on next page*)

Table 4 (*continued*)

Author, year	*Definitions / Descriptions*	*Critical Infrastructures*
(Robert et al., 2008)	'*every-one is extremely dependent on Lifeline Networks, providing vital resources,* [that] *are interdependent on each other* [and] *increasingly automated and interlinked*' (p. 392f)	– Electricity system – Drinking water system – Transportation
(Sajeva and Masera, 2006)	'*composed of many constituent systems with multiple operators, but characterised by high levels of structural, functional, administrative and jurisdictional complexity*' (p. 380)	– Market and technical – Electric power supply – Oils, gas, water storage and delivery – Finance and insurance – ICT – Health end emergency – Law enforcement
(Gheorghe, 2004)	'*vital*' (p. 120) and '*complex and interdependent systems*' (p. 122)	

elements constitute infrastructure, and which functions can it serve (for an observer or user).

With regard to the first inquiry, several authors have addressed the system elements of infrastructure. One issue is that there is no precise designation of the level of abstraction regarding systems or infrastructure. Descriptions by Lykou et al. (Lykou et al., 2017) illustrate the dilemma of de–/composition. A detailed discussion of this example follows the presentation of descriptions and examples of critical infrastructure in Table 4.

Lykou et al. (Lykou et al., 2017) have noted that '[t]ransport is a[n] […] infrastructure that greatly supports' a society. Subsequently, they have stated that 'transport is the movement of people and goods from one location to another', which represents the service that the infrastructure enables or provides. This infrastructure has been further decomposed into transport infrastructure, vehicles and operations, the latter of which includes 'people, institutions, laws, policies, and information systems that convert infrastructure and vehicles into working transportation networks' (ibid). This example reveals that the particular meaning of the term 'infrastructure' depends on the context in which it is used and the perspective of an observer or user. The same applies with respect to ICT. Whereas Schaberreiter et al. (Schaberreiter et al., 2016) have indicated that 'infrastructures are *driven by* complex and interacting systems' (emphasis added), Spyridopoulos et al. (Spyridopoulos et al., 2014) have reported that 'Industrial Control Systems […] are of the most important components of National Critical Infrastructure'. Furthermore, Katina et al. (Katina et al., 2017) have acknowledged that ICT is both a prevalent controlling system for physical processes and an emerging infrastructure, and it is therefore becoming increasingly critical. Although the literature recognises workforce and institutional or legal regulation in the context of infrastructure, these elements are mainly considered operators or environmental factors of infrastructure. For example, Gonzva et al. (Gonzva et al., 2016), have perceived infrastructures as socio-technical systems, which entail the provision of a service and an amalgamated character of all operators or customers or both. Eusgeld and Kröger (Eusgeld and Kröger, 2008) have encouraged further research on 'whether or not the operating environment (in the wide sense, incl. socio-economic and institutional factors) needs to be considered'. However, this operative perspective of systems obscures the view of infrastructure as a necessary precondition for the production process of an intended service. For instance, many articles identify the transport system as infrastructure (Abedi et al., 2019; Antonsen et al., 2017; Cedergren et al., 2019; Coaffee and Clarke, 2017; Di Maio, 2014; Große and Olausson, 2019; Johnsen and Veen, 2013; Katina et al., 2017; Katina and Keating, 2015; Lykou et al., 2017; McGee et al., 2016; Normandin and Therrien, 2016; Ouyang, 2014; Gonzva et al., 2016; Große and Olausson; Prelipcean, 2010; Robert et al., 2008; Tehler et al., 2018). From the perspective of a consumer of transportation services, the availability of appropriate connections is a precondition for business, commuting or leisure activities, for example. Moreover, for the provision of transportation services, the existence of vehicles and qualified chauffeurs is a precondition. Similarly, for performing transportation, the established road or railway network is a precondition, and so on. Hence, all of these preconditions that are subsumed as infrastructure incorporate a *physical* layer of material, an *operative* layer of (man-) power and knowledge, and a *strategic* layer as an expression of will (i.e. strategic objectives about the purpose of the construction or service provision).

With regard to the second inquiry, all of the reviewed articles emphasise the dependency of the well-being of the final consumer—mostly aggregated to a regional society or national population—on the services that are provided upon and by infrastructures. As illustrated above, goods and services are framed as common goods similarly to the underlying infrastructures (Eusgeld and Kröger, 2008). Seager et al. (Seager et al., 2017) have further broadened this perspective by acknowledging 'infrastructure as the principal mechanism by which human rights are realized as human capabilities'. Accordingly, the authors have expressed the critique that, in many cases, the 'approach to critical infrastructure suffers from a misplaced emphasis on the physical condition of the infrastructure, rather than the services provided' (Seager et al., 2017). With regard to the deliberations above, the physical conditions of infrastructure are arguably often ignored; instead, the physical conditions of the operation process are considered. However, the key point of the discussion in Seager et al. (Seager et al., 2017) is that the resilience of infrastructure must take into account the various perspectives and capabilities of users, and it thus extends beyond the physical components, which necessitates both 'multiple adaptive pathways' and holistic, interdisciplinary research.

The majority of the reviewed articles assume that the system of interest continuously fulfils its function, and they thus consider deviant behaviour that requires particular action, such as the 'failure process' (Liu et al., 2017; Gonzva et al., 2016), 'process control' (Katina et al., 2017), 'the recovery process' (Liu et al., 2017; Prelipcean, 2010; McGee et al., 2016) or 'the integration process' (van der Vleuten and Lagendijk, 2010b). Many of the reviewed articles subsume regular iterations of a reference process as an operation; however, a few articles consider particular processes and their impacts on the evolving systems, such as the development of the European power grid and its properties (van der Vleuten and Lagendijk, 2010b,a), the process of developing and generating resilience (Häring et al., 2016) and the planning process for CIP in the Swedish context, which relies on an SoS (Große and Olausson, 2019; Große and Olausson). Ultimately, Coaffee and Clarke (Coaffee and Clarke, 2017) have argued that a more process-based viewpoint could facilitate the orchestration of a coherent, socio-technical and integrated approach in SoS.

The indicated interdependency of systems and processes as well as of produced services and goods and their consumers has accelerated alongside societal development. Such interdependency has two implications. First, if one process fails, then the subsequent processes are affected; this outcome is often referred to as that of cascading failures (Abedi et al., 2019; Katina and Keating, 2015; van der Vleuten and Lagendijk, 2010b; Große and Olausson; Seager et al., 2017). Second, it is difficult to identify the correct order of processes and the degree of dependence (i.e. the criticality of a delivering process under consideration of the potential consequences for customers). The review of the selected articles reveals several types of interdependency among infrastructures and between infrastructures and the environment. Many of the articles follow the classification from previous literature (Rinaldi et al., 2001), which is considered the only self-contained classification (Ouyang, 2014). Gheorghe et al. (Gheorghe et al., 2018) have expanded this list by extracting two aspects from the logical type: policy (regulation and procedural changes) and societal (effects of public opinion).

