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Abstract

The capacities of our infrastructure systems to respond to volatile, uncertain, and increasingly complex environments are increasingly recognized as vital for resilience. Pervasive across infrastructure literature and discourse are the concepts of centralized, decentralized, and distributed systems, and there appears to be growing interest in how these configurations support or hinder adaptive and transformative capacities towards resilience. There does not appear to be a concerted effort to align how these concepts are used, and what different configurations mean for infrastructure systems. This is problematic because how infrastructure are structured and governed directly affects their capabilities to respond to increasing complexity. We review framings of centralization, decentralization, and distributed (referred to collectively as de/centralization) across infrastructure sectors, revealing incommensurate usage leading to polysemous framings. De/centralized networks are often characterized by proximity to resources, capacity of distribution, volume of product, and number of connections. De/centralization of governance within infrastructure sectors is characterized by the number of actors who hold decision-making power. Notably, governance structures are often overlooked in infrastructure de/centralization literature. Next, we describe how de/centralization concepts are applied to emerging resilient infrastructure theory, identifying conditions under which they support resilience principles. While centralized systems are dominant in practice and decentralized systems are promoted in resilience literature, all three configurations—centralized, decentralized, and distributed—were found to align with resilience capacities in various contexts of stability and instability. Going forward, we recommend a multi-dimensional framing of de/centralization through a network-governance perspective where capabilities to shift between stability and instability are paramount and information is a critical mediator.

1. Introduction

The environments in which infrastructure need to function, adapt, and thrive appear to be faced with increasing complexity as a result of accelerating volatility, uncertainty, and system dynamics (Chester and Allenby 2018, Desha *et al* 2009, Sharma 2019, Steffen *et al* 2015). Cybertechnologies are being integrated into legacy infrastructure at rapid rates, creating remarkable new opportunities but also vulnerabilities (Chester and Allenby 2020, Rinaldi *et al* 2001). Climate change is creating deep uncertainty for weather extremes and is threatening to exceed design envelopes of critical systems (Ayyub 2018, Bondank *et al* 2018, Burillo *et al* 2017, Chester *et al* 2020b, Helmrich and Chester 2020, Nasr *et al* 2019, Underwood *et al* 2017). In the United

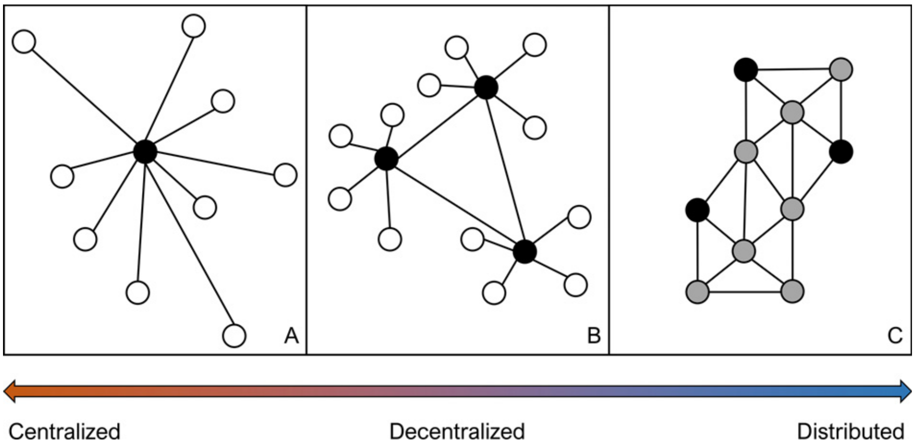

Figure 1. De/centralization configurations from a network perspective. Black lines represent distribution pathways. (A) Centralized system: single producer (black circle) linked to many consumers (white circles). (B) Decentralized system: multiple producers, connected together, that service specific consumers. (C) Distributed system: producers and cooperative consumers (grey circles) coupled together, who collectively work towards a common objective (adapted from (Baran 1964)).

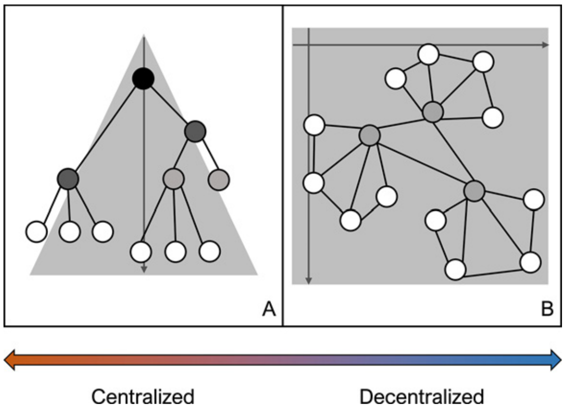

Figure 2. De/centralization configurations from a governance perspective. Darker shaded circles indicate individuals with more power. Shaded shapes depict either horizontal or vertical decentralization dependent upon grey arrow direction. (A) Centralized system: power rests with select individuals. Hierarchical structures, such as the one depicted, are classified by vertical decentralization and horizontal centralization. (B) Decentralized system: power is held by numerous individuals in the organization. Matrix structures, such as the one shown, are characterized by both vertical and horizontal decentralization.

