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The emergence of new critical infrastructures. Is the COVID-19 pandemic shifting our perspective on what critical infrastructures are?

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\textbf{A R T I C L E I N F O}

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\textbf{A B S T R A C T}

Our modern world is highly dependent on the functioning of a complex system of interdependent infrastructures. Failure of one infrastructure can have severe and far-reaching impacts on other infrastructures and jeopardize the functioning of the whole system. While certain infrastructures have been considered highly critical and their dependencies and protection has been addressed extensively and for decades, others have been considered less or not at all critical and have been barely debated. The COVID-19 pandemic has caused an unprecedented strain on infrastructure systems and has revealed that different infrastructures become highly critical throughout an ongoing and long-lasting crisis rather than during a sudden but short-term crisis. This paper investigates the representation of critical infrastructure dependency descriptions in the literature before and since the start of the COVID-19 pandemic. In this qualitative study, the quantity of descriptions per critical infrastructure dependency is analyzed and visualized and used to discuss the perception of how critical those infrastructures are. The study revealed that new infrastructures have been identified as critical in recent literature and that the focus was shifted to specific infrastructures that were in more pressing need during the pandemic. This shift of focus was observed to happen from the sectors of energy, water, transport & traffic, and ICT before the start of the COVID-19 pandemic to the sectors public health, constitutional institutions, transport & traffic, and food since the start of the COVID-19 pandemic. Further, analysis of the literature revealed infrastructures which had previously not been classified as critical, being discussed as new critical infrastructures. Urban green spaces, for example, have proven to be essential for the health and well-being of citizens during lockdown times. Further, social services like childcare, care of the elderly, delivery services, and online grocery shopping have been highlighted as essential services for maintaining workforces and the functioning of society during a pandemic. Overall, the analysis of descriptions of critical infrastructure dependencies before and since the start of the COVID-19 pandemic has revealed changes in the focus on critical infrastructures and in the perception of what makes critical infrastructures critical.

\section{1. Introduction and state of the art}

Dependencies of critical infrastructures can be documented, analyzed and investigated in multiple ways. Case studies (e.g., Schneidhofer & Wolthusen (2015) [1]) or incident reports (e.g., Hassanzadeh et al. (2019) [2]) document failures and their effects in...
real scenarios, while theoretical modelling and simulations (e.g., Rinaldi 2002 [3], Setola 2008 [4], Oliva et al. (2010) [5], Cavallini et al. (2014) [6]) investigate and envision what might be done in order to prepare responsible actors, processes and systems to protect critical infrastructures from potential threats. Luijif et al. (2009 [7]) took an empirical approach, analyzing critical infrastructure dependencies in Europe from a database of public reports. All these investigation approaches focus on either past or potential future events or failures of critical infrastructures in order to gain a comprehensive understanding of critical infrastructures, their systems, interactions and dependencies. However, documentation and research articles align in their perception of what critical infrastructures are, focusing efforts on those pre-defined critical infrastructures. Meanwhile, the COVID-19 pandemic unraveled and challenged what is seen as a critical infrastructure. Prior to 2020 the topic of new or emerging critical infrastructures was a rather rare focus in the literature. Since the start of the global COVID-19 pandemic events have started to emerge addressing potential new, situational critical infrastructures and their impacts on society and citizens’ welfare (e.g., urban green spaces: Xie et al. (2020) [8]; Venter et al. (2020) [9]). However, no substantial overview analysis has been conducted yet, analyzing those newly emerging topics, and reflecting on the perception of critical infrastructures in the literature affected by the impacts of the COVID-19 pandemic. This study aims to fill this knowledge gap and analyze if and how the COVID-19 pandemic impacted the representation and understanding of critical infrastructures in the literature.

The objectives of this study are:

1. To identify changes of critical infrastructure dependencies described in the literature before the start and since the start of the COVID-19 pandemic.
2. To investigate the impact of the COVID-19 pandemic on the understanding of what critical infrastructures are.

2. Critical infrastructure and society

Our contemporary society depends on infrastructures and their services, as well as the supply of essential goods. Critical infrastructures are those infrastructures and their components and services, which are essential for the functioning of the social system [10]. Critical infrastructures include basic supply networks (water, electricity), networks of information and communication services, social services (e.g., care of children or elderly), as well as complex networks of essential supply to the population (e.g., medical supply, food supply). Infrastructure systems and their components are interdependent. If a disruption or failure occurs in one system, it can spread to other systems and subsequently amplify the impact of a disruption many times and impact further systems. Due to the constant growth and increase in complexity of the connections between infrastructures, the interdependencies within the overall system also continue to increase, causing the system to become more susceptible to disruption [3]. A critical infrastructure system (e.g., public health system) comprises several sectors, with networks and components, interconnected at nodes. This creates a complex network of interconnections, whose characteristics determine how and with what intensity the effects of critical infrastructure system failures spread to dependent subsystems and society [11].

Records of past events illustrate how severe and far-reaching the effects of critical infrastructure system failures can be. During the past months, the world’s countries and their infrastructures have faced a new challenge: the COVID-19 pandemic. Unlike sudden events, such as flash floods or terrorism attacks, a pandemic causes continuous stress on infrastructures. Failure does not occur abruptly, but rather announces itself and the cascading effects reach sectors which have typically not been affected in past events. For example, the Austrian food sector was affected by border closures as harvest workers from Eastern Europe could not enter the country. The lack of suitable workers threatened the harvest and thus the food production of the season [12-14]. Within the social and distribution systems sector, there was a shortage of elderly care workers who could not travel to their workplaces due to the border closures and lack of transportation [15]. With a large portion of the population working from home, the strain on information and communication services increased significantly [14]. To prevent overloading the connections, major providers such as YouTube and Netflix decided to temporarily reduce the video quality to relieve the Internet lines [16]. These are just a few examples of the impacts the COVID-19 pandemic has had on critical infrastructure systems. The consequences are far-reaching and long-lasting and cannot be fully assessed at this point in time. But what can be said with certainty is that the current situation highlights the importance of researching critical infrastructures, with their interrelationships, impacts, and the interconnectedness of our modern world more thoroughly than ever before. After all, only interconnections that are recognized and understood can be protected.

2.1. When systems fail – cases of critical infrastructure failure

What happens when system failures of critical infrastructure occur despite all precautions? In recent years, there have been several incidents worldwide that led to disruptions and failures of critical infrastructures and continued as cascading failures in other systems. A few example cases are described below in more detail in order to give real-world insights on potential causes of failure and the following impact those failures caused on other infrastructures and subsequently, people’s lives.

One of the first extensively documented events was the Canadian ice storm in the winter of 1998. The event began with several waves of freezing rain that caused outages in the transmission and distribution network of the power supply. Power supply disruption turned an originally climatological catastrophe into a technological disaster, as infrastructures dependent on electricity began to fail. 4.7 million inhabitants were without power, and for many the disruption lasted for hours, days or even weeks. The transport & traffic sector was immediately affected as traffic lights failed, causing several rear-end collisions and subsequent traffic jams. Furthermore, rail traffic had to be stopped, as crossing signals, operating signals, and the setting of points failed. As the power outage continued, it started to affect food production and other infrastructures. Farmers suffered major losses due to lack of ventilation and heating in barns, and even the loss of dairy cows due to milking machine failures. Countless other problems arose due to heating system failures.
Four people died from hypothermia and seven others died from carbon monoxide poisoning due to the use of poorly ventilated heating sources. An additional burden was placed on firefighters when some homes and apartments caught fire due to inadequate heating sources. The events of the 1998 ice storm led to increased awareness of the interdependencies of critical infrastructures in Canada, and the protection of these was included as an essential element of disaster preparedness [17].