Several definitions of critical infrastructure and the services that it enables can be identified in public policies, which many of the articles adopt. For example, Gonzva et al. (Gonzva et al., 2016) have simply stated that 'critical infrastructures are considered as critical in view of populations' increasing dependence on them', whereas Coaffee and Clarke (Coaffee and Clarke, 2017) have stressed their 'potential to significantly affect public safety, security, economic activity, social functioning or environmental quality'. A similar view of (national) sovereignty has been adopted by Ouyang (Ouyang, 2014) in noting that '[s]ystems whose incapacity or destruction would have a debilitating impact on the defense and economic security are regarded as critical'. In addition, Sajeva and Masera (Sajeva and Masera, 2006) have mentioned that infrastructure 'is considered to be critical when its partial or total inability would affect the security and social welfare of a given context, sometimes at the national or the international level'. The label of 'critical' indicates the existence of its counterpart—namely infrastructure that is less or non-critical—which in turn implies that a classification scale can be used to assess criticality [see e.g. Fekete, 2011; Fekete et al., 2012]. In addition, several authors have noted that each stakeholder tends to concentrate on his or her own values and their relation to the potential risk (Antonsen et al., 2017; Gheorghe et al., 2018; Große and Olausson, 2019; Sajeva and Masera, 2006; van der Vleuten and Lagendijk, 2010b; Große and Olausson).

The notations of key resources and key assets emerged from the literature review and are interrelated with critical infrastructures and the essential goods and services that are produced and delivered by them. Although damage or destruction of a key asset would not necessarily affect human existence, its symbolic, economic or societal value suggests that severe disturbances or loss of life could occur in society if such key asset is the target of an attack (Katina et al., 2019; Gheorghe et al., 2018; Gheorghe et al., 2018; Fekete et al., 2012). Key resources are those that are necessary for a process but which, because of their scarcity, limit the capacity of processes (e.g. those whose results are critical for a subsequent consumer, such as further processes or society). Depending on the type of process, such key resource can be natural, material, computational, informational, organisational, or related to people and services. The reviewed articles cite examples of key resources with respect to their limited availability, such as railways (Cedergren et al., 2019), electricity (Große and Olausson, 2019; Robert et al., 2008), drinking water (Robert et al., 2008), telecommunications (Robert et al., 2008) and orbital bands (Gheorghe et al., 2018).

The majority of the articles stress the need to protect critical infrastructure from disturbances and safeguard the dependent society from potentially disastrous consequences. Robert et al. (Robert et al., 2008) has noted that 'it is crucial to protect interdependent networks' since 'the loss of an LN [lifeline network] is [...] likely to result in major crises'. Although the common label of such networks has changed to'critical infrastructures', as previously discussed, such protection can involve many challenges, especially given the scarcity of resources and the interdependencies of infrastructures (Gheorghe et al., 2018) as well as the ambiguity of concepts and policies. Gheorge (Gheorghe, 2004) has stated that '[p]roblems come from solutions', which indicates that recent developments in society with regard to technology, population, politics and environmental factors are likely to broaden the spectrum of challenges in the context of CIP.

Cedergren et al. (Cedergren et al., 2019) have recently discovered that 'restructuring of the [railway] sector has created long-term challenges related to balancing the use of the infrastructure with a sufficient level of maintenance', which confirms the above argument that infrastructure is frequently overlooked in both theory and practice for the benefit of a higher efficiency of operation. Katina et al. (Katina et al., 2019) have called for more comprehensive problem formulations beyond technology-only solutions that also expand the boundaries of the investigated system and involve 'the wider array of human/social, organisational/managerial and policy/political aspects influencing' developments in critical infrastructure and technology. Research has highlighted additional emerging aspects that deserve consideration in the context of CIP, such as legal regulation and economic calculation and information security in a comprehensive sense (Antonsen et al., 2017; Di Maio, 2014; Gheorghe et al., 2018; Große and Olausson, 2019; Johnsen and Veen, 2013; Spyridopoulos et al., 2014; Große and Olausson; Schaberreiter et al., 2016). Many of the investigated articles emphasise a focus on resilience as a complement to or substitute for technology-focused CIP. In contrast, Häring et al. (Häring et al., 2016) have adopted the opposite position with the advice 'to deliberately limit the scope of Resilience Engineering towards engineering, i.e. mainly technological solutions'. According to these findings, there is a heightened demand for multidisciplinary research to obtain more integrated solutions, yet scholars and practitioners are still challenged by the complexity of the task, institutional and disciplinary boundaries and limitations regarding methodologies, and issues of long-term funding and imagination (Seager et al., 2017).

Coaffee and Clarke (Coaffee and Clarke, 2017) have contrasted protection and resilience as the poles of the CIP spectrum. Thereby, protection is portrayed in a 'hard', technical sense, while resilience is assigned a 'flexible', socio-technical character. Although this classification seems enticing, it presents two flaws. First, it still neglects the purpose of both topics for society, which entails how the functionality of critical infrastructure affects dependent people. Second, it improperly meshes perspectives of systems and infrastructures, as the previous discussions have explained. However, *protection* is an expression of will (i.e. a strategic objective) under which a system is approached from the outside through activities such as risk and vulnerability analyses, planning, implementation of measures, and monitoring of realised and emerging effects. In accordance with the key points of the article, this CIP must concern the socio-technical system that executes processes upon infrastructures, apply a multi-focal perspective of both short- and long-term goals and develop adequate margins to balance disturbances in a flexible manner. Thus, *protection* actively aims to influence the *adaption*, *emergence* and *entropy* of a system by mediating hardening and awareness, efficiency and redundancy, and dependence and autonomy. Consequently, *resilience* is a behaviour of the system itself that results from its capability to handle its vulnerabilities through adaption and emergence.

4.3. *Expressions of governance*

The literature review discovered a broad range of applications with regard to the concept of governance. Table 5 illustrates the usage of the term 'governance' as it appears in the reviewed articles and excludes those that do not define the concept. In their article, Sajeva and Masera (Sajeva and Masera, 2006) extensively explore the concept of governance in terms of the risk of infrastructures in the European context. They notice the difficulty of simply defining governance given that 'it has different meanings for different people, according to the level at which it is applied, the goals to be achieved and the preferred approach' (Sajeva and Masera, 2006). Such difficulty has also been acknowledged by other authors (Coaffee and Clarke, 2017; Gheorghe, 2004; Gheorghe et al., 2018; Große and Olausson, 2019; Große and Olausson). Moreover, Sajeva and Masera (Sajeva and Masera, 2006) have remarked that governance entails the inclusion and co-operation of public and private stakeholders to approach complex problems, which are labelled 'systemic risks' (Prelipcean, 2010; Eusgeld and Kröger, 2008; Gheorghe, 2004). In contrast with traditional government, many of the articles indicate that governance implies broader participation, informed decision-making and a commitment of participants to deliberate action for governing. Such approach has a multitude of applications to, for example, organisational, public–private, national or transnational contexts as well as complex, socio-technical SoS, such as societies or critical infrastructures. Sajeva and Masera (Sajeva and Masera, 2006) have further opined that governance acts 'as an interface among the stakeholders, as the source of information and support for strategic decisions, and as the instrument through which the principle of accountability can be properly implemented'.