States, ageing infrastructure are increasingly confronted with these new challenges and must adapt with scant resources to meet demand and deliver services. Infrastructure are caught between goals, administrative structures, and technologies rooted in the past, and a future defined by complexity, uncertainty, and accelerating change.

The domains of infrastructure—physical networks and governing institutions—are of major importance when examining the capacities of our critical systems to adapt and transform. Concepts of centralized, decentralized, and distributed systems are pervasive across academic literature and discourse. Centralization is often associated with networks distinguished by a small number of producers serving a large number of consumers (figure 1(A)) and a top-down governance model (Alanne and Saari 2006, Albalate *et al* 2012, Bardhan 2002, Chandler 1977, Chester *et al* 2020a; Derrible 2017, Makropoulos and Butler 2010, Pagani and Aiello 2011, Quezada *et al* 2016, Rodrigue 2020, Tomlinson *et al* 2015, Wilder and Romero Lankao 2006). Generally, centrality measures the importance of a single node in a larger network, where increased emphasis on a node produces vulnerability (by, e.g. consumers relying on the operation of a single producer for a service). A decentralized system (figure 1(B)), where the ratio of producers to consumers increases, places less reliance on a few nodes, thereby, decreasing vulnerability (Baran 1964, Freeman 1978). There does not appear to be a clear definition of distributed in the infrastructure literature, but at times the concept is used synonymously with decentralization (Ackermann *et al* 2001, Alanne and Saari 2006, Makropoulos and Butler 2010). Following framings in computer science, a distributed system is one where nodes in a network work towards a common goal (Ge *et al* 2017, Srinivasa and Muppalla 2015). A distributed network, considered here to be a subset of decentralization, is where consumers are provided with a larger variety of service options (producers) and are connected with other consumers to achieve an objective (figure 1(C)). For example, in the power sector, installed residential solar panels may produce excess energy, which can supply the grid or be stored in electric vehicles (or other batteries) and used or released back to the grid a later time (especially during emergencies). Under this configuration, the consumer becomes a coordinating node to help manage supply and demand across the system (Calma 2021, Ghasempour 2019).

In governance literature, broadly, centralization (figure 2(A)) is isolation of power to select individuals while decentralization (figure 2(B)) is the dispersion of power to many individuals of an organization (Faguet 2014, Mintzberg 1979). Decentralization can be further classified as either vertical or horizontal. Vertical decentralization is the movement of power down a chain of command, commonly found in bureaucracies, whereas horizontal decentralization is the reallocation of power across divisions (Dubois and Fattore 2009, Mintzberg 1979). Degrees of vertical and horizontal decentralization can be found in most institutions. To achieve a truly decentralized system, power would be distributed vertically and horizontally so each individual holds equivalent power. The configuration of infrastructure networks and governance has taken on a new importance under the emerging field of resilience, a field which studies a system's ability to persist, adapt, and transform to disturbances within and beyond the design envelope. Yet, there does not appear to be a concerted effort to align how centralization, decentralization, and distributed framings are used, and what different configurations mean, when adapting and transforming systems to be able to respond to increasing complexity.

Given a growing interest in configuring infrastructure to better respond to increasingly complex environments (Baldwin and Clark 2006, Chester and Allenby 2018, Gilrein *et al* 2019, Rinaldi *et al* 2001, Tomlinson *et al* 2015), a coherent framing of centralization, decentralization, and distributed (hereby referred to as de/centralization) is needed. A *polysemic* framing (i.e. carrying multiple meanings) is particularly problematic given the importance of de/centralization within network and governance domains, how systems are physically configured and how authority is structured towards adaptive capacities (Hines *et al* 2015, Mintzberg 1979). In this work, infrastructure is defined as human design spaces that produce built environment systems, including their technologies and institutions of governance. Power, water, and transportation systems are the primary infrastructure sectors of focus. The upcoming section starts by reviewing key de/centralization framings across infrastructure domains. Following, de/centralization is contextualized within emerging resilient infrastructure theory. Last, a multi-dimensional framing of de/centralization through a coupled network-governance perspective with information as a mediator is proposed, emphasizing the capabilities that infrastructure will need in the Anthropocene.

2. Background

2.1. Physical infrastructure as networks

Framings of built infrastructure de/centralization often focus on network configuration characteristics that primarily assess whether production of a good or service to a consumer occurs on a large and isolated (i.e. centralized) or small and integrated (i.e. decentralized) scale (Alanne and Saari 2006, Derrible 2017, Makropoulos and Butler 2010, Pagani and Aiello 2011, Rodrigue 2020, Tomlinson *et al* 2015). Drawing from a select body of literature that covers a diversity of framings, the use of de/centralization across infrastructure sectors is explored, and whether these framings are consistent.