An event that shook the world was the terrorist attack on the World Trade Center in 2001. In addition to the social and political impact, the attacks also led to failures in several of New York City’s infrastructure systems. The collapsing buildings caused severe damage to the pipes of the water system. Initially, flooding of the area and surrounding areas occurred, followed by a loss of pressure in water mains and fire hydrants, which hampered the work of firefighters. The outflowing water from burst pipes flooded the underground tunnels of the PATH trains, which subsequently failed. In addition, the basement of Verizon’s 140 West Street building was flooded, resulting in a loss of data and communications network outages which affected approximately 24,000 customers. A long-term consequence of this event was, that the U.S. tightened its critical infrastructure protection strategies [18].

In 2005, the city of New Orleans was hit hard by Hurricane Katrina. Hurricane Katrina was an infrastructure disaster: when the levees failed, all infrastructure systems (power, communications, water, energy, sewage) necessary for human survival in New Orleans failed as well. Without the necessary infrastructure services, medical care, public health, and relief and emergency services failed. In addition to the damage from high winds, excessive rainfall and resulting flooding and failure of parts of the levee system caused severe damage to New Orleans’ infrastructure. New Orleans’ two major water treatment plants were inoperable due to excessive wind damage and flooding, and pumps of the city potable water systems failed due to power outages, resulting in a shortage of potable water [19]. About seven years later, Hurricane Sandy hit the North American East Coast, causing power outages and flooding. The most critical impact on transportation infrastructure was caused by the flooding of the New York Metropolitan Transit Authority (MTA) subway tunnels, which left millions of commuters stranded for several days. In terms of interdependencies between infrastructures, the traffic & transportation sector was mainly affected by cascading failures, initiated from areas of commercial power generation, oil and gas supply, and ICT systems. Simultaneously, cascading effects of the transport & traffic sector prolonged repair work: blocked roads or lack of access to the terrain prolonged outages, especially of the energy and ICT infrastructures [20].

### 2.2. Critical infrastructures in the literature

Critical infrastructures consist of a complex composition of systems, facilities, processes, networks, or parts thereof [10,21]. A **dependency** between infrastructures arises from the linkage or connection between two infrastructures through which the state of the second depends on the state of the first. There is a unidirectional connection between them: in a dependency from infrastructure $j$ to infrastructure $i$, infrastructure $i$ depends on infrastructure $j$ through the link; but infrastructure $j$ does not depend on infrastructure $i$ through that link. For example, a power plant requires supplies such as workforces, fuel, and a functioning transport & traffic sector in order to operate. In this case, the energy sector is the supported sector, while the sectors transport & traffic and chemical industry are the supporting sectors. In case of an emergency, the type of dependency on critical infrastructures needed for the immediate functioning of the power plant might shift (e.g., transport & traffic needed for the deployment of repair crews) [3].

An **interdependency** refers to a bidirectional relationship between two infrastructures through which the states of the two infrastructures affect each other: Infrastructure $i$ is dependent on Infrastructure $j$; and Infrastructure $j$ is dependent on Infrastructure $i$. The concept of interdependencies is simple, meaning the connection between different parts of infrastructures, including paths,

| Table 1 | This table describes four types of possible effects between two infrastructures, where a change in an initially affected infrastructure $i$ impacts the functioning of the affected infrastructure $j$. Those effects can be positive (an improvement of an infrastructure e.g., repair) or negative (causing stress on an infrastructure and lead to further disruption or failure). |
| Effect | Initially affected infrastructure $i$ | Effects on infrastructure $j$ | Example |
|---|---|---|---|
| positively reinforcing | positive (+) | positive (+) | Repair of a transmission tower (+) |
| negatively reinforcing | negative (−) | negative (−) | Power failure (−) |
| worsening | positive (+) | negative (−) | Emergency services cannot access sites (−) |
| improving | negative (−) | positive (+) | Pumps at gas stations for fuel delivery are supplied with emergency power (+) |

- emergency teams can communicate better (+) |
- faster repair of further transmission towers (+) |
- Disruption of the traffic network (−) |
- Emergency services cannot access sites (−) |
- Power failure lasts longer (−) |
- Pumps at gas stations for fuel delivery are supplied with emergency power (+) |
- Traffic volume increases (−) |
- Traffic situation worsens (−) |
- Power outage (longer lasting) (−) |
- people stay at home (−) |
- free roads (+) |
- emergency services can travel faster (+) |
feedback, and feedforward in a system is bidirectional. However, the complexity of the system is strongly increased with the increase of interdependencies between infrastructures. This complex web of connections and linkages can transmit shocks across numerous infrastructures and cause far-reaching and unforeseeable impacts. Therefore, it is essential to analyze and understand infrastructures in their interconnected environment. For example, the ICT sector requires power supply for its operation; the energy sector, in turn, depends on an intact ICT network in order to function and to coordinate repairs in case of a failure [3].

**Impact**

Due to the dependencies and interdependencies between critical infrastructures, there are several ways how an event in one infrastructure can have an effect on or within another infrastructure (Table 1).

**Failure**

Critical infrastructures are constantly exposed to threats that fall into five categories [22):

- Climatological threats (e.g., hurricanes, major fires, flooding)
- Geological threats (e.g., earthquakes, volcanic activity, landslides)
- Biological threats (e.g., pandemics)
- Technological threats (e.g., radiation emergencies, chemical accidents, major road, rail, or air accidents)
- Criminal threats (e.g., terrorism, criminal activities, armed conflicts)

Depending on the characteristics and temporal development of the initiating event, threats can evolve into crisis or disasters of two types [23]:

- **Sudden-onset disasters** are initiated by a hazardous event which emerges unexpectedly or within a very short time period (e.g., flood, earthquake, chemical explosion, transport accident, etc.).
- **Slow-onset disasters** emerge gradually over a longer period of time (e.g., sea-level rise, desertification, drought, epidemics, etc.). Slow-onset disasters differ from sudden-onset disasters in their spatio-temporal scale and impacts. While there is still a debate about the exact definition of slow-onset disasters, within this study they are understood as phenomena, which evolve slowly (over weeks, months up to years), impacting a system in various and complex ways. Typically, the type, reach, and intensity of those impacts are very difficult to anticipate. The COVID-19 pandemic is considered a slow-onset disaster within this study due to its characteristics and slow development of impacts and reach. Further, the pandemic has been affecting multiple infrastructures and their dependencies and interdependencies in ways which were not anticipated, which is an example of the complexity of slow-onset disasters.

Both, sudden-onset and slow-onset disasters can cause disruptions or, in extreme cases, failures of critical infrastructure systems or subsystems. These lead to a performance drop of certain functions, whereby the severity of the drop depends on the intensity of the disruption and the resilience of the system components. Rinaldi et al. [3] defines the basic types of fault propagation in a critical infrastructure system as follows: **Cascading failure** (e.g., a power failure leads to the failure of a subway line), **Escalating failure** (e.g., the blockage of a road by a fallen power pole impedes emergency responders from getting to a damaged transmission tower to repair the failure of an ICT network), **Common cause failure** (e.g., a hurricane causes simultaneous damage to the power grid, water grid, and road network in a city) [3].

