# The Architecture of Connectivity: A Key to Network Vulnerability, Complexity and Resilience

***Bildungscampus Heilbronn, 08 April 2022***

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**METHODOLOGICAL REFLECTIONS:**

***Relevance of Connectivity Architecture for Network Vulnerability, Complexity and Resilience issues***

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# The Architecture of Connectivity: *Background*

**Tomlinson (1999): *Complex connectivity/*Globalization -->ever-densening network of interconnections and interdependencies -> limits to growth? ->Vulnerability…**

**Reggiani (2021): *New forms of connectivity* through their dynamic and complex interplay with the economic and driving forces**

***Fundamentals:***

1. **Herbert Simon (1962) (Nobel in economics 1978): "The Architecture of Complexity" -> *Complexity* frequently takes the *form of hierarchy***

1. **Albert-Lasló Barabási (2007/45 years later the same title!): "The Architecture of Complexity"-> Complex systems require an understanding of networks dynamics, topology *and architecture***

# The Architecture of Connectivity: *My Research Question*

**My RQ:**

Can the **network architecture of connectivity**,

i.e., the interacting ***connectivity structure*** **underlying network complexity,**

be considered as a **useful** (also analytical) **framework** for understanding and interpreting – in the (spatial-) economic systems – ***vulnerability and resilience***?

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***and the related Limits to Growth?***

**Network Vulnerability and Resilience:**

1. **Definitions of** the two concepts
2. **Several indicators** of vulnerability and resilience

# Methodological Considerations: Outline

## Key Element: *Connectivity Architecture*

1. ***Explicit Connectivity:*** **Network Vulnerability and Shock Propagation:**

2. ***Hidden Connectivity:*** **Complexity in the space-economy spatial economic modelling**

3. ***Relevance of Connectivity:*** **Complexity in network analysis**

4. ***The Architecture of Connectivity*****: Resilience (capacity of absorbing shocks) Vs Vulnerability**

*Two Perspectives:*

***Spatial and Transport Economics***

# *Allan Pred (Univ. of Berkeley)(1984):*
## *31th Regional Science Association Meeting*
## *Presidential Address*

- **<To speak of spatial structures is to speak of the *behavioural rules* and *power relations*...>**

- **<The structuring of *space* is inseparable from *social structuring* processes. In the becoming of regions, the *social becomes the spatial* and the spatial becomes the social.>**

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***Spatial structure strictly linked to behaviour***

## *Peter Nijkamp & Waldemar Ratajczak (2015)*
## *The Spatial Economy: A Holistic Perspective*

**<Space is not only a passive attribute (geographical component). It plays *an active role*: it determines industrial location, commuting patterns of residents, connectivity of cities, accessibility of inner cities, transport and migration flows and so forth.>**

**38 years after Allan Pred:**

***Dynamics of interaction and integration* between *(non)physical* spatial network structures and human activities: Role of connectivity architecture?**

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**Theory? Analytical Framework? Modelling?**

# Spatial Economic Networks

- **Net-works: 'operations via nets'**: **NECTAR (1990)**

- **Spatial (economic) networks:** ordered **connectivity structure** for spatial communication/transportation which is characterized by the existence of main **nodes which act as receivers or senders** (push and pull centres), and which are connected by means of corridors and edges (Nijkamp and Reggiani, 1998)

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*The relevance of the **dynamic function** of the (spatial) networks via **organized connectivity patterns** is embedded in this definition*

# Handbook of Regional Science (Springer, 2014; 2021)

**Eds: M.M. Fischer**, Vienna University of Economics, Austria;

**P. Nijkamp**, VU University, Amsterdam

***Section: Location and Interaction***

***My Chapter: Complexity and Spatial Networks***

**by Aura Reggiani**

2. ***Complexity and Spatial Networks***
3. *Static Complexity and Models*
4. *Dynamic Complexity and Models*
5. *Complexity and Network Analysis*
6. *Spatial Economics and Network Analysis:* ***Connectivity, Emergence, and Resilience***

# Why Vulnerability?

- Over the past 21 years, there have been numerous examples where **a local disruption/disturbance has led to the global failure/interruption of systems** (11 Sept. 2001; terrorist attack in London in 2005; economic shock in 2007-2008; environmental disasters: e.g. the eruption of Iceland's Eyjafjallajokull volcano in 2010, the earthquake and tsunami in Japan in 2011, floods in Thailand in 2011, Hurricane Sandy in 2012, Covid in 2019, Russia-Ukraine war in 2022 (?), etc.)