Modern infrastructure systems (in the U.S. and many other developed nations) emerged to meet the rapidly increasing demand for services brought on by industrialization, and subsequent urbanization (Ansell and Lindvall 2021, Matos and Wagner 1998). Power systems initially emerged as small-scale centralized systems (a single generator servicing a portion of a city) but soon became regionally centralized as operators realized the reliability benefits of interconnected transmission; it was not until more recently that distributed generation became feasible with emerging technologies (Alanne and Saari 2006, Hines *et al* 2017, Hughes 1983, Lehtonen and Nye 2009, Pagani and Aiello 2011). A centralized or decentralized network in the power sector is determined by capacity of distribution and the proximity of generation to consumption. Power systems have been described as decentralized if their generation sources are relatively small and/or when the generation capacity is (nearly) co-located with the demand nodes. Conversely, a system leans more towards centralized when its generators are located relatively far from the loads and/or the generating capacity is relatively large (Ackermann *et al* 2001, El-Khattam and Salama 2004, Luo and Batarseh 2005). Furthermore, the power sector is discussed as becoming increasingly connected (e.g. integration of small-scale renewable technologies) (Alanne and Saari 2006, Pagani and Aiello 2011). This produces a distributed system, where greater connectivity allows more actors to work towards a goal.

Large-scale water systems (water supply, wastewater, and stormwater) emerged in urban areas because the configuration was cost-effective towards providing conveyance and treatment for growing populations. Through economies of scale, water infrastructure was able to achieve high quality service in urban areas to quickly satisfy demand and address public health concerns (National Research Council 2002, Nelson 2005). However, in low-density areas where it is expensive to expand infrastructure, site-level technologies (e.g. wells, septic tanks) can dominate (National Research Council 2002, Nelson 2005). Examining the water sector, the presence of site-level technologies that manage lower volumes of water are characterized as decentralized while municipal-scale technologies managing large volumes of water (e.g. reservoirs, combined sewer systems) are considered centralized (Gilrein *et al* 2019, Larsen *et al* 2015, Makropoulos and Butler 2010, Quezada *et al* 2016). Emerging water reuse initiatives and green infrastructure projects have provided some recent momentum towards decentralized systems (Makropoulos and Butler 2010, Nelson 2005, Quezada *et al* 2016).

Finally, the transportation sector is remarkably diverse in form and function, and as such so are its de/centralization framings of supply-demand relationships and networks. Transport supply is 'the capacity of specific transportation infrastructures and modes over a time period', and transport demand is 'mobility needs for the same time period, even if they are only partially satisfied' (Rodrigue 2020). Assessing network (infrastructure) configurations, centralized networks are described as emphasizing central nodes that minimize the number of routes to reach destinations (e.g. hub-and-spoke networks for airlines, linear transit corridors). Decentralized networks tend to be associated with point-to-point configurations where origins and destinations are directly connected, even if the route itself may not be direct (Baum and Kurte 2001, Rodrigue 2020). Network configurations are only one aspect of supply, and modes of service within the system must also be considered. Collective transportation (e.g. bus, rail, aviation) with fixed stops may be broadly classified as centralized and individual transportation (e.g. private auto, walking, biking, freight trucking) as decentralized. Collective transportation is effective at moving a large number of people (or goods in the case of freight rail, air, or marine) from one node to another within a constrained route, destination set, and/or schedule (Das and Tyagi 1997, Rodrigue 2020, Stover 1997, Toh and Higgins 1985). Meanwhile, individual transportation provides a flexibility to consumers, who are able to access destinations through a variety of routes (Rodrigue 2020). The coordination of demand enabled by emerging technologies such as navigation services informed by network-wide users can be considered distributed (Zantalis *et al* 2019).

Maybe unsurprisingly given the diverse nature of infrastructure services, framings of de/centralization in the literature differ. However, there appears to be a commonality in that framings generally consider relationships between producers (supply) and consumers (demand). Where there are few producers and many consumers the system is characterized as centralized, and many producers to consumers decentralized. Distributed appears to refer to the coordination of consumers (increasingly mediated by technology) in their consumption or production of supply. Infrastructure managers must consider tradeoffs, particularly capital costs and reliability, when designing a network (Hines *et al* 2015). Yet, there is another critical framing that must be unpacked, that of infrastructure governance configurations.