3. **Methodology**

In this qualitative study, a systematic literature review and comparative analysis was conducted to investigate differences between the representation of descriptions in the literature of:

- Critical infrastructure dependencies, interdependencies, and failure **before the start** of the COVID-19 pandemic (March 2001–March 2020)
- Critical infrastructure dependencies, interdependencies, and failure in connection with the COVID-19 pandemic **since the start** of the COVID-19 pandemic (literature published between 1. March 2020–1. March 2021)

The number of literature resources analyzed for each period was not pre-determined but was determined during the course of a trial analysis. A preliminary literature analysis and visualization of the quantity of descriptions of critical infrastructure dependencies in literature was conducted through chord diagrams. For the period before the start of the COVID-19 pandemic, this trial analysis revealed that once 45 literature sources were reached, the chord diagram showed tendencies which did not noticeably change anymore by adding additional literature. For the period since the start of the COVID-19 pandemic the same approach was taken and at 35 literature resources clear tendencies showed in the chord diagram and no more sources could be identified within the period, matching the selecting criteria, and adding additional insights to the analysis.

3.1. **Identification of literature**

In a first step “identification”, a search for articles through online libraries, Google Scholar and an online search for grey literature was carried out. Literature was selected which described at least one dependency or connection between critical infrastructures. Literature in either English or German was reviewed. For the analysis of literature since the start of the COVID-19 pandemic, only articles including topics of COVID-19 and critical infrastructures were included. The authors are aware that this causes a bias towards articles focusing on infrastructures impacted by the pandemic. However, since this analysis focuses on changes in context of the pandemic, it was decided to apply this selection criterion. Keywords used in the search included: “critical infrastructure dependencies”; “critical infrastructure failure”; “critical infrastructure protection”; “critical infrastructure & COVID-19”. In a second step, the “snowballing” approach was applied to identify articles which did not show up in the initial search requests. In this approach, the
references listed by a source that were relevant for the search topic were reviewed to identify further relevant literature. The authors decided not to limit literature to only scientific journal articles but also include case studies of real incidents, failure reports, guidelines for prevention, articles, books on critical infrastructure dependencies and/or failure, and studies of possible failure scenarios.

Specific topics of literature that was selected included among others, failure analysis of real events (e.g., ‘power outage consequences in the 1998 Ice Storm’ analysis published in Natural Hazards Journal [17]), critical infrastructure protection (e.g., ‘Water Critical Infrastructure Security and its Dependencies,’ published in ‘Journal of Terrorism Research’ [24]), analysis of types of failure (e.g., ‘The state and the threat of cascading failure across critical infrastructures: The implication of empirical evidence from media incident reports’ published in ‘Public Administration’ Journal [25]), topics of dependencies between specific infrastructures (e.g., ‘On the Rising Interdependency between the Power Grid, ICT Network, and E-Mobility: Modeling and Analysis’ published in ‘Energy Journal’ [26]), or specific analysis of the COVID-19 pandemic impacts on critical infrastructure sectors (e.g., ‘The COVID-19 Pandemic: Energy Market Disruptions and Resilience’ published in ‘Critical Infrastructure Policy’ Journal [27]).

3.2. Comparative analysis

Sectors of critical infrastructure that were analyzed included: public health (e.g., hospitals), the chemical industry (e.g., water treatment products), first responders (e.g., police), research facilities (e.g., epidemiological research institute), finance (e.g., banks or ATMs), ICT (e.g., cell service), transportation and traffic (e.g., street network, railway), water (e.g., water supply and sanitation), energy (e.g., electricity supply), constitutional institutions (e.g., government institutions), social systems (e.g., schools, elderly- or childcare facilities), and food (e.g., production and packaging). The sectors were defined, based on the Austrian Council of Ministers decision of April 2, 2008, classifying critical infrastructure into the above-mentioned sectors [21].

Dependency matrices were used to conduct a systematic, comparative analysis of selected literature’s content. Each description of a dependency between two sectors that was identified in a literature source was noted in the matrix. ‘Active sectors’ (an initiating sector, which performance impacts other sectors) were listed along the x-axis and passive sectors (a sector which performance is impacted by the functioning of other sectors) were listed along the y-axis. After conducting the literature review, the quantity of recorded representations per dependency between two sectors was counted, representing the frequency of descriptions in literature. Further, infrastructures which were discussed as critical infrastructures in the literature but did not match any of the sectors described above were identified and discussed as “emerging critical infrastructure”.

3.2.1. Visualisation of dependencies

Chord diagrams were used to visualize the results of the analysis of the quantity of descriptions of critical infrastructure dependencies between sectors in the literature. The program used for data visualization was R version 4.0.4 (2021) [28] together with the package “chorddiagram”. The dependency matrix that was created was imported into R as a matrix and visualized as an interactive graph using the Chorddiagram package.

3.2.2. Limitations

This study evolved due to the opportunity and desire to gain insights into an ongoing, and unprecedented case of a phenomenon impacting people, systems, and infrastructures around the globe. The authors acknowledge that this study is limited in its scope and that conducting this type of research has inherent limitations. Firstly, the COVID-19 pandemic is still ongoing which impacted the author’s work schedule, access to resources, and collaboration opportunities. Further, no complete picture of the pandemic from the start to end can be gained and assessing longitudinal effects is currently not possible. This analysis provides a snapshot of the current situation, but insights and findings are limited to this particular period of time.

An inherent limitation of literature reviews is the subjectivity in the collection and analysis process of data and subsequently the question of reliability and replicability of results. While the authors aimed to maximize rigor and minimize susceptibility to bias in this study, it is acknowledged that analyzing literature on infrastructure dependencies and failures specifically in connection with the COVID-19 pandemic creates a selection-bias. It is further acknowledged that comparing 19 years of literature (pre-pandemic) with one year of literature (since the start of the pandemic) means analyzing across very different periods of time. The time frame of 2001–2020 was chosen in order to capture varying topics and trends across the period prior to the COVID-19 pandemic. Considering the variation in the focus on topics of critical infrastructures throughout the past two decades, the authors decided to analyze literature across a long time period, leading up the COVID-19 pandemic rather than focus on, for example, the one year before the pandemic (2019) and create a bias towards focusing on topics in that year only. A further limitation inherent to this type of research is the limited availability of reliable data. Especially in a context such as the pandemic, which is a first-time case and a new field, the validity of available information is less assured than in a well-known and well-researched field. In particular, throughout the period since the start of the COVID-19 pandemic, the number of available sources limits the scope and comprehensiveness of the study. Therefore, the authors decided to also include grey literature which may compromise the validity of the results. However, due to the objective to identify newly evolving topics and trends, the inclusion of grey literature was considered a valid addition, with the benefit outweighing the risk of compromising validity. The current limited availability of literature resources on infrastructure dependencies and failures in connection with the COVID-19 pandemic highlights the need for future research.

It is noted that an inherent limitation to literature research is that approaches can result in overly descriptive summaries, providing an overview of topics or numbers of publications without generating any deeper analysis. This paper aims to provide valuable insights and conduct a deeper analysis of emerging topics, by including an analysis of the timeline of published articles and topics since the start of the COVID-19 pandemic, identifying knowledge gaps, and using chord diagrams to analyze and derive information on perceptions and newly evolving topics of future interests and research. This study focuses on changes in topics in critical infrastructure literature.
and visualizing frequency of descriptions to support the argument. However, the study does not aim to make a quantitative statement, as the number of literature sources and differing time periods do not allow for a quantitative data analysis. The limited number of literature resources (45 pre-pandemic and 35 since the start of the pandemic) allows an initial insight into those changes and topics in the context of the ongoing COVID-19 pandemic. However, to gain full insight into the impact of the COVID-19 pandemic, a study will need to be carried out after the end of the COVID-19 pandemic, analyzing all COVID-19 and critical infrastructure related literature from the beginning to the end of the pandemic.

