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Christian Bucher, Bruce R. Ellingwood, Dan M. Frangopol (Editors)

Implications of Combined Infrastructure Concentration and Interdependency for Extreme Event Recovery

Rae Zimmerman[a]

[a]Wagner Graduate School of Public Service, New York University

Abstract: Infrastructure resilience in the context of extreme events is potentially affected positively or negatively by the combined effects of infrastructure concentrations and interdependence, occurring together. Concentration and interdependence are usually analyzed separately, and additionally, without reference to infrastructure resilience, an important need given the centrality of infrastructure to society. Concentration refers to density of facilities and/or operational controls and users at single points, extending the author's previous research using broader geographic areas. Concentrations of economic activities, social settlements, and supporting infrastructures reflect traditional economies of scale. Alternatively, literature defines infrastructure interdependence as spatial, functional, or control connectivity. Resilience used here is recovery after destructive events, though the concept is broader. The methodology involves first, defining concepts and identifying actual, representative joint infrastructure concentration/interdependence combinations from cases. Second, key prototypes and typologies for concentrated, interdependent infrastructure combinations are developed and related to resilience (duration of post-event restoration and pre-event recovery), extending research considering them separately. Third, for quantitative analysis, databases are used to define and evaluate characteristics of different concentration/interdependence combinations e.g., recovery role (positive/negative), vulnerability to threats, tightness of combinations, and flexibility. Fourth, the role of adaptations, e.g., renewable resources and green infrastructure, in reducing or redirecting concentration/interdependence to promote positive impacts are discussed in terms of effectiveness at socioeconomic and technological interfaces. Finally, implications of concentration and interdependence combinations for infrastructure management and policy are presented. The methodology is applied and evaluated for transit ridership at NYC subway stations under normal conditions and disruptions such as an electric power outage. Results indicate that concentration and its effect on interdependence varies depending on assumptions about ridership redistribution during or following an outage.

1 Introduction, Rationale and Approach

Infrastructure failures occur particularly when infrastructure facilities and operations are both concentrated and interconnected. Research on infrastructure failures typically addresses concentration or interconnectivity but not both. A unique approach is developed here that combines concentration with interconnectivity as inputs to risk assessment and other decision tools to promote infrastructure and societal resilience. The research questions integrating the two concepts are that (1) if infrastructures are both concentrated and interdependent, then adverse consequences of failure and recovery can potentially be magnified and (2) if such weak linkages are identified, then they can be isolated and strengthened by directly focusing on concentration and interdependency simultaneously. First, infrastructure concentration and interdependency concepts are introduced at multiple scales (component, system-wide, area-wide, etc.). Second, concentrations are then quantified using concentration ratios. Third, alternative interconnections are gradually introduced to identify their effect on concentration, thereby integrating the two. The method is illustrated with NYC rail transit ridership as an infrastructure activity measure. Concentrated ridership is quantified under normal (undisturbed) conditions. Then changes in concentration are observed from disturbances as power outages are introduced. Conclusions imply scalability of the integrated concepts geographically and by risk agent type. These provide valuable insights about policies and practices for deploying and designing infrastructure concentration and interconnections in positive directions to increase resilience.

2 Concepts and Types of Interconnectivity and Concentrations

2.1 Interconnectivity Concepts: Interdependence and Dependence

The term interconnection is used here as a more general term encompassing both dependence and interdependence. According to Rinaldi, Peerenboom and Kelly [31:13-14], interconnections occur in one direction (dependency) or multiple directions (interdependency), and they present a typology [31:14-16]. Characteristics of interdependency have been addressed in a large literature for engineered and economic systems [4, 6]. These attributes also emerge in the context of extreme events [54, 3], security (U.S. DHS's National Infrastructure Protection Plan), and resilience [47]. Examples of infrastructure interconnectivity are extensive. Petit et al [27: 11] organize this with a typology of interdependency effects. Interconnectivity and concentration are related to single points of failure (SPOF), where one damaged unit of a system can disable the entire system, i.e., cease its operations [49]. Infrastructure interdependencies alone are beginning to be incorporated into risk modeling for consequences, vulnerabilities, and resilience [30, 8]. Combining interdependencies and concentration provides a new direction and important, new focused inputs for risk modeling of interdependencies.

2.2 Concentration Concepts

Infrastructure concentration is used here to signify the convergence or density of facilities or activities at many different scales or levels of aggregation, from component to global levels. Concentrations can take many different forms or be described in many ways. They can be single locations or facilities that provide large shares of critical functional needs, such as a large transportation hub, an energy facility e.g., a large power plant or substation, a water collection, storage or distribution facility, or concentrated communication facilities (carrier or telecom hotels) [12: 73]. They can account for a sizable amount or percentage of a service where no or few feasible alternatives exist and where a disturbance would have widespread, widely distributed effects. They can also refer to supply or material constraints, e.g. for lithium for batteries and silicon for many infrastructures. Both are experiencing shortages. Damages at or to concentrated areas can shorten infrastructure lifespans and increase recovery times, hence affecting resilience. Concentration can occur at nodes or links, and can contribute to vulnerabilities [12: 71], and concentration points appear along many points in the supply chain.