2.2. Governance as networks of power

The governance of infrastructure and its associated organizational and bureaucratic structures has significant impact on system ability to manage changing conditions (Chester *et al* 2021, Chester *et al* 2020a, Mintzberg 1979, Uhl-Bien and Arena, 2018). Decentralization of governance can be classified as either vertical through the dispersion of power through a formal chain of command (i.e. strategic leadership to middle managers to front line workers), or horizontal where decision-making power is dispersed across many employees, including those outside of the chain of command, such as analysts and operators (Mintzberg 1979). Centralization exists when the decision-making power rests with a select few, for example, strategic leadership (Mintzberg 1979). Governance—a process involving collective action for resource allocation and use across multiple civic and private actors (Kooiman 1993)—is the balance between the authority, responsibility, and power of management and individuals within an organization through rules, values, and norms (Chester *et al* 2020a, Dubois and Fattore 2009, Faguet 2014, Mintzberg 1979). While this definition emphasizes decentralization as a process, the term is also used to reference organizational structure (Abimbola *et al* 2019, Dubois and Fattore 2009, Siggelkow and Levinthal 2003). Infrastructure governance is critical for resilience because human and organizational power structures, if structured appropriately, create knowledge, allocate resources, and form bureaucracies capable of handling both stability and instability.

In the power, water, and transportation sectors, the characterization of governance de/centralization depends on the jurisdiction and scale of the organizations which manage services between the producer and consumer. Power networks (e.g. the grid), water (e.g. distribution pipelines, wastewater treatment), and transportation (e.g. roadways and railways) system governance, are often characterized as centralized governance models (Albalate *et al* 2012, Chandler 1977, Quezada *et al* 2016, Rodrigue 2020) where divisional bureaucracies emphasize a concentration of power at strategic leadership (Chester *et al* 2020a, Mintzberg 1980). In these centralized structures, the leadership team can assess where to allocate and reallocate resources across their jurisdiction to meet demand through authoritative power. Conversely, water privatization, power generation, and transportation services are characterized by numerous, independent decision makers, and therefore

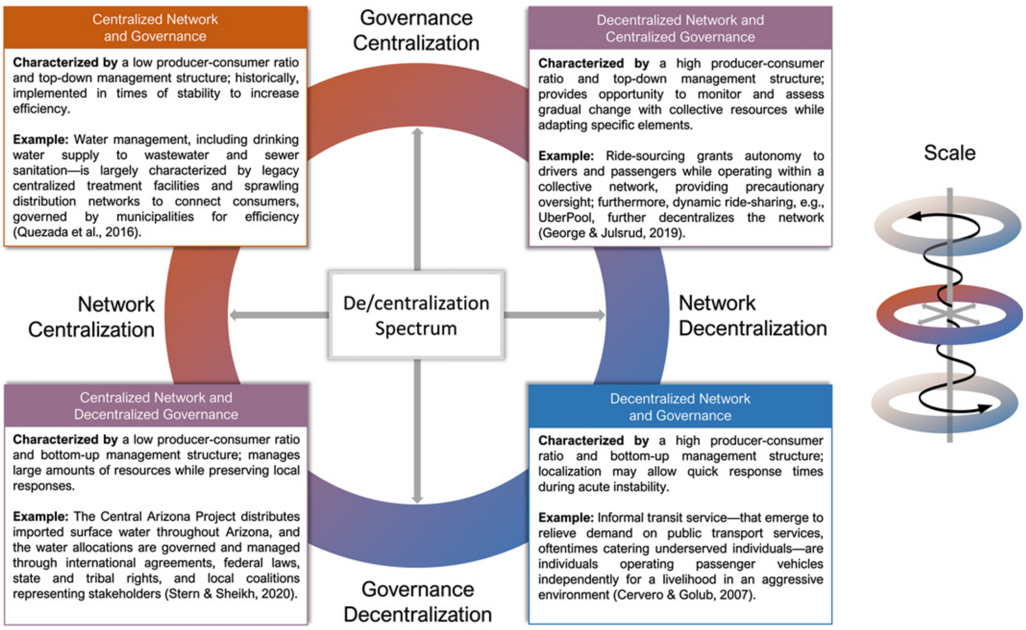

Figure 3. Examples of de/centralization classifications across network and governance domains, where water and transportation sectors are explored. De/centralization classification is highly context specific and will vary depending on scale (as depicted by the third axis on the right, where the spiral indicates that scale may shift the spectrum towards a particular configuration. At large scales, a system may tend towards centralization while at small scales decentralization.

decentralized (i.e. multiple actors, for example airlines, set their own policy) (Bardhan 2002, Larsen *et al* 2015, Quezada *et al* 2016, Rodrigue 2020, Wilder and Romero Lankao 2006). In decentralized structures, the decision-makers will be more directly connected with their producer and consumer needs; however, their access to resources may vary, which could elevate inequality of supply across marginalized jurisdictions with less power. Each governance structure allows infrastructure managers to address supply and demand within their jurisdiction.