Overall, the limitations mentioned impact the study’s scope which provides a very specific analysis of a subset within a limited period of time, allowing for initial insights but with limited perspective regarding future conditions. Further information and reliable publications will be essential in order to conduct an extensive and comprehensive analysis of change. As we move forward in time, the pandemic is taking its course and new articles are being published, and the trends will become clearer. In this study, new topics might be over-rated while future analysis might conclude that interest in those topics was lost with the end of the pandemic. It can be expected that time will show which new topics are truly evolving topics and which are situational and were only addressed and of interest throughout the ongoing COVID-19 pandemic.

4. Results

4.1. Critical infrastructure dependencies and failures

Critical infrastructures are interconnected in many ways and interrelationships arise through mutual dependencies and impacts. In today’s world, these interconnections are increasing, and infrastructures are more interwoven than ever. These pronounced interdependencies mean that infrastructures can no longer be seen as individual, self-contained systems, but must be viewed and treated as interconnected systems. Case studies from the past show the vulnerability due to this high degree of interconnectedness between the critical infrastructure sectors and potentially severe consequences that failure can trigger [17–20,29]. In this study, based on a preliminary screening and analysis process, 45 literature sources were identified and analyzed for the time before the start of the COVID-19-pandemic, and 35 literature sources for the time since the start of the COVID-19-pandemic. The analysis of existing literature on critical infrastructure interconnections revealed that dependencies between certain infrastructures are described particularly

![Fig. 1. Frequency of descriptions of dependencies between critical infrastructures in literature published before the start of the COVID-19 pandemic. The band between two sectors in the graph represents the direction of dependency and frequency of description. The width of the bands at their base shows the frequency of descriptions of sectors and the direction of connections between two sectors (e.g., The sector Energy has the widest base of bands, indicating that it was most often described as the ‘active’ sector in literature, compared to all other sectors). The color shows which sector was predominantly described as ‘active’ and which was predominantly described as a ‘passive’ sector: the band has the color of the sector predominantly described as ‘passive’ (e.g., the band between Energy (yellow) and Water (dark-red) is dark red, showing that more descriptions of the dependency between those two sectors described Energy as the ‘active’ and Water as the ‘passive’ sector). A band whose base on either side has about the same width indicates that the dependency was described as equally directed in both ways (e.g., Sector Energy depends on sector ICT, and sector ICT depends on sector Energy). If a band is narrow at one base but wide at the other, it indicates that one sector has been often described as impacting the second sector, while the second sector was rarely or not described as impacting the first sector (e.g., the band between Energy and Public Health is wide at the base on the Energy side but very narrow at the base on the Public Health side. This shows that most descriptions of dependencies between the two sectors mentioned Energy as the active sector and Public Health as the predominately passive sector). Source: own diagram.](image-url)
frequently. The focus of infrastructure dependency descriptions differs between the time before COVID-19-pandemic and the time since the start of the pandemic, as explained in the following sections.

Before the COVID-19 pandemic.

Dependencies between the sectors ICT, transportation & traffic, water, and energy are the ones most frequently described in the literature in the time before the COVID-19-pandemic. Fig. 1 shows the trend in the frequency with which the individual sectors are described: The link between energy to the other sectors is most prevalent in the literature, while sectors such as constitutional institutions or research facilities are hardly mentioned.

ICT, transport & traffic, water, and energy sectors are the infrastructures most frequently affected by disruptive events and most extensively described in the literature. The sectors are interlinked in complex and diverse ways and failure in one sector may rapidly and severely impact the others. The analysis further revealed trends in the focus of the descriptions of the interrelationships of these four sectors (Fig. 2). While some scenarios can be found described extensively in the literature (e.g., power failure [30]), there are far less precise descriptions of other dependencies (e.g., water sector impacts on transport & traffic [31]). In most cases, major infrastructure operators are already well prepared for these forms of disruptions (e.g., emergency generators for water pumps [30]). Conversely, impacts and mitigation measures in other sectors are much less frequently described (e.g., impacts of the water sector on

Fig. 2. Frequency of descriptions of dependencies between energy (upper left), water (upper right) transportation & traffic (lower left), ICT (lower right) and other sectors in literature published before the start of the COVID-19 pandemic. The band between two sectors in the graph represents the direction of dependency and frequency of description. The width of the bands at their base shows the frequency of descriptions of sectors and direction of connections between two sectors. The color shows which sector was predominantly described as ‘active’ and which was predominantly described as a ‘passive’ sector (the band has the color of the predominantly described as ‘passive’ sector). Source: own diagram.
A comparison of the four sectors showed that in the case of cascading failure, the initiating event usually originates from the energy sector [25]. This is also reflected in the fact that critical facilities or organizations (e.g., hospitals [30,33]) usually have security measures primarily for power supply and only secondarily for failure of other infrastructures. Conversely, disruptions to the other sectors, result far less often in impacts on the energy sector. The sectors of constitutional institutions, research facilities and social and distribution systems are mentioned least frequently in the literature with regard to infrastructure interdependencies (e.g., descriptions of effects of infrastructure failures due to sudden-onset events like hurricanes on social systems [34]). Fig. 3 shows the quantity of descriptions of each sector described as an active sector (providing services to other sectors), highlighting the role of energy, water, transportation & traffic, and ICT as service-providing sectors, on which services other sectors depend.

Dependencies that lead to a rapid and severe failure of essential functions are both well researched and in practice already secured with safety measures, and the majority of case studies and research papers deal with sudden-onset events (e.g., storms), while dependencies that would only have an impact in the event of a longer-lasting disruption (several days or longer) are addressed less often and in less detail in the literature. Effects of failures that occur slowly and last for a long time are rarely described. For example, while failures initiated due to the impact of a flood or hurricane were often described, no description of infrastructure failure due to a drought was described in the literature that was reviewed.

4.2. Since the start of the COVID-19 pandemic

For the period of March 2020 to March 2021 a total of 35 literature sources were identified that address themes of critical infrastructure protection, dependencies or failures in the context of the COVID-19 pandemic. In order to illustrate the initiation and trajectory of those evolving topics, the number of publications per month were mapped in the timeline below Fig. 4.

Topics of publications included supply chain interruptions, impact on health infrastructures, transportation interruptions, food chain interruption, safety of essential work forces, education, or overall impact. Table 2 lists the publishing month and title of identified literature. A detailed reference list of identified literature can be found in Appendix A.

The analysis of literature published between March 2020 and March 2021 and including themes of the COVID-19 pandemic and critical infrastructure has revealed a strong representation of descriptions of dependencies between the sectors public health, transportation & traffic, constitutional institutions and food (Fig. 5).

The sector public health was the one most often discussed as the active sector that others depend upon and as providing services to other sectors. Following public health were the sectors transportation & traffic and constitutional institutions as providing sectors. The sector food was discussed most frequently as the one depending upon other sectors (primarily public health and transportation & traffic) to function (Fig. 6).

Public health is the sector most frequently described as the ‘active’ sector, affecting other sectors during the time of the COVID-19 pandemic (Fig. 7). The analysis of Fig. 6 focused on direct sector-to-sector dependencies, but it was noticeable that many descriptions in the literature mentioned the impacts of public health on multiple sectors and society in general. Public health includes among other services the treatment of patients, and facilitation of COVID-tests and vaccinations [14,35]. These services have proved to be crucial for the functioning of society and all other critical infrastructures [36]. The severity of potential failure and importance of the public health sector is the most frequent theme among the articles reviewed.