Infrastructure concentrations are often driven by economic forces such as economies of scale and land availability for infrastructure needs as well as population concentrations in urban areas that are magnets for infrastructure [12: 73]. Other concentration forces are more opportunistic and accidental, analogous to interconnectivity (interdependencies or dependencies) [31], but the difference is that concentration does not specify connections whereas interconnectivity does. Some attributes can be highly concentrated but not be interconnected and vice versa.

Concentration per se has usually not been a direct or explicit focus of the infrastructure literature with some exceptions [26, 51]. The concept appears implicitly in network theory literature as the distance between nodes or "betweenness" [25] applied extensively to infrastructure, particularly for transportation [20] but does not capture concentration within nodes. Infrastructure concentration can occur beyond spatial or geographic concentration, i.e., not confined to a particular infrastructure location [7]. Concentration and density are related, e.g., infrastructure density is analyzed by Simonoff et al around points [35]. The simplicity of the concentration formulation presented here allows spatial and temporal flexibility in defining aggregation.

An important point is that though concentration may have negative effects on infrastructure, decentralizing infrastructure does not necessarily mean spatial decentralization, since infrastructure decentralization can occur within small areas with otherwise dense populations.

3 Framework: Metrics and Application

3.1 Interconnectivity Metrics: Dependence and Interdependence

Numerous frameworks and models portray interconnectivity described in definitions above and illustrated by cases below. Interconnectivity draws from or builds upon network principles. Networks characterize dependencies and interdependencies as nodes and links, and effects on networks can be evaluated in terms of altering the relationships among nodes and links from different assumptions about interconnections and resulting network size changes [25, 53].

Interconnections, that is, the flows among infrastructure systems at component or global scales, can be quantified in a number of different ways, as: (1) Intensity/usage factors to characterize product and service usage from each interdependent system component (2) Recovery rates for one infrastructure when affected by another upon which it is dependent [55] (3) Impact measures that signify how one infrastructure affects another (4) Resource dependency, e.g.,water demand for power production (cooling etc.) and vice versa [45], and (5) Reinforcing concentration that brings multiple infrastructures in close spatial or functional proximity.

3.2 Concentration Metrics

3.2.1 Concentration Ratios

The concentration ratio (CR) is commonly used in economics as is a related modification called the Herfindahl-Hirschman Index (HHI). The HHI was developed by Herfindahl and Hirschman about the same time (1950s-1960s). The U.S. Bureau of the Census [38] defines concentration ratios as a measure of industry competition: "the percent of output accounted for by the largest 4, 8, 20 and 50 companies (at the national level only).” The HHI uses the square of the values, and as applied to industry market share it can reflect degree of competitiveness, though Matsumoto, Merlone and Szidarovszky [13] presenting a definition of HHI identify caveats. It has been applied beyond industry sectors, e.g., to identify repetition in travel activity [36]. This paper expands the concept beyond industry applications to infrastructure which is rarely done.

Other measures and methods capture different aspects of concentration. Location quotients [39] are applied to firms or employment [40] and used in shift-share techniques in urban economics to estimate and project growth spatially [28]. Cluster analysis and spatial statistics are common [5].

3.2.2 Application of Concentration Ratios to Transportation Infrastructure

The CR and HHI in terms of rail transit station ridership are formulated as follows:

Concentration ratio (CR):

$$\sum_{i=1}^{k} R_i \qquad (1)$$

R_i=share of ridership of the i^{th} station up to threshold X%; $R_i \geq R_{i+1}$ (descending order assumed)
k=the total number of stations examined until a selected threshold is reached
k<n and is only equal to n if the threshold is 100% (but the threshold is normally << 100%).
n= total number of stations

Herfindahl-Hirschman Index (HHI):

$$\sum_{i=1}^{n} R_i^2 \qquad (2)$$

i=the station number
R=share of ridership of the i^{th} station
n=total number of stations
The CR only looks at entities below some pre-defined threshold. The HHI, however, looks at all entities. The higher the HHI relative to the minimum HHI, the more concentrated the industry is in specific firms, and conversely. The minimum HHI=1/n (no concentration). The higher the n, the lower the HHI, therefore the HHI / 1/n ratio is the significant value to use.