Table 5
Appearance and Definitions of Governance in the Reviewed Articles.

Author, year	*Usage of the term governance*	*Nature / Tasks*
(Cedergren et al., 2019)	'*the governance system* […] [is] *(overly) generous with allowance of train operation at the expense of granting access to maintenance operations*' (p. 6)	– Resource allocation – Co-ordination
(Große and Olausson, 2019)	'*The concept of governance is the common element of the continuum that extends from traditional top-down control on one end to self-organisation and networks on the other [regarding] the management of society*' (p. 425)	– Network management – Control/co-ordination – Information and communication – Integration
(Katina et al., 2019)	'*a mechanism for providing oversight, accountability and congruent direction*' (p. 123)	– Identity and vision – Communication and integration – Management
(Große and Olausson)	'*The concept of governance describes how a society is organized, governed and who is involved in dialogue, participation, and networking*' (p. 1894)	– Policy and identity – Network for steering – information and communication – Management
(Gheorghe et al., 2018)	'*relates not just to decision making, but also to the tools, mechanisms, organizations, and mental modes that influence that decision making*' (p. 558)	– International – Public-private policies – Management
(Antonsen et al., 2017)	'*Risk governance processes are usually focused on individual enterprises, overlooking important interorganizational issues*' (p. 1837)	– Governmental supervision – Policies and regulation
(Coaffee and Clarke, 2017)	'*the changing material politics, geographies and governance arrangements associated with critical infrastructure* [are] *the 'collective equipment' of state power* […] *by which control might be exerted, socio- economic restructuring advanced and inequity concretised*' (p. 364)	– Organisational – Governmental – Policies and principles – Management – Risk analysis
(Katina et al., 2017)	'*is focused on design, execution, and evolution of 'metasystem' functions necessary to provide for [sic] communication, control, coordination, and integration (C3I) in CPS* [cyber-physical systems]' (p. 168)	– Cybernetic – Management – Organisational – Integration
(Lykou et al., 2017)	'*governance (i.e. regulations, legislations, and guidance)*' (p. 5); '*effective transport governance for adaptation are 'soft' type* […] [i.e.] *creating the appropriate framework to enable adaptation action at local and regional level*' (p. 9)	– Governmental policy – Resource allocation – Planning/co-ordination – Management
(Seager et al., 2017)	'*refers to the combination of laws, protocols, and norms that dictate decision-making activities taken for service provision*' (p. 99)	– Policy – Administrative structures – Functional layering
(Gonzva et al., 2016)	'*the city is composed of different elements* […] *organized by governance*'(p. 2)	– Steering and organising – Holistic understanding
(Normandin and Therrien, 2016)	'*governance role played by local governments*' (p. 112)	– Government
(Schaberreiter et al., 2016)	'*is organized using a multi-stakeholder approach, complemented by a global forum to address core Internet decisions*' (p. 670)	– Policy – Norms and laws
(Katina and Keating, 2015)	'*private–public governance policies*' (p.318)	– Governmental action
(Di Maio, 2014)	'*means the importance of coordinate people, processes and technology to govern security "end to end"*' (p. 6)	– Policy – Management – Control & integration
(Spyridopoulos et al., 2014)	'*establishing a baseline of the current information security operations system*' (p. 441)	– Policy – Goal setting
(Prelipcean, 2010)	'*The governance* [of] *risk should avoid a inadequate/ poor governance*' (p. 222)	– Official action – Communication
(van der Vleuten and Lagendijk, 2010b, a)	'*the very perception of Europe's decentralized power infrastructure and governance as "vulnerable" is contested and bound up with current re-negotiations of transnational electricity infrastructure governance*' (p. 2046)	– Political influences – Governmental rules – Steering networks – Management
(Sajeva and Masera, 2006)	'*is a decision-oriented management process by which public and private actors jointly deal with societal sensitive and complex issues*' (p. 384)	– Public-private – Management – Co-operation
(Gheorghe, 2004)	'*asks for 'scientific analysis of risks, integration of societal perception and amplification of risk into the risk assessment process, structuring decision making in a consistent rational and democratic way (with a multitude of 'abstract' societal values involved) to transparent and open communication*'' (p. 123)	– Policy – Management – Public-private – Trans-cultural

In general, the presence of the term 'governance' in the articles creates a close relationship to manifestations of will in the form of policy documents. Although the literature often directly or indirectly addresses the political/public will and official policies, some of the articles focus on organisational or corporate governance, the management of public–private partnerships or processes of decision-making (Antonsen et al., 2017; Di Maio, 2014; Große and Olausson, 2019; Katina et al., 2019; Katina and Keating, 2015; Sajeva and Masera, 2006; Große and Olausson; Prelipcean, 2010). In addition, Sajeva and Masera (Sajeva and Masera, 2006) have provided an overview of principles for good governance that public policies have stated. Considering such policy documents, there is evidently a strong focus on operative processes of policy-making and implementation that aim to be open, participatory, transparent, accountable and coherent (Sajeva and Masera, 2006). However, the strategic perspective of visions, strategic objectives and long-term goals is underrepresented in the reviewed articles.

Gheorghe (Gheorghe, 2004) has emphasised a need for appropriate governance that accounts for the complexity of critical infrastructure and societal systems. Likewise, Coaffee and Clarke (Coaffee and Clarke, 2017) have requested 'new modes of equitable governance across multiple systems, networks and scales'. Some authors have suggested concrete targets and measures, such as planning for adaption to climate change (Lykou et al., 2017), governing technology development (Katina et al., 2017; Katina et al., 2019), managing public resources (Prelipcean, 2010; Cedergren et al., 2019; Gheorghe et al., 2018; Johnsen and Veen, 2013), simultaneously ensuring openness and freedom of the Internet and information security (Schaberreiter et al., 2016) and considering centralised or decentralised approaches (Di Maio, 2014; Normandin and Therrien, 2016; van der Vleuten and Lagendijk, 2010b,a; Seager et al., 2017).

Many of the reviewed articles recognise that it is difficult for governance to effectively implement measures that impact the private sphere, which is encouraged to comply with public policies. To enhance adherence, several authors have promoted incentives as a means of managing such implementations (Seager et al., 2017; Lykou et al., 2017; Sajeva and Masera, 2006; Schaberreiter et al., 2016; Cedergren et al., 2019; Tehler et al., 2018; Gheorghe et al., 2018).

Apart from presenting several perspectives on governance, Katina et al. (Katina et al., 2019) have concluded that governance not only relates to the nature of a system of interest but also 'involves three essential aspects: direction, oversight and accountability'. This perception of governance seems to adopt the concept of the'organism' (see Section 2.1), wherein a governance network constitutes the head of the system, and is referred to as a *meta*-system (Katina et al., 2017). This *meta*-system intends to govern a complex system and unites the management of an operating system and strategic development. However, the aforementioned perspective of a governance system as the head of a system has blurred the transparent and participatory nature of governance, as already described, which can be ascribed to the fact that transparency and participation are acknowledged as resource-consuming (Sajeva and Masera, 2006). Sajeva and Masera (Sajeva and Masera, 2006) have further remarked that in specific contexts, such as that of Sweden, co-operative and participatory decision-making may be expected, while steering in the form of rigid directing is considered rude and disrespectful.