The most discussed dependent sector is food with a special focus on food supply chains. The COVID-19 pandemic interrupted numerous parts of the food supply chains such as production, packaging, transportation, and distribution, highlighting the dependence and vulnerability of food supply chains. The effects of the COVID-19 pandemic impacted this sector through absence of workers, closure of packaging factories and interruptions in logistics and transportation due to border-closings [37–41]. Transportation & traffic is discussed multiple times in connection with critical infrastructure dependencies and the COVID-19 pandemic. The interruption of

![Fig. 3. Quantity of descriptions of active sectors, affecting other sectors before the COVID-19 pandemic. The size of each section represents the count of each sector, reflecting how many of the descriptions of dependencies in the literature that were analyzed addressed each sector as an active/service-providing sector (The color scheme of the sectors has no special meaning and is intended to aid the visual interpretation of the chart). Source: Own diagram.](image-url)
transportation caused far-reaching effects on dependent sectors and supply shortages of various goods [14,40].

Further, the impacts and dependencies of constitutional institutions is well represented in the literature. For example, a paper by Levinson et al. (2020) discusses the impact of the decision by policy makers on whether schools would be re-opened on the health of children and the overall impact on society [42]. Due to the responsibility for establishing measures to mitigate the pandemic (e.g., lockdown regulations) this sector has proved to have a large impact on all other sectors. The impact can be restrictive (e.g., school

**Table 2**

| Month of publication | Title of identified literature published between March 2020 and March 2021 and including themes of the COVID-19 pandemic and critical infrastructures. |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| Mar-20 Considerations about the Cascading Effects of COVID-19 on Critical Infrastructure Sectors. | Coal sector nudges feds to deem supply chain critical as COVID-19 spreads. |
| Apr-20 A Holistic View of Health Infrastructure Resilience before and after COVID-19. The Impact of Cyber on “Critical Infrastructure” in the Next Normal - COVID-19 creates a new generation of critical infrastructure requiring new levels of security. | Covid-19 and operational resilience: addressing financial institutions’ operational challenges in a pandemic. Increases in Health-Related Workplace Absenteeism Among Workers in Essential Critical Infrastructure Occupations During the COVID-19 Pandemic. Food supply chains during the COVID-19 pandemic. How COVID-19 may disrupt food supply chains in developing countries. |
| May-20 COVID-19 Among Workers in Meat and Poultry Processing Facilities. | Vulnerability of the United Kingdom’s food supply chains exposed by COVID-19. Emergency preparedness after COVID-19: A review of policy statements in the U.S. water sector. Reopening Primary Schools during the Pandemic. |
| Jun-20 Maintaining critical infrastructure resilience to natural hazards during the COVID-19 pandemic: hurricane preparations by US energy companies. City-Scale Dark Fiber DAS Measurements of Infrastructure Use During the COVID-19 Pandemic. | COVID-19 and SME Failures. Prevalence of Underlying Medical Conditions Among Selected Essential Critical Infrastructure Workers. Food and Agricultural Transportation Challenges Amid the COVID-19 Pandemic. Covid-19 pandemic and online learning: the challenges and opportunities. COVID-19 and Food Supply Chains. US Foreign-Born Workers in the Global Pandemic: Essential and Marginalized. COVID-19-induced visitor boom reveals the importance of forests as critical infrastructure. |
| Aug-20 Destinations Matter: Social Policy and Migrant Workers in the Times of Covid. | After the COVID 19 outbreak in Italy: What have we learnt? |
| Sep-20 COVID-19 and SME Failures. | Lessons from the COVID-19 Pandemic for Federalism and Infrastructure: A Call to Action. Post-COVID-19 Reflections Around the World: A New AJPH Forum. The impact of COVID-19 on transport and logistics connectivity in the landlocked countries of South America. |
| Oct-20 COVID-19 as a Harbinger of Transforming Infrastructure Resilience. | Towards assessing critical infrastructures’ cyber-security culture during Covid-19 crisis: A tailor-made survey. COVID-19 and the Case for A National Food Emergency Stockpile. Designing a Cyber-security Culture Assessment Survey Targeting Critical Infrastructures During Covid-19 Crisis. The ERNCIP Survey on COVID-19: Emergency & Business Continuity for fostering resilience in critical infrastructures. The COVID-19 Pandemic: Implications for Critical Infrastructure. |
| Nov-20 | The COVID-19 Pandemic: Energy Market Disruptions and Resilience. Health Care Access Among Essential Critical Infrastructure Workers. The Gendered Consequences of a Weak Infrastructure of Care: School Reopening Plans and Parents’ Employment During the COVID-19 Pandemic. |
| Dec-20 | Post-COVID-19 Reflections Around the World: A New AJPH Forum. The impact of COVID-19 on transport and logistics connectivity in the landlocked countries of South America. |
| Feb-21 | The COVID-19 Pandemic: Energy Market Disruptions and Resilience. Health Care Access Among Essential Critical Infrastructure Workers. The Gendered Consequences of a Weak Infrastructure of Care: School Reopening Plans and Parents’ Employment During the COVID-19 Pandemic. |
Fig. 5. Frequency of descriptions of dependencies between critical infrastructures in literature published between March 2020 and March 2021 and including themes of COVID-19 pandemic and critical infrastructure. The band between two sectors in the graph represents the direction of dependency and frequency of description. The width of the bands at their base shows the frequency of descriptions of sectors and direction of connections between two sectors. The color shows which sector was predominantly described as ‘active’ and which was predominantly described as a ‘passive’ sector (the band has the color of the predominantly described as a ‘passive’ sector). Source: own diagram.

Fig. 6. Frequency of description of dependencies between other sectors and constitutional institutions (top left), food (top right), public health (bottom left), transport & traffic (bottom right) in literature published between March 2020 and March 2021 and including themes of COVID-19 pandemic and critical infrastructure. The band between two sectors in the graph represents the direction of dependency and frequency of description. The width of the bands at their base shows the frequency of descriptions of sectors and direction of connections between two sectors. The color shows which sector was predominantly described as ‘active’ and which was predominantly described as a ‘passive’ sector (the band has the color of the predominantly described as a ‘passive’ sector). Source: own diagram.
What if access to parks, forest, or green spaces was disrupted (e.g., through closures) and green infrastructures were not accessible during lockdown times. The authors highlight the value and previous underestimation of green areas as critical infrastructure in the past (e.g., social systems) as their functioning is rarely severely affected during or after sudden-onset disasters, have helped to avoid potential exposure to the virus in grocery stores [39, 47]. Further, infrastructures that have been considered less important of constitutional institutions as decision-makers [43] and the strain noted on ICT due to the increased use of services for business continuity and an increase in cybercrimes [47, 48].

The COVID-19 pandemic further revealed the importance of essential workers for the functioning of society [45, 49]. The absence of workforces due to sickness, transportation interruption, border-closings or private matters has jeopardized the functioning of critical services. For example, in June 2020, the German news station ‘Tagesschau’ published an article on a critical lack of trained workers in the care of the elderly in Germany. This shortage was caused by border closings due to the pandemic, which prevented Polish care workers to travel to Germany for work [15]. Walters et al. (2020) describe how the absenteeism of workforces in concentrated industries (e.g., meat packaging) due to either illness or the fear of exposure to COVID-19 caused delays in operations. Those delays

| Category                  | Description                                                                 |
|---------------------------|-----------------------------------------------------------------------------|
| Constitutional Institutions| Functions of constitutional institutions as decision-makers [43]              |
| Food                      | Essential workers for the functioning of society [45, 49]                    |
| Health                    | Essential workers for the functioning of society [45, 49]                    |
| Safety                    | Essential workers for the functioning of society [45, 49]                    |
| Security                  | Essential workers for the functioning of society [45, 49]                    |
| Economic                  | Essential workers for the functioning of society [45, 49]                    |
| Social Well-being         | Essential workers for the functioning of society [45, 49]                    |
| ICT                       | Essential workers for the functioning of society [45, 49]                    |
| First Responders          | Essential workers for the functioning of society [45, 49]                    |
| Chemical Industry         | Essential workers for the functioning of society [45, 49]                    |
| Research Facilities       | Essential workers for the functioning of society [45, 49]                    |
| Finances                  | Essential workers for the functioning of society [45, 49]                    |
| Transportation and Traffic| Essential workers for the functioning of society [45, 49]                    |
| Energy                    | Essential workers for the functioning of society [45, 49]                    |
| Water                     | Essential workers for the functioning of society [45, 49]                    |
| Public Health             | Essential workers for the functioning of society [45, 49]                    |