- Relevance not only of **shock entities, but also of propagation of shocks (large scale networks)**

- Policy Issue: Relevance of the identification of the **potential 'risk areas'** in order to identify shocks in an early stage

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***How to model network vulnerability?***

# Why Resilience?

- Response to shocks: growing popularity in research
- Interconnections between economic, ecological and socio-political domains
- Batabyal (1998): "The concept of resilience itself appears to have been rather resilient"

*Other fields:*

- Andrew Zolli (2010) (entrepreneur) "Resilience: Why things bounce back"
- David Whythe (philosopher) (2014): "Robust vulnerability" (Amsterdam, 26 Sept., 2014)

# *1. Explicit Connectivity*

## Network Vulnerability and Shock Propagation

# Network Vulnerability (1)

Lack of ***a commonly accepted definition*** (Berdica, 2002; Taylor & D'Este, 2003; Mattsson & Jenelius, 2015; Reggiani et al. 2015)

**Susceptibility** of the (socio-economic) system **to harmful external pressures** (incidents, disruptions, etc.) (Seeliger & Turok, 2013)

***Vulnerability should focus on the impacts of the different threats to the network*** (Husdal, 2006):

- "***Vulnerable…where?",*** to identify the location within the network
- "***Vulnerable…to what?",*** identifying the particular circumstances or external threats and their probable occurrences
- "***Vulnerable…how?",*** addressing the particular scenario and its impact and **how the network may or may not cope with it**

# Network Vulnerability (2)

- **Vulnerability analysis: different approaches** (generalized travel costs, risk analysis, weighted multi-criteria decision approach, network weakeness indicators, etc.)

- The vulnerability of spatial economic networks is ***not a readily quantifiable concept*** **(Husdal, 2012)**

However, **strenuous conditions may not necessarily lead to a full breakdown of the network**, **if the network architecture is sufficiently equipped** to handle such events

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**Relevance of network connectivity**

Important: ***Ability to deal with the impacts and to adapt to the consequences***

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***Resilience…***

# Methodological Issues: Vulnerability and Connectivity

**Connectivity (the ease of two/multiple nodes to interact)**

**– and, mostly, its architecture –**

**seems to be a necessary condition**
**for *network vulnerability…* and mostly for…**

***Shock Propagation*!**

**How to *model shock propagation***
**in a connected network?**

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***Modelling Issues?***

# Background: Modelling Propagation
## (Contagion/Diffusion Models: Vermeer, 2012)

| | | | | | |
|---|---|---|---|---|---|
| Burt | 1987 | Contagion/ diffusion | Diffusion of medic/ technolog. innovat. | Adoption of tetracycline prescriptions | Multiple OLS regressions |
| Guler et al. | 2002 | Diffusion | Firm's adoption of the ISO 9000 in 85 Countries (1993-1998) | The use of ISO 9000 standard Quality Certification | Poisson models of regression |
| Reagans & McEvily | 2003 | Information Diffusion | Knowledge transfers within a contract R&D firm in the US | Knowledge | Auto-correlation models |
| Valente | 2005 | Innovation Diffusion | Network structures vs flow of information | Adoption of innovation | Diffusion models |
| Iyengar et al. | 2010 | Social Contagion | Adoption of a new drug among pysic. | Adoption of drug prescription | Hazard Modelling |

# Shock Propagation and Connectivity

Ragnar Frisch (**1933**) (Nobel prize with J.Tinbergen in 1969): dynamic theory in propagation studies

Propagation as a (Multidimensional)
**Flow in a Network** (Borgatti, 2005)
↓
*How the actors/nodes are affected by a propagation process (-> dimensions)*:

- ***Depth***: How far propagation effects ***will reach*** the actors/nodes? (Lee et al, 2007)
- ***Strength***: *Tendency* for the strength of a shock ***to amplify/dampen*** when the depth to which it propagates increases/decreases (Lee et al., 2007)
- ***Width***: the extent to which the propagation moves in the different ***directions*** in the network (Borgatti,

# Measures of Shock Propagation
## (Vermeer, 2012)

- ***The Depth of Propagation:***
  refers to **the distance from the origin to which a shock propagates (in network analysis: *the number of consecutive vertices which are affected)***

- ***The Strength of Propagation:***
  **refers to the extent to which a shock is propagated, i.e., *either an amplifying shock*, which increases as the depth increases, *or a dampening shock,* in which the depth causes the propagation to weaken**

- ***The Width of Propagation:***
  refers to **the direction in which a shock is propagated (in network analysis: *the percentage of vertices connected to the affected vertex in which a shock is propagated)***

***Relevance of connectivity architecture…!***

# Modelling Shock Propagation in Spatial Economic Networks (1)

- **In a network, a *shock* can manifest:**

  ***a) by adding/removing a node or a link***

  ***b) by changing parameter(s) of an actor(node) or a link***

***Cascading Disaster Models***
(Watts & Dodds, 2007)***:***

- ***Cascading disaster models* capture all three dimensions** of propagation: they consider ***the size of cascade*** to be an important characteristic of the cascade (Buzna et al., 2006)

# Modelling Shock Propagation in Spatial Economic Networks (2)

***Cascade Models***

In order **for a cascade to spread globally**, the population must contain a ***connected network*** **of vulnerable elements/individuals/nodes (easily influenced nodes), i.e., a 'critical mass' that "percolates"** and "reaches" the whole network (Stauffer and Aharony 1992)

**Connectivity – and its architecture – is a key element in network *vulnerability*!**

**My RQ:**

***What about shocks & connectivity architecture in conventional dynamic modelling?***

***-> complexity?***

# *2. Hidden Connectivity*

## Complexity in the Space-Economy

# Complexity

**"Complexity has turned out to be very difficult to define" ('From Complexity to Perplexity' Heylighen, 1996)**

- **31 Definitions of complexity and associated concepts**

➢ *From Latin:* ***Complexus*** **means 'entwined', 'twisted together'**

➢ *Oxford Dictionary*: 'Complex' if it is 'made of (usually several) closely connected parts'

- **The term 'complexity' embeds both the assemblage of different units in a system and their intertwined dynamics**

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**In other words, the term 'complexity' embeds the** *concept of dynamic network*

# Complexity and Spatial Networks (1)

## Complexity of Space-Time Phenomena

***"Large number of parts that interact in a non-simple way"*** (**Simon**,1962)

***"The primary idea of complexity concerns the mapping of a system's non-intuitive behaviour, particularly the evolutionary patterns of connections among interacting components of a system whose long-run behaviour is hard to predict"*** (**Casti**, 1979)

## Static vs. Dynamic Complexity

- ***Static Complexity*: network configuration, where the components are put together in an interrelated and intricate way** (high dimension of the network, high no. of hierarchical subsystems, type of connectivity patterns etc.)

- ***Dynamic Complexity*: dynamic (random) network behaviour** governed by *non-linearities* in the interacting components (computational complexity and the evolutionary complexity; for the latter measure: chaos and evolutionary models)

# Complexity and Spatial Networks (2)

**Important element which – in addition to the network concept – characterizes complexity:**

***the (random) dynamic interacting behaviour, which is difficult to predict***

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- The ***simplicity concept*** appears to be intrinsically related to the concept of complexity, since it seems the only way of 'governing' complexity from the scientific viewpoint

- ***Harnessing Complexity*** (Axelrod and Cohen, 2000): necessity to provide a device for channeling complexity

# When Complexity?
# Modeling the Space-Economy:
# The State of the Art

- **Static Framework (60s'-70s'):** we borrowed from other sciences, like physics, Universal Principles like *Newton's Law*, *Entropy*, etc. We refined them and applied: ***Spatial Interaction Models***