One-third of the articles do not contribute to a deeper understanding of the concept of governance, which may reflect the mentioned ambiguity. On the one hand, the reviewed articles view governance as *Gegenbegriff* to government concerning the entire continuum of modes of steering that deviate from rigid, top-down steering towards self-organising networks; on the other hand, they perceive governance as *Oberbegriff* with reference to all types of steering in which the governing body is not clearly identified and addressed.

The deliberations above illustrate that governance is a multi-faceted, multi-layered and recursive concept that is similar to those of systems and infrastructure, because of which a system-theoretical perspective can facilitate analysis and a clearer understanding. Specifically, governance mainly concerns the steering of another system with the aid of policy networks and related processes which also entails the management of the policy process and the existence of higher-level, strategic objectives.

5. Discussion

The previous sections have clarified the origins, interpretations and current use of the concepts of system, infrastructure and governance in scientific literature and emphasised their recursive, multi-level structure. A specific focus was on a system's structure, represented by components, interactions and an environment, its properties, such as adaption, emergence and entropy, and its delineation by a particular purpose. The review concentrated on the systems of infrastructure and governance and their representations in scientific literature. The analysed body of knowledge demonstrates that a system perspective is a valuable anchor to understand, develop and maintain safe and reliable infrastructure and the steering of such complex systems, albeit in occasionally vague terms. However, interrelations and interdependencies among these concepts, system levels and processes reveal the complexity of the examined concepts.

First, to facilitate system understanding and further analysis, a system's structure needs consideration. For example, infrastructure can be associated with a network of fixed assets, such as roads or railways, or with a network of busses or airplanes providing transport services, or both. It can further involve different levels of steering, such as car driving, traffic control, public transport administration or transport policy. In turn, governance networks concerned with transportation issues can also work at different levels, such as strategical, managerial or operational levels. In the review, the human actors appear however often vaguely in the periphery, which leaves ample room for interpretation in terms of whether they are part of the system or belong to an environment. Despite developments in the perception and design of socio-technical systems—particularly with regard to ICT and its tendency to entangle technical systems and interconnect them with social systems (Mumford, 2006), it seems that those systems are still threated separately rather than as a unit because of greater heterogeneity and complexity (Katina and Keating, 2015; von Bertalanffy, 1950). Thus, the literature review revealed a need to enhance the general understanding of the recursive multi-level character of systems, such as infrastructure and its governance, whereas a tripartite structure could achieve more clarity in public and scientific debate. As Fig. 1 exemplifies, integrated system analysis needs to address the structure, properties and delineation of a particular SoS to clarify its character.

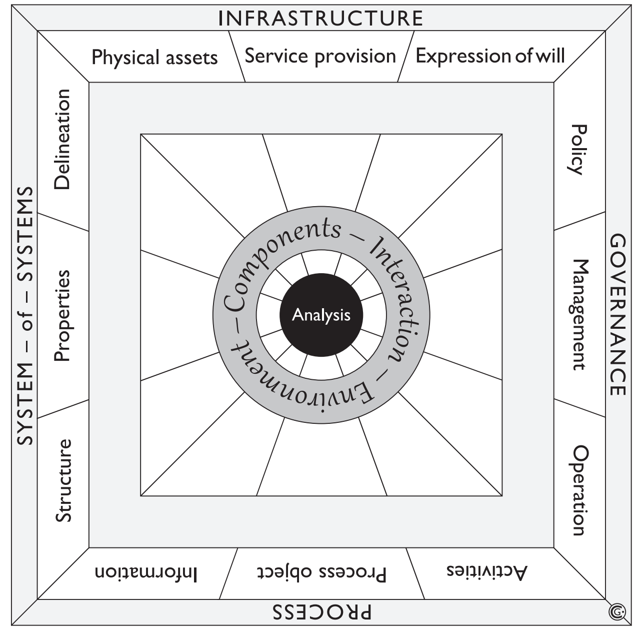

Fig. 1. System Analysis Perspectives
adopted from Große, 2021

Associated with infrastructure, such triad consists of fixed/physical assets, service provision and an expression of will. Consequently, the specification of the system of interest, for example by describing the constituting components, interactions and environment, warrants further attention in studies of networks that represent (critical) infrastructure and governance systems as well as their particular properties and processes.

Second, a proper understanding of fundamental system properties is important to examine a concrete representation in practice. For example, concepts regarding complex adaptive systems have been applied for modelling and simulating non-deterministic and dynamic phenomena in complex systems and to model complex social systems (Onik et al., 2016). In addition, the strong focus on interactions and interdependencies is apparent in the sociological view of social systems. Thus, the understanding of systems as complex adaptive provides valuable concepts for integrating several perspectives to approach SoS in a multi-disciplinary manner. The literature review revealed also some difficulties with system properties such as complexity, emergence and entropy. For example, one article depicts the complexity of a system as means that 'allows to divide it into elementary, constitutive, and especially independent subsystems in a transitory manner' [Gonzva et al., 2016, p. 2]. However, this description is contradictory and refers to the concept of abstraction that is considered a means of handling complexity when modelling a system by 'zooming out' of the considered real system, which is accompanied by a lesser richness of detail (Stachowiak, 1973). Another example have claimed that interactions between components at a micro-level cause macroscopic properties of a social system, such as emergence (Normandin and Therrien, 2016). However, the specification of emergent behaviour in complex systems remains vague, which indicates that further research must address this issue. Similarly, the concept of entropy is important for understanding complex systems;

however, its application can be challenging. For example, one article employs a pair of contrasting concepts, namely negentropy and entropy, but struggles with the accurate interpretation and classification of resilience factors that emerge from interaction within a social system (Normandin and Therrien, 2016). However, a more consistent adoption of the concept of entropy mainly relates it to the decay of a system, which either engages in an exchange with its environment to obtain capacity for further activity or uses certain isolation to reach a maximum of entropy (i.e. an indelible incapacity to act). Such termination of the purpose-giving processes within a system signifies the termination of the system itself, which does not necessarily apply to its components. This connection illustrates both the interdependency between systems and the relation of entropy to a certain process (or purpose).