De/centralization of governance within infrastructure sectors is characterized by the number of actors who hold decision-making power. Centralization is often framed as dominant in infrastructure systems, a remnant of system design emphasizing efficiency for times of stability, but infrastructure systems may take on various network-governance configurations—a system may tend towards centralized–centralized network and governance, decentralized–decentralized, centralized–decentralized, or decentralized–centralized. Each configuration can be found across infrastructure sectors, and select examples are presented in figure 3. There does not appear to be clear boundaries between centralized and decentralized configurations, but instead that a gradient is applicable where the degree of de/centralization is inherently relative to the geographic and operational scale (or level of complexity, (Snowden and Boone 2007)) of the infrastructure systems. Reframing de/centralization across networks and governance to support resilience is a necessary and timely endeavour.

3. De/centralization for resilience

A rigorous investigation into the conditions by which de/centralization lead to improved capacities to respond to disturbances remains underexplored and is critical for understanding how to adapt and transform infrastructure for future complexity. To respond to increasing complexity, infrastructure systems will need to be resilient while maintaining services; infrastructure resilience is defined broadly as the ability of infrastructure to respond and change to known and unknown disturbances (Park *et al* 2013, Woods 2015). Infrastructure managers can prepare for complexity by 1) recognizing the unpredictability of a future that cannot be based on past events (i.e. non-stationarity) across social, ecological, and technological contexts and 2) understanding that traditional infrastructure design approaches, and thereby much of centralized infrastructure, relied upon assumptions of stationarity (Chester and Allenby 2018, Helmrich and Chester 2020; Klein Tank *et al* 2009, Milly *et al* 2008). By relying on stationarity, it is more likely an infrastructure design envelope will be exceeded, leading to either temporary or catastrophic failure. Given the long design lives of built infrastructure, it is important to highlight governance, which may be more responsive, in periods of instability. Within infrastructure resilience literature, decentralization has been promoted as a tool to increase system resilience (Cascio 2009, Kwasinski *et al* 2019, Meerow and Stults 2016, Tomlinson *et al* 2015). This section reviews uses of