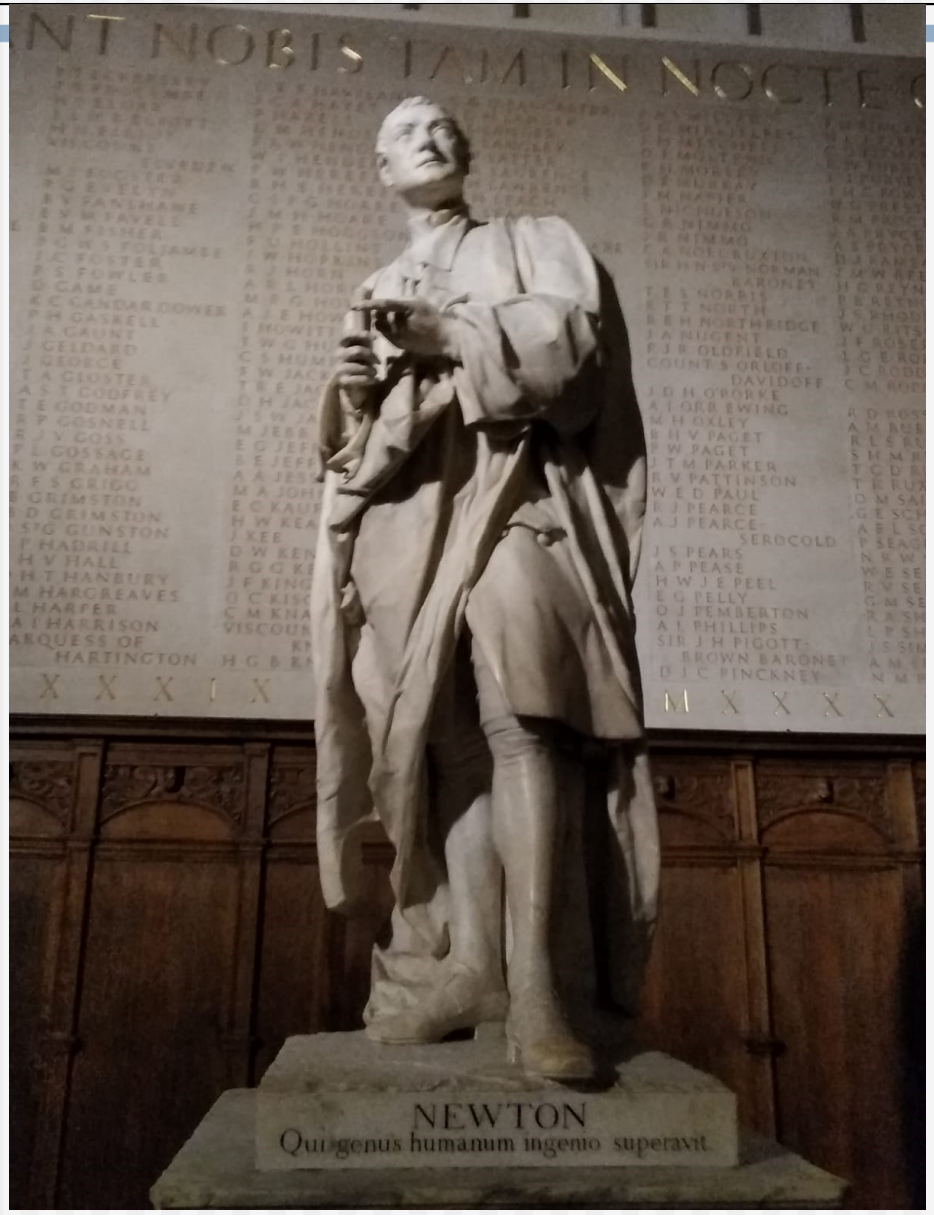
- **Dynamic Framework (80s'-90s'):** we borrowed further models from biology/ecology, like *May-model (logistic)*, *prey-predator model*, and *niche models* (*interrelated logistics*)

- **Interdisciplinary effort** by formally linking discrete choice models, especially *logit models* (from micro-economics) to entropy models (static level) and May-type models (dynamic level): stability/instability relationships

After the 1990s:

- **Complexity and Network issues**

# Spatial-Economic Models based on Newton's Law of Gravity …



# Newton's Tree (Botanic Garden, Cambridge)

# Dynamic Complexity

Chaos Theory deals with deterministic non-linear systems which are able to ***produce complex motions of such nature that they seem completely random***

- Chaos models
- Prey-predator/competition models, etc.