Third, the purpose of a system thus necessitates special emphasis. The review indicates that the system of interest is often deliberately limited to a certain, purpose-giving process, such as transportation or policy-making. It further revealed that more clarity about the level of abstraction is advisable, which means that the deliberate delimitation of the system to be examined, for example by a particular process, could further improve the comprehensibility and usefulness of specific analyses of infrastructure or governance networks. In this regard, processes and process landscapes facilitate transparency and evaluability of activities of the governed system(s), which in turn enables constructive feedback for the governing system(s). Systemic thinking in establishing and evaluating processes must thus not only include proper systematics in the particular processes but also consider the dynamics within the governing and governed system, and the relations between them and their environments. Process hierarchies and interdependencies require similar proper consideration as those associated with systems, infrastructure and governance. Contemplations about a purpose-giving process (e.g. public transport) include information about its objectives (e.g. number/amount of passengers/freight per week) and intended conduct (e.g. mode of transportation), process objects (e.g. passengers or goods) and activities (e.g. stops at stations, transport, or payment) that are performed by persons, tools and technologies (i.e. the system of interest). The review illustrated that systems, infrastructure and governance are multi-faceted, multi-layered and recursive concepts. Specifically, governance processes mainly concern the steering of another system with the aid of policy networks, wherein the implementation of policies and the execution of measures relate to the managerial and operational functions of subordinate systems. However, the policy creation and development process can be viewed as an operational task which also entails the management of this process and the existence of higher-level visions, strategic objectives and process goals, which manifest through the initial step of the policy process, comprising problem recognition and agenda setting.

6. Concluding remarks

The research for this article conducted a systematic literature review that focused on how recent literature communicates and applies the multi-facetted concepts of systems, infrastructure and governance. This article provides a comprehensive overview about relevant theoretical foundations with regard to structure, properties and purpose of systems, infrastructure and governance and their applications in current research in the CIP field, for example related to transportation, energy supply and ICT. To this end, the results not only summarise the content of the included literature but also discuss the system-theoretical foundation in the CIP field and related areas, concerned with systems analysis and resilience engineering to enhance societal safety and security. To support further progression of these research areas, this article contributes with both a conceptual study of the terms system, infrastructure and governance and a detailed review of the state of the art regarding these concepts in the current scientific literature to an enhanced understanding of the theoretical foundations of the CIP field.

The provided overview substantiates a comprehensive understanding of CIP and its governance. Infrastructure is mainly perceived as an always-existing common good, whereas the interconnected processes and governance are underrepresented. However, reliable functionality of important societal functions depends on not only fixed or physical assets but also multi-level systems that perform interrelated processes, such as operation, maintenance and development (i.e. management), and decision-making (i.e. governance) regarding operational, managerial and strategic objectives. This study views CIP as a common, societal concern that is located in the field of governance between governmental control and competitive market dynamics as well as the private sphere of citizens. Protection is thereby an expression of will (of a steering entity) under which the system of critical infrastructure is approached from outside. Thus, CIP actively aims to influence adaption, emergence and entropy of this SoS by mediating between hardening and awareness, efficiency and redundancy, and dependence and autonomy. In turn, the governance of CIP similarly concerns the SoS of public and private actors that effectuates CIP, which consequently involves relations to and between the sub-levels of the governed and governing systems. However, the recursive and multi-level nature of the involved systems of infrastructure and governance provides degrees of complexity, ambiguity and uncertainty that are difficult to manage. One explanation of such limitations refers to the interdependency between the extent of the system to govern and the governing system. As outlined, the complexity of the SoS of critical infrastructure requires similarly complex systems to organise and govern CIP. In contrasting government and governance as the two ends of the spectrum of steering modes, research has attributed rigid hierarchy and bureaucratic processes to the former while viewing the latter as a 'knight in shining armour' that is fully capable of steering the dynamics of the complex SoS through self-organising networks. Nevertheless, the findings indicate that both steering modes present advantages and disadvantages. A proper balance between these contrapositions can enable a systemic mode of steering that actively addresses ambiguity and uncertainty, which are inherent to the context of CIP, by integrating governance, management and leadership efforts.

Another fundamental aspect for understanding infrastructure and governance is the difference between systems and processes. The existence of a system can be independent of the process that it is intended to facilitate, whereas a process relies on an executing system. This difference implies that they are not easily interchangeable, particularly when the executing system is an SoS, and sub-levels relate to different parent systems. Conflicts can emerge in the sphere of the various actors in the form of, for example, other tasks or competing goals. In addition, a process can contain one or more sub-levels, while each process activity can be decomposed into a sub-process (e.g. at a certain actor). Complexity intensifies if an activity is part of multiple processes and involves a specific executing system which also interrelates with the mentioned SoS. Hence, the governance network needs to drive an understanding of the CIP system's structure, its properties and processes at both the general and sub-levels to facilitate alignment and further development.

CRediT authorship contribution statement

Christine Große: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abedi, A., Gaudard, L., Romerio, F., 2019. Review of major approaches to analyze vulnerability in power system. Reliab. Eng. Syst. Saf. 183, 153–172. https://doi.org/10.1016/j.ress.2018.11.019.

Ackoff, R.L., 1971. Towards a System of Systems Concepts. Manag. Sci. 17 (11), 661–671.

Ahrens, J., Rudolph, P.M., 2006. The Importance of Governance in Risk Reduction and Disaster Management. J Contingencies & Crisis Man 14 (4), 207–220. https://doi.org/10.1111/j.1468-5973.2006.00497.x.

Antonsen, S., Bodsberg, L., Kringen, J., 2017. In: User Needs for Resilience indicators in Interconnected Critical Infrastructures. CRC Press, Milton, pp. 1836–1868.

Ashby, W.R., 1956. An Introduction to cybernetics. Chapman & Hall, London.

Avison, D.E., Taylor, V., 1997. Information systems development methodologies: A classification according to problem situation. J. Inf. Technol. 12 (1), 73–81. https://doi.org/10.1080/026839697345224.

Bar-Yam, Y., 2009. General Features of Complex Systems. In: Kiel, L.D. (Ed.), Knowledge Management, Organizational Intelligence and Learning, and Complexity. Eolss Publishers, Oxford.

Becker, J., Schütte, R., 2004. Handelsinformationssysteme, 2nd ed. Redline Wirtschaft bei Verl. Moderne Industrie, Frankfurt am Main.

Becker-Beck, U., 1997. Soziale Interaktion in Gruppen. VS Verlag für Sozialwissenschaften, Wiesbaden.

Beer, S., 1995. Brain of the firm, 2nd ed. John Wiley & Sons, Chichester.

Bierhoff, H.W., Frey, D., 2017. Kommunikation. Interaktion und soziale Gruppenprozesse. Hogrefe Verlag GmbH & Co, KG.

Bräuer, H., 2005. Interaktionsprozesse in Lerngruppen [University Lüneburg. Dissertation]; University, Lüneburg.

Breuer, F., Mruck, K., Roth, W.-M., 2002. Subjektivität und Reflexivität: Eine Einleitung/ Subjectivity and Reflexivity: An Introduction. Forum Qualitative Sozialforschung / Forum Qualitative Social Research 2002;3(3):Art. 9.

Cedergren, A., Lidell, K., Lidell, K., 2019. Critical infrastructures and the tragedy of the commons dilemma: Implications from institutional restructuring on reliability and safety. J. Contingencies Crisis Manage. https://doi.org/10.1111/1468-5973.12262.

Checkland, P.B., 1989. Soft Systems Methodology. Hum. Syst. Manag. 8, 273–289.

Clausius, R., 1850. Ueber die bewegende Kraft der Wärme und die Gesetze, welche sich daraus für die Wärmelehre selbst ableiten lassen. Ann. Phys. Chem. 155 (3), 368–397. https://doi.org/10.1002/andp.18501550306.