Fig. 7. Quantity of descriptions of active sectors, affecting other sectors since the start of the COVID-19 pandemic. The size of each section represents the count of each sector, reflecting how many of the descriptions of dependencies in literature that were analyzed addressed each sector as active/service-providing sector (The color scheme of the sectors has no significance other than to aid the visual interpretation of the chart). Source: Own diagram.
further impacted the supply chains and the availability of food products in the USA [49]. The first example showcases the issue of how the pandemic impacted one infrastructure (transportation & traffic due to border closings) which led to far-reaching impacts on the availability of workforces in other sectors (health and social services). The second example shows how the pandemic directly impacted the infrastructure food, through the absence of workforces due to illness and/or fear of contracting the virus at the workplace. Those examples highlight the important role of workforces as essential elements in critical infrastructure systems and their functioning.

Considering preparedness and protection of critical infrastructures in case of a pandemic, the sudden absence of a large number of workforces must be considered and prepared for. Further, occupational safety measures need to be put in place in order to keep operations functioning, to provide essential goods and services [50,51].

Altogether, the analysis of emphases and topics connected to the COVID-19 pandemic and critical infrastructures has revealed that new and emerging topics are increasingly discussed by authors, raising questions about what is understood as critical infrastructure.

5. Discussion

5.1. Impacts of a slow-onset crisis

Critical infrastructure failures triggered by sudden-onset events (e.g., blackout, earthquakes) are extensively described in literature, while the effects of slowly evolving strains on critical infrastructure systems (e.g., effects of an ongoing pandemic) were rarely described before the start of the COVID-19 pandemic. One of the reasons that impedes the mitigation of slow-onset crisis is that the effects of the crisis are not immediately visible. They form over time, and some can be predicted, while some cannot, but overall, it is highly challenging to assess the approaching crisis in advance. The COVID-19 pandemic poses an example of how a crisis was approaching, but awareness alone did not equate to mitigation. This is also reflected in the strain on infrastructures. While sudden-onset events like blackouts may cause severe and immediate failure, a slow-onset event like the COVID-19 pandemic starts to form slowly and the strain on critical infrastructures builds up over time. For example, the pandemic did not cause immediate and absolute disruption of work and education like a significant, sudden disaster would have done, but impacts were slowly yet long-lasting. The advantage of dealing with slow-onset crisis in contrast to sudden-onset disasters is that potentially there is time to set new mitigation measures and coping strategies tailored to counteract the effects of the approaching crisis. A disadvantage is that the perception of an approaching crisis might be subject to doubt and a government and people might be reluctant to embark on action for something that has not happened and therefore not yet affected them. The pandemic further highlighted the differences of a crisis impacting society as a whole as opposed to a sudden and intense but localized disaster (e.g., earthquake). While the impacts of localized disasters are immediate and severe, the region’s or country’s infrastructure usually maintains its functioning, supporting the limited geographic area impacted by the disaster.

The literature analysis revealed that before the COVID-19 pandemic, critical infrastructures which are typically not affected or less affected during a sudden-onset crisis, were considered as overall less critical. Recent events of the COVID-19 crisis showed that a pandemic causes steady and prolonged stress on the overall system which causes different infrastructures to become critical compared with those impacted by sudden-onset events. It will need further investigation after the end of the COVID-19 pandemic to determine whether the impact of a slow-onset crisis reveals critical infrastructures which are critical but were not recognized before, and their criticality continues to be recognized after the pandemic ends, or whether certain infrastructures only become critical in the immediate context of and only for the duration of a certain crisis. For example, the services and products of research facilities (e.g., vaccines, epidemiological analysis & information provision) became highly essential commodities during the COVID-19 pandemic, resulting in a major impact on the overall system. While research services and products are important independently of any crisis, their direct and far-reaching impact on other critical infrastructures (e.g., providing vaccines to essential health care workers) strongly increased their situational criticality in context of the COVID-19 pandemic. So far, there has been little description of which infrastructures become essential for the well-being of the population in such a case. The example of the importance of urban green spaces for physical and mental health during lock-down times shows how criticality can emerge due to a specific crisis setting. The COVID-19 pandemic led to many sports and recreational facilities (e.g., gyms, public pools) being closed for long periods of time. Considering the temporal aspect of a slow-onset crisis, if those facilities were only closed for a few days, it would hardly impact citizens’ health and well-being. But the long-term closure (weeks to months) created an essential need for people to find alternative spaces for recreation and physical activity, which were provided by green infrastructures. This example shows a situational creation of criticality due to the impacts and characteristics of a slow-onset crisis.

A further characteristic of a slow-onset crisis is the impact on the overall vulnerability of society. An analysis of the impact of the functioning of the public health sector has shown that health institutions, social systems and constitutional institutions significantly impact vulnerabilities across society. Health institutions, care centers for the elderly and schools have a high density of vulnerable individuals, who depend on service provisions [36]. During a pandemic, those most vulnerable are also those most at risk. Failure of service-providing infrastructures affects the most vulnerable individuals of our society most intensely. This emphasizes the role and the importance of functioning health, social and constitutional infrastructures during a slow-onset crisis like an ongoing pandemic.

5.2. “Humans” as a component

Humans are rarely described as a component in a system of critical infrastructures, considering their vulnerabilities, failure, and protection (e.g., effects of failure of irreplaceable experts due to sickness in the water sector; essential workers not showing up to work due to concern of their own family). A study from 2006 on the possible impact of an influenza pandemic and critical infrastructure dependencies on hospitals, addresses the importance of skilled and qualified workers to the functioning of hospitals and other critical infrastructure facilities. If a significant number of workers of critical infrastructures fall ill, the functioning of those infrastructures and
subsequently all the other ones connected to them, such as hospitals, are jeopardized [52]. An additional example is the water networks of Vienna, where operators of the infrastructure are excellently prepared for a wide range of technical failures (e.g., power outages). However, another essential component for the operation of water networks is professionally experienced workers since the water network cannot be operated without trained and experienced professionals. An analysis of the US water sector supports this, by highlighting that the functioning of drinking water utilities relies on multiple trained and specialized workers within water facilities, and also outside them (e.g., chemists, microbiologists, engineers, or public relations staff). These essential workers are crucial for the functioning of the water supply [53]. In most literature sources describing precautionary and protective measures for critical infrastructure, the measures are aimed at preventing or mitigating technical failure, and before the start of the COVID-19 pandemic the essential role of specialists was rarely mentioned. However, during the pandemic, the term ‘essential worker’ became widely known and much discussed. For example, in August 2021, US Cybersecurity and Infrastructure Security Agency published a guidance document on the safety of essential workers at their workplace. The document lists who qualifies as an essential worker (workers who conduct a range of operations and services that may be essential to continued critical infrastructure operations) per critical infrastructure sector during the pandemic and provides advice for COVID-19 risk management at workplaces [51]. This example emphasizes the importance of considering the potential effects on an infrastructure if several skilled personnel were to fail at the same time, for whose expertise or professional experience there is no substitute. Considering the risk of a shortage of workers due to illness, Flynn (2020) suggests reaching out to recent retirees and reintegrating them into the workplace for the duration of the pandemic for support as one possible solution [50]. Overall, the human being as an essential component in a critical infrastructure system needs to be paid more attention to and explored in more detail.