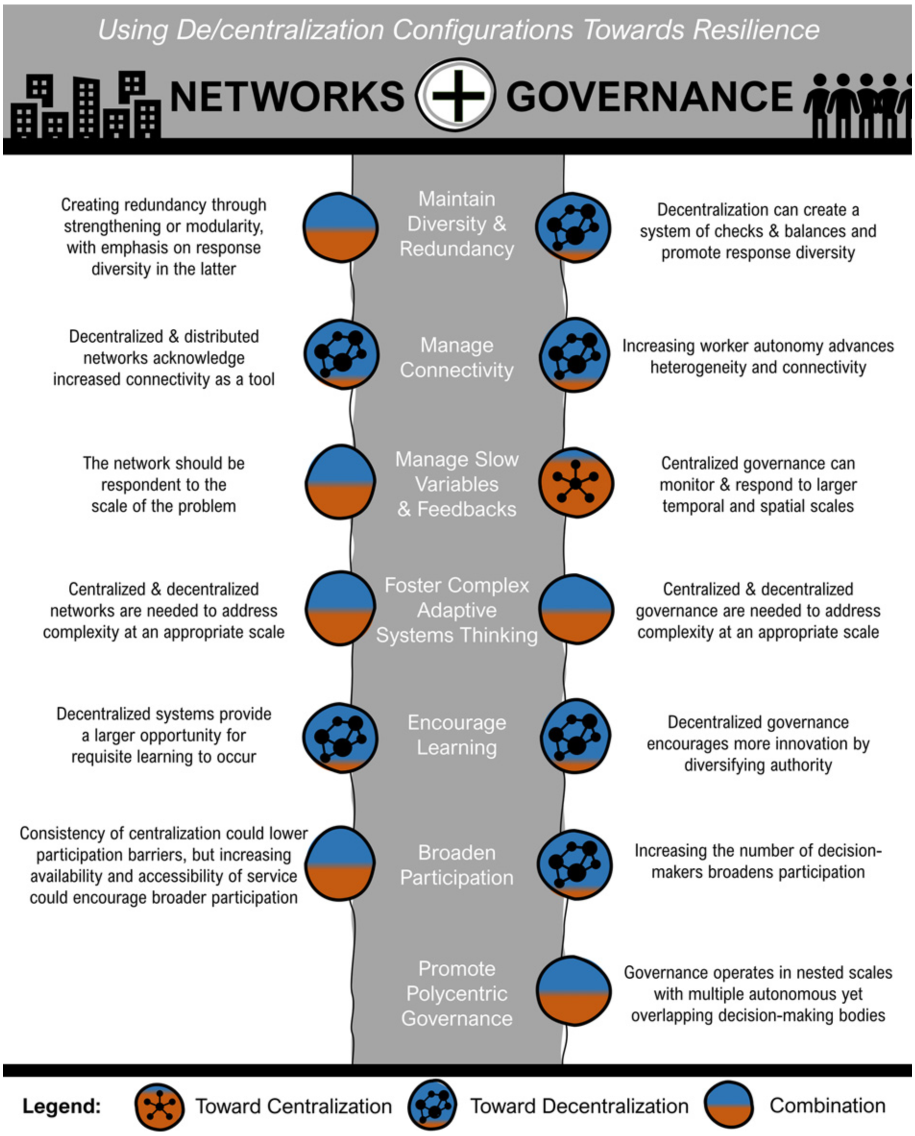

Figure 4. Examples of how increasing centralization (orange), increasing decentralization (blue), or dynamic combinations of both de/centralization in infrastructure networks and governance can influence resilience principles.

de/centralization in resilience literature and examines how de/centralization can be used to promote resilience principles.

Large-scale, centralized infrastructure systems across the United States were created to provide basic services to citizens while taking advantage of economies of scale to reduce costs, contrary to decentralized systems which leverage economies of scope to enable multifunctionality and flexibility (Faguet 2014, Gilrein *et al* 2019, Goldthau 2014, O'Flaherty 2005). While centralized governance can coordinate disturbance responses through top-down authority, it can be restricted to perspectives of leadership, who may be removed from local contexts; therefore, centralized governance is best equipped to manage known, rather than unknown, disturbances (Mintzberg 1979, Rinaldi *et al* 2001, Uhl-Bien *et al* 2007). Centralized networks, which are designed for a low probability of failure, may have increasingly severe failure consequences when they do fail (Gilrein *et al* 2019). Furthermore, centralized networks and governance are less adaptable, limited by their scale or jurisdiction (e.g. the water sector is divided into wastewater, stormwater, drinking water, etc.) (Chester and Allenby 2018, Leigh and Lee 2019, Markolf *et al* 2018, Mintzberg 1979). Centralized systems have been deemed more vulnerable to failure than their decentralized counterparts, due to their fail-safe approach and lack of redundancy and/or modularity (Ahern 2011, Baran 1964, Gilrein *et al* 2019, Leigh and Lee 2019). Decentralized infrastructure are frequently depicted as systems that service local consumers through redundancy within the network (e.g. multiple producers or pathways), and the network redundancy is seen as a principle of resilience (Ahern 2011, Zodrow *et al* 2017). Decentralization also provides an opportunity for modularity, or the capability to readily adapt or scale a system by reorganizing individual technical or institutional components without significantly disrupting the overall system (e.g. smart grids increase information flows to identify and respond

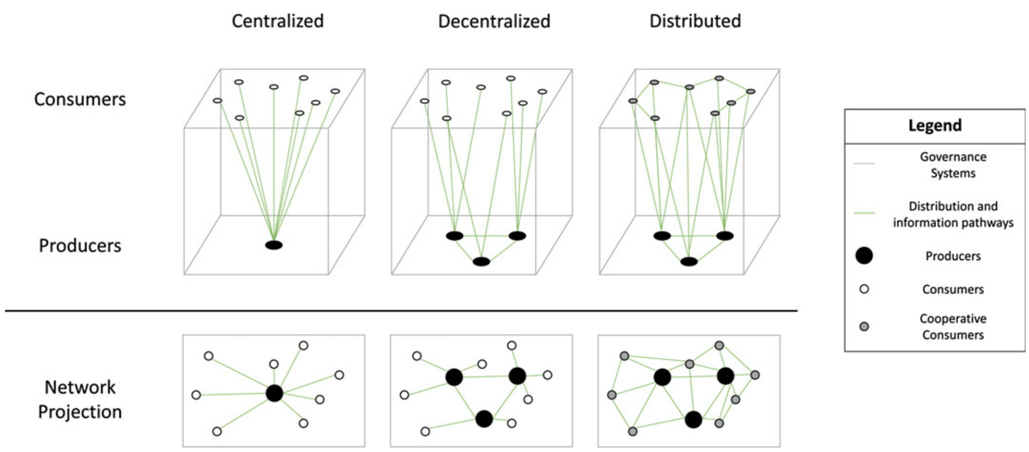

Figure 5. Multidimensional framing of de/centralization through a coupled network-governance perspective with information as a mediator. Above the horizontal line, there is an exploded view of network dynamics between producers (black), consumers (white), and cooperative consumers (grey). The green lines represent distribution and information pathways; these will be either unidirectional or bidirectional depending on the system. The grey cubes represent the governance boundaries of the system—or the rules, regulations, and norms in which the infrastructure operates. Below the horizontal line, a projection of the network is provided.