3.3 Concentration and Interconnectivity Combined

Using equations 1 and 2, CR and HRR ratios are a starting point and infrastructure interconnections are gradually introduced in the form of an electric power outage at points of concentration defined as transit ridership in a transportation application in NYC to test resilience. Electric power is one possible type of disruption, and the method is applicable to others. NYC has over 400 stations [19] - a good data set. To integrate concentration and interconnectivity, a number of scenarios were used for normal and disturbed conditions. First, no interconnections are assumed for a baseline comparing changes in concentration and interdependency:
(1) The ratios are first computed assuming equal distribution of ridership across all stations, which is the baseline representing complete dispersion. Stations utilize electric power equally, and if electric power goes out equally at each station, there is no effect on the concentration ratio.
(2) The ratios are then computed using actual 2015 ridership distribution among the stations [19].

Second, various alternative ridership distributions across stations are introduced given a disruption, e.g., an electric power outage, in certain parts of the system impacting ridership at stations differently:
(3) Stations are affected differently by electric power outage, thus usage differs at each station, i.e., ridership declines, is lost, or the slack is not compensated for by other stations unaffected by the outage. A specific application is presented where stations with highest ridership (42nd Street, Grand Central, 34th Street, 14th Street) are assumed to lose power and all their ridership. The CR and HHI are recomputed assuming reduced total ridership for the assumed power outage.
(4) As a key recovery mechanism for system resilience, rather than reducing total 2015 ridership, ridership lost by those few stations with highest ridership is redistributed over the remaining stations in proportion to the existing ridership at each station.
(5) Finally, rather than an even distribution, total ridership is unchanged, since ridership lost at the 4 stations is assigned evenly among 3 other stations – 59th Street nodes (west and east). They are logical ones for rerouting since they enable riders to avoid more congested stations and still connect to other routes and stations. For the CR if electric power affects stations unequally, then the order of the stations ranked by ridership share changes since ridership distribution changes. The HHI is unaffected, but changes if overall system ridership is reduced. Table 1 summarizes the five scenarios and results. The approach is flexible to accommodate other assumptions based on different distributions of ridership across the stations.

Table 1: Results of Concentration Ratio (CR) and Herfindahl-Hirschman Index (HHI) Calculations for New York City Rail Transit

	HHI***		CR
Assumptions for Ridership Distribution Among Transit Stations	Concentration Ratio (HHI) %	Relative to 0.24% base	50% highest no. of Stations
1. Equal distribution among transit stations	0.24	---	211
2. Actual 2015 distribution for transit stations	0.72	3.00	61 (the highest)
3. Elimination of ridership at top 4 stations* (10.7% decline in total 2015 ridership)	0.42	1.75	70
4. Redistribution of the ridership of highest 4 stations (no decline in 2015 ridership) equally across all remaining stations	0.47	1.96	67
5. Redistribution of the ridership of highest 4 stations (no decline in 2015 ridership) equally across three 59th St. stations**	1.07	4.50	57

Notes: *These stations are Times Sq-42 St (N,Q,R,S,1,2,3,7)/42 St (A,C,E); Grand Central-42 St (S,4,5,6,7);34 St-Herald Square (B,D,F,M,N,Q,R), and 14 St-Union Sq (L,N,Q,R,4,5,6); **These stations are 59 St-Columbus Circle (A,B,C,D,1); Lexington Av-53 St (E,M)/51 St (6); and Lexington Av (N,Q,R)/59 St (4,5,6). ***HHI scaling usually multiplies the % by 10,000, however, values here are 0-1. "Relative to base" = 1/n or 1/421 = 0.24%.

4 Examples of Actual or Potential Infrastructure Failures for Concentration and Interdependence Separately and Combined

Cases and examples of infrastructure concentration and interdependency are presented that support the research direction above. First, examples are presented for concentrations or interconnectivity of services and facilities separately [51, 52, 54], and then combined for both normal and extreme events.

4.1 Examples of concentration or interdependence separately

4.1.1 Examples of Interconnectivity Only

- The Colonial pipeline is heavily interconnected with digital technologies for operations, detection and connectivity to other infrastructures [41, 44], evident in disruptions [43].
- A power cable was removed disabling a second backup line that disrupted transit along MTA's Metro-North Railroad for over a week, demonstrating a severe ramification of an interconnection [16]. Resiliency was reflected in recovery which took close to two weeks [16], though temporary restoration measures offered passengers some service.

4.1.2 Examples of Concentration Only

Many infrastructure resources and services are concentrated at specific points from origin to use. These characteristics are relatively "benign" unless adversely influenced by an extreme event or environmental condition. Concentration has been measured as the share of some overall service or service use. For comparability 50% is used as a threshold below for some cases.