5.3. COVID-19 as paradigm shift

A clear change can be perceived between the focus in the literature on critical infrastructures before the COVID-19 pandemic and the literature focusing on critical infrastructure in connection with COVID-19 since the start of the pandemic. Galbusera et al. (2020) [47] conducted a study on emergency & business continuity and impacts on critical infrastructures during the COVID-19 pandemic. The results showed that the sectors transportation & traffic, public health, university & research, and public safety & civil protection were strongest affected by the COVID-19 pandemic in March and April 2020. The functioning of institutions and organizations was most affected due to health & hygiene protocols, mobility restrictions, staff unavailability, site & area isolation and working hours limitations [47]. The survey’s results showed that critical infrastructures which were identified by experts as most affected during the COVID-19 pandemic are also the ones identified in this study as intensely discussed in the literature on critical infrastructure dependencies since the start of the COVID-19 pandemic (public health, transportation & traffic, constitutional institutions). One major difference in the findings is the strong impact of the pandemic on university & research facilities, which is not reflected as a topic in the literature sources analyzed. Overall, the comparison between descriptions of critical infrastructure dependencies before the COVID-19 pandemic and since the pandemic’s start, revealed differences in the focus on sectors. While pre-COVID-19 pandemic, the main focus was on energy, water, ICT and transportation & traffic, the main focus since the start of the COVID-19 pandemic has been on public health, transportation & traffic, constitutional institutions, and the high dependency of the food sector on other sectors. These results highlight the importance of these three sectors as service providing sectors and the fragility of the food sector during an ongoing crisis like a pandemic.

Further, discussions on new critical infrastructures have emerged during the past year. In multiple countries, the importance of urban green spaces and forests for well-being and health during a pandemic has been highlighted through the COVID-19 pandemic, matching the classification of a critical infrastructure. The availability of social services like childcare services for essential staff with children has proved to be crucial for maintaining workforces and the functioning of sectors. With the increase in working from home, the dependency of many sectors on ICT increased. Though ICT had already been one of the most discussed critical infrastructures prior to the COVID-19 pandemic, its characteristic and way of impacting other sectors has changed. For example, online shopping delivery is strongly linked with ICT and has become an infrastructure providing especially vulnerable individuals with essential goods. These examples highlight the criticality of those infrastructures in maintaining vital societal functions, health, safety, security, and the economic and social well-being of people. A disruption or destruction can have a severe impact on the overall system (e.g., a disruption in child-care services can cause absenteeism of essential workers in other critical infrastructures if parents have no one to look after their children during work hours). These examples further show how situational critical infrastructures emerge due to specific circumstances. It needs to be considered whether to treat those infrastructures as overall new critical infrastructures or recognize them as situational critical infrastructures, becoming critical in specific settings.

What long-lasting impact on the perception of critical infrastructures could the COVID-19 pandemic have? The analysis from this study has shown how, in the context of the COVID-19 pandemic, new topics of critical infrastructures have emerged and have been increasingly discussed. This raises the question of whether this is a short-term phenomenon in the context of the COVID-19 pandemic, which will subside with the end of the pandemic. Or is the COVID-19 pandemic not just a phenomenon but an initiation and has it caused a permanent shift in considerations of criticality and discussions that will be carried on long after the end of the pandemic? Since the COVID-19 pandemic is still ongoing at the time of writing, no final answer can be given to these questions. However, examples from history have shown how severe disasters with a strong impact, which shocked a whole society (e.g., ice storm of 1998 led to improvements in critical infrastructure protection in Canada [17]; The terrorist attack on the World Trade Center in 2001 caused permanent changes in critical infrastructure protection measures in the USA [18]) can cause permanent changes in critical infrastructure protection, the effects of which ripple through research and policies. Even though the total impact that the COVID-19 pandemic will have on the understanding of critical infrastructures cannot be anticipated yet, the discussions that have started already show that it has provided an opportunity for an alternate perspective on criticality. Examples from guidance notes on essential
workers and workplace safety during the COVID-19 pandemic (e.g., CISA [51]) show how new considerations are integrated and adapted to existing structures and approaches, serving as an extension rather than a separate, disconnected topic. In addition, the review of critical infrastructure issues discussed in relation to COVID-19 has shown how the impact of the pandemic relates to experience and existing knowledge on criticality. This shows that emerging topics of criticality are treated as a learning experience on critical infrastructure protection, dependencies and failures, and are connected and integrated with existing topics and knowledge rather than creating a new, separate domain and school of thought.

The pandemic has impacted society as a whole. The insights gained through the impact of the recent pandemic have unraveled essential elements and weaknesses of today’s system of critical infrastructures and can be leveraged to plan for better infrastructure protection in the future. Due to this first real-world example of the impact of a global pandemic on our modern society, the COVID-19 pandemic has the potential to cause a paradigm shift in the understanding of what critical infrastructures are and what it is that makes critical infrastructures “critical”.

6. Conclusion

The COVID-19 pandemic is an unprecedented example, revealing the dependencies of our system of critical and non-critical infrastructures and how our modern society depends upon the functioning of this system. While infrastructures like water, energy, transportation & traffic, and ICT have always been perceived as highly critical, prioritized for protection measures, and well discussed in the literature, other critical and non-critical infrastructures have been neglected in discussions of what is critical and essential to our society. This study has revealed the following three main insights into the impacts of the COVID-19 pandemic on the perception of critical infrastructures and what is understood as critical:

- Often overseen critical infrastructures have been brought into the spotlight through the COVID-19 pandemic, highlighting the importance of infrastructures such as public health, social systems, and constitutional institutions. Services such as child-care, care of the elderly, and distribution systems have become highly critical and essential for the functioning of society during the pandemic. Seeing the effects of a crisis jeopardizing these services, has revealed the high dependency of our society on not only technical infrastructures but also social and other infrastructures.

- Infrastructures which were not perceived as critical before the pandemic were revealed to be critical during the pandemic. For example, online shopping and parcel delivery have become critical during the pandemic by providing essential goods to citizens and protecting vulnerable individuals from exposure to the virus during on-site shopping. Another example are urban green spaces and natural recreational areas. During lockdown periods green areas have become essential for the mental and physical well-being of citizens in multiple countries (e.g., urban forests in Germany). In those places, green infrastructure has played a significant role in providing essential services to citizens especially in urban areas, and without this infrastructure, the well-being of people and subsequently the functioning of critical infrastructures, would have been at risk. Consequently, issues arose for local communities in the surroundings of large cities to guide the mass of visitors, recreation-seeking and sporting people and to cope with negative side-effects like increased numbers of cars and road cyclists, and increased human impact on nature areas and wildlife, posing a threat to forest biodiversity [46,54]. In the context of a pandemic, the protection of natural areas therefore becomes more than just natural protection, but also protection of essential service provision to citizens.

- The COVID-19 pandemic could be a paradigm shift and act as motivator to reconsider the understanding of criticality and what classifies it. The definition of critical infrastructures by the EU law includes “… health, safety, security, economic or social well-being of people…” [10]. This inclusion of the well-being of citizens highlights its essential role in the functioning of society. Therefore, it is necessary to understand what affects the well-being of citizens and how it can be best ensured and protected. Overall, the COVID-19 pandemic has provided insight, in a way which has not been seen before, into what keeps our society functioning. This insight should act as an impulse to reflect on the values and essentials of our society and how to best protect them.