to network component failures (Li *et al* 2010)). Decentralized infrastructure systems may limit cascading failures amongst infrastructure sectors by quickly recognizing and isolating the failure (Gleick 2003, Goldthau 2014, Zodrow *et al* 2017). However, across these studies of de/centralization and resilient infrastructure, there is recognition that, while decentralized networks are frequently promoted for increased resilience, there are situations in which centralization can also be beneficial (e.g. balancing budget, reliability, and network size) (Gilrein *et al* 2019, Hines *et al* 2015, Leigh and Lee 2019, Zodrow *et al* 2017). There is less exploration of de/centralization in governance; however, complexity leadership and organizational science literature assert that the ability to transition between de/centralization, vertically and horizontally, is crucial for long-term viability because this flexibility allows organizations to traverse between modes of exploitation, i.e. business as usual, and exploration, i.e. innovation (Mintzberg 1979, Siggelkow and Levinthal 2003, Uhl-Bien and Arena 2018).

3.1. Infrastructure resilience as a de/centralization spectrum

Leveraging de/centralization as a spectrum across domains increases pathways for infrastructure managers to address growing complexity and develop resilient infrastructure. Biggs *et al* (2012) describe seven key principles of resilience: maintain diversity and redundancy, manage connectivity, manage slow variables and feedbacks, foster complex adaptive systems thinking, encourage learning, broaden participation, and promote polycentric governance. Using these principles, and the specific characteristics attributable to each, conceptual linkages between the de/centralization spectrum and resilience are proposed (figure 4). These conceptual linkages highlight the importance of recognizing both the network and governance domains of infrastructure systems, as well as the need to consider these domains in the de/centralization spectrum. As illustrated in figure 4, both centralization and decentralization can contribute to resilience efforts. Although decentralization appears to be more closely aligned with the resilience principles, there are instances where increased centralization may be warranted. Particularly, increased centralization appears beneficial when circumstance require greater levels of coordination and/or an understanding of the entire system (rather than sub-systems or individual components). Implementing and achieving all seven of the resilience principles, or even simply a subset, requires focus on both the network and governance domains of infrastructure systems. Specifically, it is important to recognize that there may be instances where resilience efforts necessitate more centralized governance in conjunction with a more decentralized network infrastructure. This dichotomy is likely to have limits, i.e. at some point, a network can become decentralized to the point of being unmanageable by a more centralized governance structure. Therefore, infrastructure managers must reimagine how de/centralization is used and promoted in network and governance domains.

4. Reframing centralization and decentralization

Towards supporting infrastructure resilience, we propose a dynamic, multi-dimensional framing of de/centralization through a coupled network-governance perspective with information as a mediator (figure 5). We hope that the perspective gained from this framing motivates managers to identify and consider trade-offs of different configurations along both the network and governance spectrums in their design process. There are two important considerations when applying the framework. First, the classification of de/centralized networks and governance relies heavily on context, specifically scale, as explored in figure 2. Second, context is further complicated by information flow—coupling legacy infrastructure with emerging information communication technologies (e.g. Internet of things, artificial intelligence) accelerates the capacity for distributed networks by increasing node connections and providing near real-time information and producing adaptive capacity that was not previously achievable. For instance, traffic maps have evolved to integrate wireless and GPS data to warn users in real-time of traffic jams and provide alternative routes (Zantalis *et al* 2019). Similarly, smart grids are growing capacity to monitor and manage electricity consumption through smart charging, taking advantage of non-peak hours and renewable energy sources, to improve service (Calma 2021 and Ghasempour 2019). Information flows must be recognized as increasingly powerful forces that are able to forge new connections between producers and consumers (as well as other emerging stakeholders, such as activists or lobbyists), while mediating existing relationships between governing bodies, infrastructure networks, and consumers. By empowering more producers and/or consumers with information (and, therefore, sense-making), as well as decision-making power to act, a system can more readily respond to instances of instability or failure.

By managing the contributions of networks, governance, and information towards de/centralization, infrastructure managers increase their opportunities to address instability. While de/centralization configurations have often been applied to infrastructure networks, exploration of de/centralization within the governance domain of infrastructure has largely been ignored. Decentralized governance has generally been shown to increase organizational performance in periods of instability since it brings the decision-making power closer to those experiencing instability or those with expertise on the topic of conflict, while centralized governance typically performs well in stability (Andersen 2004, Mintzberg 1979, Uhl-Bien and Arena 2018). As identified in complexity leadership theory (Uhl-Bien and Arena 2018), instability creates a need for organizations to: (a) transition between operational (centralized) and entrepreneurial (decentralized) leadership, a skill labelled as enabling leadership and (b) recognize a regime shift to initiate this leadership shift. First, enabling leadership must take advantage of vertical and horizontal de/centralization. While vertical decentralization brings the decision-making power closer to the situation, horizontal decentralization diversifies who has the ability to make decisions. Divisional bureaucracies seen in infrastructure systems offer limited horizontal and vertical decentralization by concentrating decision-making and sense-making towards the top of divisional hierarchies (Chester *et al* 2020a, Mintzberg 1979). Second, leadership must identify and have the capacity to respond—individually and as an institution—to shifts in the environment. If an organization continues to operate during instability with governance processes designed for efficiency under stability, they will experience failure (Snowden and Boone 2007). By recognizing the multidimensional network-governance spectrum of de/centralization, infrastructure managers are provided a more nuanced view of de/centralization that creates more solution pathways to respond to instability.