Energy infrastructure contains numerous points of concentration across the entire energy management system and types of energy resources:

- Natural gas transmission, distribution and storage are often concentrated, e.g., Henry Hub, where numerous inter- and intra-state natural gas distribution lines converge, under a single company's ownership [32] accounting for a substantial amount of U.S. natural gas and the centralization of U.S. natural gas futures pricing.
- U.S. electric power production facilities are concentrated: about half of total U.S. petroleum refineries are in just a few states, half of the power plants are in only a dozen states, and energy transmission lines often enter urban areas in a few ways [52]. Certain energy-related emissions are concentrated by industry sector also [9].
- Oil products transport occurs via pipeline, roadways, rail, or waterborne transport representing both transportation and energy infrastructures. The U.S. EIA [42] identified 8 choke points worldwide for oil transport by sea. The Colonial pipeline (also noted above for interconnection) which accounts for a large share of east coast petroleum products transported, is a single pipeline, and owned by a single company [11: 38, 43]. Spills increase impacts of concentration [2, 43].

Transportation infrastructure is concentrated by mode [51, 52: 222, 227]:

- Concentration occurs in road networks as choke points measured as traffic volume and hours of delay by INRIX [10] and the TTI [34: 42], and choke points are concentrated in a few urban areas and a few intersections within urban areas [51: 446-447). Tomer and Kane [37: 1, 6] identified goods shipment concentration across few trade corridors.
- Bridges have unique concentration characteristics evident during extreme events: single (concentrated), non-redundant components contributed to the collapse of the Mianus Bridge [21], the Schoharie Bridge [22], the Nimitz freeway in the Loma Prieta earthquake [24], and the Minnesota Bridge [23]. Some industrial accidents exhibit

analogous types of concentration [50]. Concentration also appears in normal situations, e.g., as large traffic shares at the Peace Bridge linking NYS and Ontario, the Portal Bridge where northeast coast rail traffic converges [14], and the San Francisco Oakland Bay Bridge where if it fails the commuting alternative is to go around the Bay [48].

- Rail transit is similarly concentrated for certain areas, routes and transfer points [46: 15]. Zimmerman [51, 52] summarized the following examples for rail concentrations: Far less than half of the 15 heavy rail, 25 commuter rail and 30 light rail categories in the U.S. have accounted for over half of the travel activity expressed in terms of passenger trips, rail mileage and number of stations.

4.2 Examples of concentration and interconnectivity combined for electric power, transit, and information technology (IT) infrastructure

4.2.1 Transportation/IT

On September 29, 2011, a lightning strike disabled large portions of the The Long Island Railroad (LIRR) exemplifying a concentrated system plus interconnections with IT, and the combination contributed to an increase in adverse effects. The LIRR is concentrated in being a highly centralized network (most trains go through Jamaica station), having the highest U.S. commuter rail volume, with few rail travel alternatives (MTA), and at the time of a lightning strike, the system was controlled by a single computer not well protected from weather effects. Massive delays occurred system-wide due to the singularity of the computer and convergence of lines through one station. The result was 17 stranded trains and 9 standing trains [15].

4.2.2 Electric Power and Transit

The MTA New Haven rail transit line and an electric power feeder cable are heavily interconnected, described above. In addition, the Metro-North line represents a concentrated infrastructure: ridership is second to the LIRR in U.S. commuter rail ridership [17, 18]. On September 25, 2013 the entire 8 mile New Haven Railroad service stopped for 12 days as a result of a disabled power feeder cable [16]. This affected system users [1]. The cause of the outage was attributed to damage to one feeder cable from work on an adjacent back-up feeder line – the main feeder and the back-up were located very near one another [1]. As a way of reducing the impact on passengers, the MTA relied on buses and alternate MTA Metro-North Railroad and subway lines not affected by the outage.

4.2.3 Electric Power, Transit and IT

The NYC subway system has gradually centralized its electric power controls to increase reliance of signaling on computerized control at NYC Transit's Power Control Center. It interconnects and concentrates IT, power, and transit at a single location in Manhattan; electric power is moved from signal towers located at interlockings to master towers, and then to a centralized center – the NYC Transit Power Control Center [33]. Centralization of the communications system – the "Communications-Based Train Control" (CBTC) system – replaced a "fixed-block system" where information and settings had to be made at the track level and at interlocks [29: 21]. Monitoring equipment is still decentralized but controls are centralized. The objective is to increase train performance by reducing delays from wait times and congestion due to the fixed signaling system.

5 Discussion and Conclusion

The advantage of the approach of integrating infrastructure concentration and interconnectivity rather than treating each individually is the ability to relate infrastructure attributes directly and holistically to resilience in natural or human factor contexts including climate change. In the quantification and case illustrations presented, the degree and distribution of concentration is influenced by interconnectivity. Many ways exist to change negative impacts of concentration and interconnectivity relationships with knowledge of how they are related. Many policies and practices already exist but can be strengthened, such as resource sharing, mutual assistance agreements, and improving combined concentration and connectivity in infrastructure design.

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