Clausius, R., 1850. Ueber die bewegende Kraft der Wärme und die Gesetze, welche sich daraus für die Wärmelehre selbst ableiten lassen. Ann. Phys. Chem. 155 (4), 500–524. https://doi.org/10.1002/andp.18501550403.

Clausius, R., 1865. Ueber verschiedene für die Anwendung bequeme Formen der Hauptgleichungen der mechanischen Wärmetheorie. Ann. Phys. Chem. 201 (7), 353–400. https://doi.org/10.1002/andp.18652010702.

Coaffee, J., Clarke, J., 2017. Realising critical infrastructure resilience. In: Linkov, I., Palma-Oliveira, J.M. (Eds.), Resilience and Risk: Methods and Application in Environment, Cyber and Social Domains. Springer, Netherlands; Springer, Dordrecht, pp. 359–380.

Cohen, F., 2010. What makes critical infrastructures Critical? Int. J. Crit. Infrastruct. Prot. 3 (2), 53–54. https://doi.org/10.1016/j.ijcip.2010.06.002.

Colebatch, H.K., 2014. Making sense of governance. Policy and Society 33 (4), 307–316. https://doi.org/10.1016/j.polsoc.2014.10.001.

Davenport, T.H., 2017. New Industrial Engineering: Information technology and business process redesign (classic reprint). FORGOTTEN BOOKS.

Davenport, T.H., Short, J.E., 1990. The new industrial engineering: Information technology and business process redesign. Sloan Manage. Rev. 31 (4).

DeLaurentis, D., 2007. Role of Humans in Complexity of a System-of-Systems. In: Duffy VG, editor. Digital human modeling: Proceedings of the First International Conference on Digital Human Modeling, (ICDHM 2007). Berlin, Heidelberg: Springer, p. 363–371.

Di Maio, F., 2014. Centralized security governance for air navigation services: Innovative strategies to confront emerging threats against Civil Aviation. In: Garzia, F., Pritchard, D.A., Thomas, G. (Eds.), Proceedings - International Carnahan Conference on Security Technology. IEEE, Lexington KY, pp. 1–6.

Easton, David, 1965. A systems analysis of political life. Wiley, New York, NY.

Ellis, B., Herbert, S.I., 2011. Complex adaptive systems (CAS): an overview of key elements, characteristics and application to management theory. Inform. Prim. Care 19, 33–37.

Emery, F.E., Trist, E.L., 1960. Socio-technical systems. In: Churchman, C.W., Verhulst, M. (Eds.), Management Science Models and Techniques, 2nd ed. Pergamon, pp. 83–97.

Espejo, R., Harnden, R. (Eds.), 1992. The Viable System Model: Interpretations and Applications of Stafford Beer's VSM. Wiley, Chichester.

European Commission, 2004. Communication from the Commission to the Council and the European Parliament: Critical Infrastructure Protection in the fight against terrorism. Brussels.

Eusgeld, I., Kröger, W., 2008. Towards a framework for vulnerability analysis of interconnected infrastructures. In: 9th International Conference on Probabilistic Safety Assessment and Management (PSAM) 2008; 2008, p. 475–483.

Fekete, A., 2011. Common criteria for the assessment of critical infrastructures. Int. J. Disaster Risk Sci.s 2 (1), 15–24. https://doi.org/10.1007/s13753-011-0002-y.

Fekete, A., Lauwe, P., Geier, W., 2012. Risk management goals and identification of critical infrastructures. Int. J. Crit. Infrastructure 8 (4), 336–353. https://doi.org/10.1504/IJCIS.2012.050108.

Gheorghe, A.V., 2004. Risks, vulnerability, sustainability and governance: A new landscape for critical infrastructures. Int. J. Crit. Infrastruct. 1 (1), 118–124. https://doi.org/10.1504/IJCIS.2004.003801.

Gheorghe, A.V., Masera, M., Vries, D.L., Weijnen, M. (Eds.), 2006. Critical Infrastructures at Risk: Securing the European Electric Power System. Springer, Dordrecht.

Gheorghe, A.V., Georgescu, A., Bucovețchi, O., Lazăr, M., Scarlat, C., 2018. New Dimensions for a Challenging Security Environment: Growing Exposure to Critical Space Infrastructure Disruption Risk. Int. J. Disaster Risk Sci. 9 (4), 555–560. https://doi.org/10.1007/s13753-018-0197-2.

Gheorghe, A.V., Vamanu, D.V., Katina, P.F., Pulfer, R., 2018. Critical Infrastructures, Key Resources, and Key Assets. In: Gheorghe, A.V., Vamanu, D.V., Katina, P.F., Pulfer, R. (Eds.), Critical Infrastructures, Key Resources, and Key Assets. Netherlands, Springer, pp. 3–37.

Gonzva M, Barroca B, Gautier P-E, Diab Y. Analysis of disruptions cascade effect within and between urban sociotechnical systems in a context of risks. In: Lang M, Klijn F, Samuels P, editors. E3S Web of Conferences: 3rd European Conference on Flood Risk Management (FLOODrisk 2016). Lyon, France; 2016, p. 7008.

Griffin, L., 2010. Governance innovation for sustainability: Exploring the tensions and dilemmas. Env. Pol. Gov. 20 (6), 365–369. https://doi.org/10.1002/eet.555.

Große, C., 2020. Towards systemic governance of critical infrastructure protection: State and relevance of a Swedish case. Mid Sweden University, Sundsvall.

Große, C., Olausson, P.M., 2019. Blind spots in interaction between actors in Swedish planning for critical infrastructure protection. Saf. Sci. 118, 424–434. https://doi.org/10.1016/j.ssci.2019.05.049.

Große C, Olausson P.M. Swedish multi-level planning system for critical infrastructure protection: The regional core. In: Haugen S, Barros A, van Gulijk C, Kongsvik T, Vinnem J-E, editors. Safety and Reliability - Safe Societies in a Changing World - Proceedings of the 28th International European Safety and Reliability Conference, ESREL 2018, June 17-21, 2018, Trondheim, Norway. Boca Raton, Florence: CRC Press LLC; Taylor & Francis Group [distributor]; 2018, p. 1893–1902.

Große C. The Kaleidoscope for Integrative System Analysis – KISA. In: Castanier B, Cepin M, Bigaud D, Berenguer C, editors. Proceedings of the 31st European Safety and Reliability Conference (ESREL 2021). Singapore: Research Publishing Services; 2021, p. 1191–1198.

Grzeszczak, R., 2015. The Concept and Practice of Good Governance in the European Union. Int. J. Law Polit. Sci. 9 (2), 449–453.

Habermas, J., 1981. Theorie des kommunikativen Handelns: Handlungsrationalität und gesellschaftliche Rationalisierung (I); Zur Kritik der funktionalistischen Vernunft (II), 1st ed. Suhrkamp, Frankfurt am Main.

Häring I, Scharte B, Hiermaier S. Towards a novel and applicable approach for Resilience Engineering. In: Stal M, Sigrist D, Wahlen S, Portman J, Glover J, Bernable N et al., editors. Proceedings of the 6th International Disaster and Risk Conference: Integrative Risk Management - towards resilient cities. Davos; 2016, p. 272–276.