Increased flexibility of network and governance domains would increase resilience, compared to the systems that are currently rigid and locked into place—whether centralized, decentralized, or distributed. Centralized systems are dominant in infrastructure networks and governances as this configuration has served well, particularly in times of stability. Acknowledging the de/centralization spectrum and the contribution of all three configurations towards resilience, there is an opportunity to integrate more attributes of decentralized and distributed systems. Infrastructure managers must design, create, and maintain infrastructure systems that augment adaptation and respond to disturbances outside their design envelope to continue operating effectively in a world characterized by instability. In terms of infrastructure networks, an immediate action would be to consider 'maintaining diversity and redundancy.' For instance, during COVID-19, passenger airlines began transporting medical supplies as well as people, showing response diversity. This change of function, additionally, required swift institutional action, allowing passenger airlines—not only to transport cargo—but to operate with larger quantities of dry ice than previously allowed in order to maintain extremely low temperatures for vaccine shipments (Kulisch 2020). This example additionally highlights how the network and governance domains do not operate in isolation—despite being analyzed separately in much literature on de/centralization.

A spectrum of de/centralization across network and governance domains, and with consideration of information flows, provides an abundance of pathways for infrastructure managers to address complexity. Scenarios describing how change might occur can illustrate these pathways. First, there is a scenario of slow, chronic change—much like that seen in climatic conditions across the world. Here, infrastructure systems need to 'manage slow variables and feedbacks' while 'encouraging learning'. This likely requires a decentralized network to allow for experimentation but, at least some degree of, centralized governance to collect and communicate information, such as successful network adaptations or emerging climate science. However, in a second scenario, where there is a sudden, destabilizing event such as an extreme weather event or a cyberattack, the physical network cannot likely be changed in a timely manner. In this situation, decision-making power should have 'broadened participation' to allow local infrastructure managers to respond immediately while 'managing connectivity' to maximize support and provisions to the impacted region. This type of response is likely best achieved through a horizontally decentralized governance structure—a feature found in 'polycentric governance.'

Furthermore, looking across infrastructure sectors, there are likely to be different priorities and definitions of operations and failures. In the power and water sectors, there is a focus on the physical network systems and their ability to maintain constant and consistent services, including within times of failure; while in the transportation sector service is maintained to meet demand and, therefore, may change over time. (Relatedly, information flow also depends on demand—e.g. demand for information increases during times of instability when decision-makers need to respond quicky.) Viewing de/centralization as a spectrum allows infrastructure managers to consider the strengths and weaknesses of each for their particular sector and create a symbiotic relationship between configurations to respond to instability rather than to place one configuration in opposition to the other, encouraging infrastructure managers to 'foster complex adaptive systems thinking.'

5. Conclusion

As infrastructure managers pursue adaptation strategies to respond to increasing complexity in infrastructure systems and environments, they will need to confront existing configurations of networks and governance and critically examine the benefits and trade-offs of de/centralization. While existing framings of de/centralization may be polysemic, reconciling these framings expands infrastructure managers' design space to include both network and governance domains, increasing the opportunities for adaptation and transformation for infrastructure systems. It is critical that governance is observed as a domain of de/centralization. Emerging technologies that allow for rapid information sharing provide an opportunity to empower producers, as well as consumers, with decision-making capabilities to respond with speed and flexibility in instances of failure. This integration of information changes infrastructure systems from centralized or decentralized, to distributed. This increases the number of decision-makers in a system, which adds complexity along with flexibility, and confronts fundamental assumptions of who holds power. Centralization is dominant in today's infrastructure systems, but all three configurations—centralized, decentralized, and distributed—are at times appropriate for supporting resilience capacities because (1) infrastructure sectors have different priorities and, therefore, different solutions will be needed to meet each context, and (2) each configuration has varying abilities to respond to stability and instability. This reframing of de/centralization challenges infrastructure managers to develop new mental models—an evolving understanding of a system that is operational but not necessarily technically correct as it is influenced, oftentimes unconsciously, by an individual's beliefs—and, likewise, institutions to create new collective cognition (Jones *et al* 2011, Stevens and Gentner 1983). Reimagining de/centralization as a spectrum may help infrastructure managers navigate infrastructure systems through periods of instability by assessing, and reassessing, de/centralization configurations to increase actionable pathways forward for infrastructure resilience.

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Data availability statement

No new data were created or analyzed in this study.

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