↓

***Irregular/unpredictable behaviour***

↓

**Explosion or Limits to growth?**

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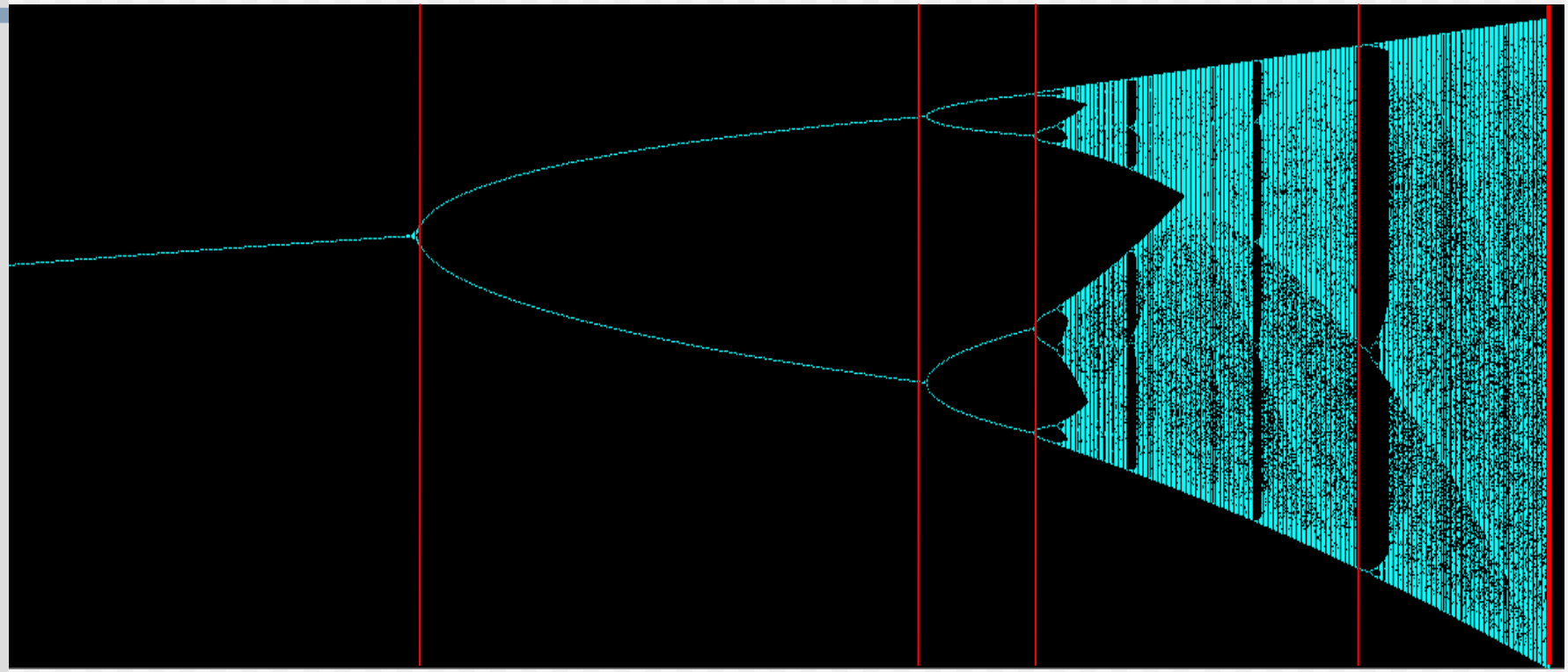
**(Hidden) Role of Connectivity Architecture?**

# Prototype Example of Chaos Model (1 dimension)-Bifurcation Diagram
## (Robert May's Logistic Map, 1976)



***Stability*** **3.0** ***Cycles*** **3.82** **4**

**Chaos**

# Evolutionary Complexity and Vulnerability

- **May's model: first 'simple'** example of **evolutionary complexity in a node/link**