Henry, A.D., 2011. Ideology, Power, and the Structure of Policy Networks. Policy Stud. J. 39 (3), 361–383. https://doi.org/10.1111/j.1541-0072.2011.00413.x.

Hill, M.J., Varone, F., 2017. The public policy process. Routledge Taylor & Francis Group, London, New York.

Hokstad, P., Utne, I.B., Vatn, J. (Eds.), 2012. Risk And interdependencies in CriticAl InfrAstructures: A Guideline for AnAlysis. Springer, London.

Holland, J.H., 2006. Studying Complex Adaptive Systems. Jrl Syst Sci & Complex 19 (1), 1–8. https://doi.org/10.1007/s11424-006-0001-z.

Ison, R., Alexandra, J., Wallis, P., 2018. Governing in the Anthropocene: Are there cyber-systemic antidotes to the malaise of modern governance? Sustain. Sci. 13 (5), 1209–1223. https://doi.org/10.1007/s11625-018-0570-5.

Jann, W., Wegrich, K., 2007. Theories of the Policy Cycle. In: Fischer, F., Miller, G., Sidney, M.S. (Eds.), Handbook of Public Policy Analysis: Theory, Politics, and Methods. Taylor & Francis, Boca Raton.

Johnsen, S.O., Veen, M., 2013. Risk assessment and resilience of critical communication infrastructure in railways. Cogn. Tech. Work 15 (1), 95–107. https://doi.org/10.1007/s10111-011-0187-2.

Johnson, R.B., Onwuegbuzie, A.J., Turner, L.A., 2007. Toward a Definition of Mixed Methods Research. J. Mixed Methods Res. 1 (2), 112–133. https://doi.org/10.1177/1558689806298224.

Katina, P.F., Keating, C.B., 2015. Critical infrastructures: A perspective from systems of systems. Int. J. Crit. Infrastruct. 11 (4), 316–344. https://doi.org/10.1504/IJCIS.2015.073840.

Katina, P.F., Keating, C.B., Gheorghe, A.V., Masera, M., 2017. Complex system governance for critical cyber-physical systems. Int. J. Crit. Infrastruct. 13 (2–3), 168–183. https://doi.org/10.1504/IJCIS.2017.088230.

Katina, P.F., Keating, C.B., Sisti, J.A., Gheorghe, A.V., 2019. Blockchain governance. Int. J. Crit. Infrastruct. 15 (2), 121–135. https://doi.org/10.1504/IJCIS.2019.098835.

Keating, C.B., 2014. Governance implications for meeting challenges in the system of systems engineering field. In: Cook, S. (Ed.), Piscataway. IEEE, NJ, pp. 154–159.

Keating CB, Bradley JM. Complex system governance reference model. IJSSE 2015;6(1/2):33. https://doi.org/10.1504/IJSSE.2015.068811.

Keating, C.B., Katina, P.F., Bradley, J.M., 2014. Complex system governance: Concept, challenges, and emerging research. IJSSE 5 (3), 263–288. https://doi.org/10.1504/IJSSE.2014.065756.

Keating, C.B., Katina, P.F., Bradley, J.M., 2015. Challenges for Developing Complex System Governance. In: Cetinkaya, S., Ryan, J.K. (Eds.), Proceedings of the 2015 Industrial and Systems Engineering Research Conference, p. I1401.

Kelley, H.H., Holmes, J.G., Kerr, N.L., Reis, H.T., Rusbult, C.E., van Lange, P.A.M., 2003. An Atlas of Interpersonal Situations. Cambridge University Press, Cambridge.

Kelley, H.H., Thibaut, J.W., 1978. Interpersonal relations: A theory of interdependence. Wiley, New York, NY.

Lasswell, H.D., 1948. Power and personality. Norton, New York.

Liu, X., Ferrario, E., Zio, E., 2017. Resilience Analysis Framework for Interconnected Critical Infrastructures. ASCE-ASME J. Risk Uncertain. Eng. Syst. Part B. Mech. Eng. 3 (2) https://doi.org/10.1115/1.4035728.