6.1. Future research

Based on the study conducted, the following topics should be the focus of future research and ideally complemented with opinions end experiences from experts and workers in the different sectors:

- **Critical infrastructures during a slow-onset crisis:** What are the effects of a slow-onset and long-lasting crisis like a pandemic on critical infrastructures? Which infrastructures are most affected and how can they be best protected?
- **Humans as a component:** What role do humans such as trained workers play in a system of critical infrastructures and what happens if a large number of workers is unable to work?
- **New critical infrastructures:** Considering the inclusion of well-being into the classification of critical infrastructures and the experience during the COVID-19 pandemic, which infrastructures classify as “critical” that were not considered critical before? What situational criticalities arise during a pandemic and how is their criticality perceived after the end of a crisis?

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.
Data availability

Data will be made available on request.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijjdr.2022.103419.

Appendix A. Identified literature

The following two tables list the literature sources which were identified and analyzed for the time period before the start of the COVID-19 pandemic (45 sources) and since the start of the COVID-19 period (35 sources).

Identified literature published before the start of the COVID-19 pandemic and including themes of critical infrastructure dependencies, protection, or failure

| Year | Author(s) | Title | Journal/Conference/Publication Details |
|------|-----------|-------|---------------------------------------|
| 2001 | Rinaldi, S.M. & Peerenboom, James & Kelly, T.K. | Identifying, understanding, and analyzing critical infrastructure interdependencies. | Control Systems, IEEE. 21.11–25.10.1109/37.969191. |
| 2004 | DelBlasio, A.; Regan, T.; Zicker, M.; Lovejoy, M.; Fichter, K. | Public Roads - Learning From The 2003 Blackout, Federal Highway Administration Research and Technology. |
| 2006 | Itzwerth, R.L., MacNulty, C.R., Shah, S., Plant, A.J. | Pandemic influenza and critical infrastructure dependencies: possible impact on hospitals. | Med. J. Aust. 185, (2006). https://doi.org/10.5694/j.1326-5377.2006.tb00712.x |
| 2006 | Lewis, L. | Critical Infrastructure Interdependency Analysis: Operationalising Resilience Strategies. | Laboratory, Argonne, IL USA. |
| 2006 | Zimmerman, R., Restrepo, C.E. | The next step: quantifying infrastructure interdependencies to improve security. | Int. Critical Infrastructures, Vol. 2. |
| 2006 | Zimmerman, R., Restrepo, C.E. | Information Technology (IT) and Critical Infrastructure Interdependencies for Emergency Response, 3rd International BCRAM Conference. |
| 2006 | Tanali, I.R. | Effects of Water infrastructure failure on response capabilities after hurricane Katrina. | The George Washington University. |
| 2007 | Gostin, L.O., Berkman, B.E. | Pandemic Influenza: Ethics, Law, and the Public’s Health. | Georgetown Public Law and Legal Theory Research Paper No. 10–62. |
| 2007 | Williams, V. | Flucomics-Preserving Our Hospital Infrastructure during and after a Pandemic. |
| 2007 | Chang, S.E., McDaniels, T.L., Mikawoz, J., Peterson, K. | Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 Ice Storm. | Nat. Hazards. 41, 337–358 (2007). https://doi.org/10.1007/s11069-006-9039-4 |
| 2007 | O’Rourke, T.D. | Critical Infrastructure, Interdependencies, and Resilience. | Engineering for the Threat of Natural Disasters, Volume 37, Issue 1. |
| 2007 | Kopyljev, J., D’Amico, A., Goodall, J. | Visualizing Cascading Failures in Critical Cyber Infrastructures. | In: Goetz, E. and Shenoi, S. (eds.) Critical Infrastructure Protection. pp. 351–364. Springer US, Boston. |
| 2008 | Riegler, C. | Risk Assessment and Critical Infrastructure Protection in Health Care Facilities: Reducing Social Vulnerability. |
| 2008 | Macaulay, T. | Critical Infrastructure: Understanding Its Component Parts, Vulnerabilities, Operating Risks, and Interdependencies. | CRC Press. |
| 2008 | Colten, C.E., Kates, R.W., Laska, S. | Three Years after Katrina: Lessons for Community Resilience. | Environment: Science and Policy for Sustainable Development, Volume 50. |
| 2008 | Fickert, L., Malleck, H. | Herausforderungen durch Abhängigkeiten der Telekommunikationsinfrastruktur vom öffentlichen Stromnetz. | E Elektrotechnik Informationstechnik. 125, 274–278. |
| 2008 | Shih, B.J., Chuang, M., Li, W.-S., Ke, S.-S. | Recent Review of Earthquake Practices on Emergency Response and Influence in Taiwan. | In: 14th World Conference on Earthquake Engineering, October 12–17, 2008, Beijing, China. |
| 2008 | Schirmpf, E.-G. | Stromausfall – und danach? | Elektrotechnik Informationstechnik 125/5: 218–220. |
| 2010 | Adams, C. et. Al. | Water Sector Specific Plan 2010 – An Annex to the National Infrastructure Protection Plan. | Waterer Security Devision. |
| 2010 | Simpson, D.M., Lasley, C.B., Rockaway, T.D., Weigel, T.A. | Understanding critical infrastructure failure: examining the experience of Biloxi and Gulfport, Mississippi after Hurricane Katrina. | Int. J. Crit. Infrastruct. 6, 246. |
| 2011 | Petermann, T., Braddock, H., Lüllmann, A., Poetsch, M., Riehm, U. | Was bei einem Blackout geschieht. | Nomos. |
| 2011 | Van Eeten, M., Nieuwenhuijs, A., Luijif, E., Klaver, M., Cruz, E. | The state and the threat of cascading failure across critical infrastructures: The implication of empirical evidence from media incident reports. | Public Adm. 89, 381–400. |
| 2011 | Grüter, T. | Offline! Das unvermeidliche Ende des Internets und Untergang der Informationsgesellschaft. | Springer Berlin Heidelberg, Berlin, Heidelberg. |
| 2013 | Kunz, M., Müh, B., Kunz-Papp, T., Daniell, J.E., Khazai, B., Wenzel, F., Vannieuwenhuyse, M., Comes, T., Elmer, F., Schröter, K., Fohringer, J., Münberg, T., Lucas, C., Zecchi, J. | Investigation of superstorm Sandy 2012 in a multi-disciplinary approach. | Nat. Hazards Earth Syst. Sci. 13, 2579–2598. https://doi.org/10.5194/nhess-13-2579-2013 |
| 2013 | FEMA: Hurricane Sandy FEMA After-Action Report, FEMA.gov. | www.fema.gov/media-library/assets/documents/33772 |
| 2014 | McRae, M. et al. | Regional Climate and Hazards Vulnerability assessment. | Eugene Springfield Vulnerability Assessment. City of Eugene. |
| 2014 | Haraguchi, M., Kim, S. | Critical Infrastructure Systems: A case study of the interconnectedness of risks posed by hurricane Sandy for New York City. | Columbia Water Center, the earth institute, Colombia University. |
| 2014 | Kicklighter, M. et al. | Water and Water Infrastructure. | The CIP report – Center for Infrastructure Protection and Homeland Security. Volume 13 Number 2. |
| 2014 | R. Zimmerman, R. | Infrastructure System Interconnectivity Effects on Resilience, presented at the National Institute of Standards and Technology International Workshop on Modeling of Physical, Economic, and Social Systems for Resilience Assessment, Dulles, VA; | continued on next page |
Continued on next page.