- **Chaos (irregular domain) as a 'shock' in a network:** relevance of the **parameter *a*** (linked to the growth rate of variable *x*):

***High values of a:***

- networks with ***fast dynamics*** (financial/internet networks, **dynamics of infectious diseases)**
- ***links/nodes*** of the **slow networks** (particular 'windows' of the traffic systems, physical infrastructure)

↓

***Key Issue on Vulnerability: Will the stable network be able to stabilize the 'shock' of the chaotic node/link/sub-network - or will it be destabilized by this unstable area?***

***The Architecture of Connectivity is important here!***

# Complexity Models and Connectivity

***Dynamic Models:***

***Connectivity – and its architecture – is 'hidden' in the interaction parameters between nodes/variables***

**(e.g., in a chain of sigmoid/logistic functions)**

↓

**(Un)Stable Network Behaviour**

***Hidden connectivity: Links' structure is not tangible***

**What about in network analysis (**Barábasi, 2007**)?**

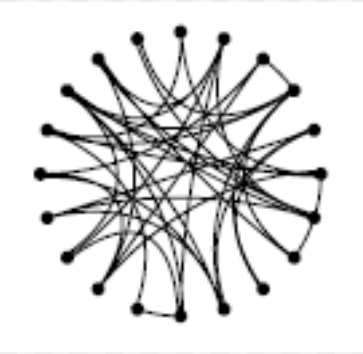
**Connectivity is the Core of Complex Network Analysis**

# 3. Relevance of Connectivity

## Complexity in Network Analysis

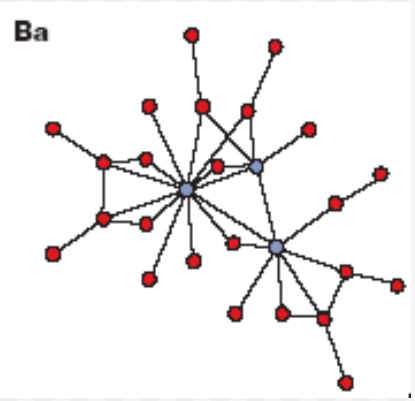
# Complex Network Analysis: Common Behaviour based on Simple Connectivity Structures (1)

***Connectivity degree distribution*: *probability that a node has k links to other nodes***



- **Random Network** (Erdos and Renyi, 1960):

  **- Most nodes have the same no. of links**




- **Scale-free (*Centralised-Hub)* Network** (Albert and Barábasi, 1999):

  **- Hubs: A few nodes with a large no. of links!**

***However: lack of theory…***

**High speed train – Air transport network – Internet – Social networks**

# Complex Network Analysis: Common Behaviour based on Simple Connectivity Structures (2)

- **Barabási**: **Hubs** **as preferential nodes/attractors**

- Very **simple operational approach**: *Hub/hierarchy of hubs* exists for specific values of *γ* coefficient of the power-law distribution of the links (2<γ<3)

**RQs:**

- Adoption of multiple connectivity indicators?
- Strength of the links? **Simon**(1962)? Same title in the two papers..- > **(Non)decomposable system** -> (strong)negligible links; **nearly-decomposable** -> strong intra-links vs. weak inter-links

↓

***Economic weight of the links…***

# Complexity and Hub Networks

Are the **more connected nodes (Barabasi)** also the most **important** from the economic viewpoint or more 'open' to innovation, growth and mobility **(Simon)? ->RQs**:

- **Current increase of SF networks (Centralised/Hub Networks)** – in this complex globalized world – as an instrument for decoding complexity? (e.g. Google)

- **Is a HN (the network of hubs/major centres)** able to **capture the complex dynamics of the whole system** (e.g. knowledge communication)?