Luhmann, N., 1984. Soziale Systeme: Grundriß einer allgemeinen Theorie, 1st ed. Suhrkamp, Frankfurt am Main.
Lykou, G., Stergiopoulos, G., Papachrysanthou, A., Gritzalis, D., 2017. Protecting the transportation sector from the negative impacts of climate change. In: Rice, M., Shenoi, S. (Eds.), Critical Infrastructure Protection XI: 11th International Conference, ICCIP 2017, Arlington, VA, USA, March 13–15, 2017: Revised Selected Papers. Springer International Publishing; Springer, Cham, pp. 3–21.
Maier, M.W., 1996. Architecting Principles for Systems-of-Systems. INCOSE International Symposium 6 (1), 565–573. https://doi.org/10.1002/j.2334-5837.1996.tb02054.x.
Maier, M.W., 1998. Architecting principles for systems-of-systems. Syst. Engin. 1 (4), 267–284. https://doi.org/10.1002/(SICI)1520-6858(1998)1:4<267:AID-SYS3>3.0.CO;2-D.
Masera, M., Gheorghe, A.V., Weijnen, M., 2006. Concluding Remarks and Recommendations. In: Gheorghe, A.V., Masera, M., Vries, D.L., Weijnen, M. (Eds.), Critical Infrastructures at Risk: Securing the European Electric Power System. Springer, Dordrecht, pp. 153–162.
Maxwell, J.C., 1871. Theory of heat. Longmans Green & Co, London.
Maxwell, J.A., 1992. Understanding and Validity in Qualitative Research. Harv. Educ. Rev. 62 (3), 279–300.
McGee, S., Frittman, J., Ahn, S.J., Murray, S., 2016. Implications of cascading effects for the Hyogo Framework. Int. J. Disaster Resilience Built Environ. 7 (2), 144–157. https://doi.org/10.1108/IJDRBE-03-2015-0012.
McIntyre-Mills, J., 2006. Systemic Governance and Accountability: Working and Re-Working the Conceptual and Spatial Boundaries, 1st ed. Springer-Verlag, s.l.
Mumford, E., 2006. The story of socio-technical design: reflections on its successes, failures and potential. Inf. Syst. J. 16, 317–342.
Neidhardt, F., 2017. Das innere System sozialer Gruppen*. Köln Z Soziol 69 (S1), 433–454. https://doi.org/10.1007/s11577-017-0415-8.
Normandin, J.-M., Therrien, M.-C., 2016. Resilience Factors Reconciled with Complexity: The Dynamics of Order and Disorder. J. Contingencies Crisis Manage. 24 (2), 107–118. https://doi.org/10.1111/1468-5973.12107.
Offe, C., 2008. Governance — „Empty signifier“ oder sozialwissenschaftliches Forschungsprogramm? In: Schuppert, G.F., Zürn, M. (Eds.), Governance in Einer Sich Wandelnden Welt. VS Verlag für Sozialwissenschaften, Wiesbaden, pp. 61–76.
Onik, A.F.M., Fielt, E., Gable, G.G., 2016. Complex Adaptive Systems Theory in Information Systemes Research - A Systematic Literature Review. In: 24th European Conference on Information Systems (ECIS).
Ouyang, M., 2014. Review on modeling and simulation of interdependent critical infrastructure systems. Reliab. Eng. Syst. Saf. 121, 43–60. https://doi.org/10.1016/j.ress.2013.06.040.
Paré, G., Trudel, M.-C., Jaana, M., Kitsiou, S., 2015. Synthesizing information systems knowledge: A typology of literature reviews. Inf. Manag. 52 (2), 183–199. https://doi.org/10.1016/j.im.2014.08.008.
Pescaroli, G., Alexander, D., 2016. Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. Nat. Hazards 82 (1), 175–192. https://doi.org/10.1007/s11069-016-2186-3.
Petridou, E., 2014. Theories of the Policy Process: Contemporary Scholarship and Future Directions. Policy Stud. J. 42 (1), S12–S32. https://doi.org/10.1111/psj.12054.
Checkland, P., 2008. Soft Systems Methodology. In: Rosenhead J, Mingers J, editors. 2008. Rational analysis for a Problematic World Revisited: Problem Structuring Methods for Complexity, Uncertainty and Conflict, 2nd ed. Wiley, Chichester, pp. 61–113.
Pfeffer J, Sutton RI. Evidence-based management. Harv Bus Rev 2006;84(1):62-74, 133.
Prelipcean G. Emerging micro finance solutions for response and recovery in the case of natural hazards. In: Grigoriu M, editor. Recent advances in risk management, assessment and mitigation: Proceedings of the International Conference on Risk Management, Assessment and Mitigation (RIMA '10) ; Universitatea Politehnica, Bucharest, Romania, April 20 - 22, 2010. Athens: WSEAS Press; 2010, p. 220–225.
Reichertz, J., 2015. Die Bedeutung der Subjektivität in der Forschung/ The Meaning of Researchers' Subjectivity. Forum Qualitative Sozialforschung/Forum Qualitative Social Research 16 (3), Art. - 33.
Rhodes, R.A.W., 1996. The New Governance: Governing without Government. Pol. Studs. 44 (4), 652–667. https://doi.org/10.1111/j.1467-9248.1996.tb01747.x.
Rhodes, R., 1997. Understanding governance: Policy networks, governance, reflexivity and accountability. Open Univ. Press, Buckingham.
Rinaldi, S.M., Peerenboom, J.P., Kelly, T.K., 2001. Identifying, understanding, and analyzing critical infrastructure interdependencies. IEEE Control Syst. Mag. 21 (6), 11–25. https://doi.org/10.1109/37.969131.
Rinfret, S.R., Scheberle, D., Pautz, M.C., 2018. The Policy Process and Policy Theories. In: Rinfret, S.R., Scheberle, D., Pautz, M.C. (Eds.), Public Policy: A Concise Introduction. Sage/CQ Press, Thousand Oaks, California, London, New Delhi, Singapore, pp. 18–44.
Robert, B., Calan, R. de, Morabito, L. Modelling interdependencies among critical infrastructures. Int. J. Crit. Infrastruct. 2008;4(4):392–408. https://doi.org/10.1504/IJCIS.2008.020158.
Sajeva, M., Masera, M., 2006. A strategic approach to risk governance of critical infrastructures. Int. J. Crit. Infrastruct. 2 (4), 379–395. https://doi.org/10.1504/IJCIS.2006.011346.
Schaberreiter T, Quirchmayr G, Juuso A-M, Ouedraogo M, Röning J. Towards a Complex Systems Approach to Legal and Economic Impact Analysis of Critical Infrastructures. In: 11th International Conference on Availability, Reliability and Security: ARES 2016 (Salzburg, Austria, 31 August-2 September 2016). Proceedings. Piscataway, NJ: IEEE; 2016, p. 668–676.
Scheer, A.-W., 1991. Architektur integrierter Informationssysteme: Grundlagen der Unternehmensmodellierung. Springer, Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Barcelona, Budapest.
Seager TP, Clark SS, Eisenberg DA, Thomas JE, Hinrichs MM, Kofron R et al. Redesigning resilient infrastructure research. In: Linkov I, Palma-Oliveira JM, editors. Resilience and Risk: Methods and Application in Environment, Cyber and Social Domains. Dordrecht: Springer Netherlands; Springer; 2017.
Shannon, C.E., 1948. A Mathematical Theory of Communication. Bell Syst. Tech. J. 27 (3), 379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x.
Spyridopoulos, T., Topa, I.-A., Tryfonas, T., Karyda, M., 2014. A holistic approach for cyber assurance of critical infrastructure with the viable system model. IFIP Adv. Inform. Commun. Technol. 428, 438–445.
Stachowiak, H., 1973. Allgemeine Modelltheorie [General Model Theory]. Springer-Verlag, Wien, New York.
Tehler H, Lindström J, Lindbom H. Using microworlds to study critical infrastructure protection—the effect of incentives on risk management. In: Haugen S, Barros A, van Gulijk C, Kongsvik T, Vinnem J-E, editors. Safety and Reliability - Safe Societies in a Changing World - Proceedings of the 28th International European Safety and Reliability Conference, ESREL 2018 // Safe Societies in a Changing World: Proceedings of ESREL 2018, June 17-21, 2018, Trondheim, Norway. Boca Raton, Florence: CRC Press LLC; Taylor & Francis Group [distributor]; 2018, p. 1865–1872.
The Sorting Demon of Maxwell. Nature 1879;20(501):126. https://doi.org/10.1038/020126a0.
Tingle, L., 2015. Political Amnesia: How We Forgot How to Govern. Quarterly Essay 60.
van der Vleuten, E., Lagendijk, V., 2010b. Interpreting transnational infrastructure vulnerability: European blackout and the historical dynamics of transnational electricity governance. Energy Policy 38 (4), 2053–2062. https://doi.org/10.1016/j.enpol.2009.11.030.
vom Brocke J, Simons A, Niehaves B, Niehaves B, Reimer K, Plattfaut R et al. Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process. In: European Conference on Information Systems (ECIS) 2009 Proceedings; 2009, Paper 161.
van der Vleuten, E., Lagendijk, V., 2010a. Transnational infrastructure vulnerability: The historical shaping of the 2006 European "Blackout". Energy Policy 38 (4), 2042–2052. https://doi.org/10.1016/j.enpol.2009.11.047.
vom Brocke, J., 2003. Referenzmodellierung: Gestaltung und Verteilung von Konstruktionsprozessen. [Dissertation]. Westfälische Wilhelms-Universität Münster, Logos Verlag Berlin.
von Bertalanffy, L., 1950. The Theory of Open Systems in Physics and Biology. Science 111, 23–29.
von Bertalanffy, L., 1968. General System Theory: Foundations, Development, Applications. George Braziller, New York, NY.
Wiener, N., 1948. Cybernetics: Or control and communication in the animal and the machine. Wiley, New York, NY.