↓

***Influential(s)? -> cascade models?***

↓

**The City Network of 17 cities in Germany crossed by High-Speed Train captured 60% of total employment (in 2007)**

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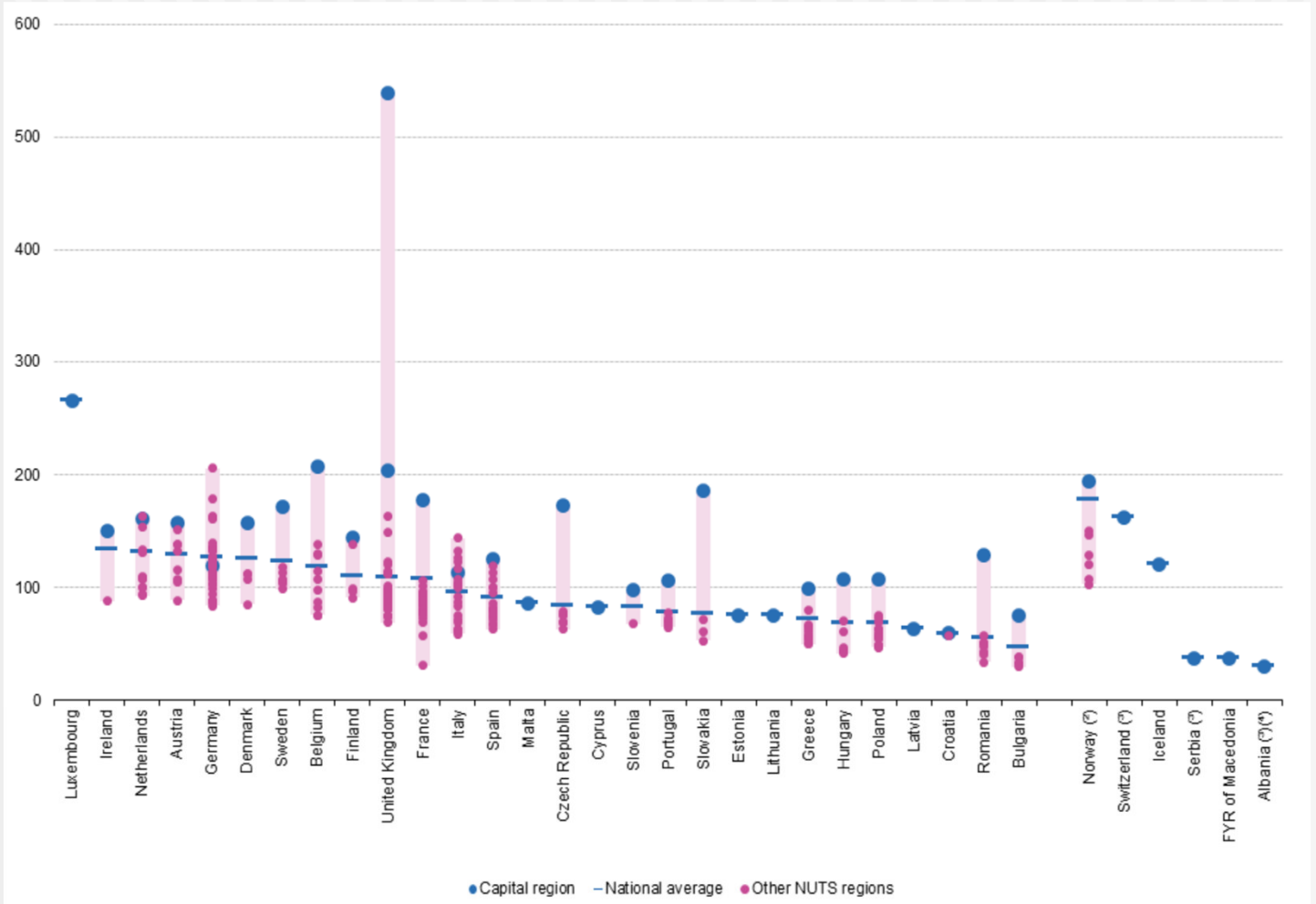
- **Is a HN able to capture complex dynamics also in terms of Vulnerability?**

# Hubs: Capital Regions in the EU (GDPpc) (Network?)




(1) The light lilac shaded area shows the range of the highest to lowest region for each country. The blue bar shows the national average. The blue circle shows the capital city region. The lilac circles show the other regions. Liechtenstein, Montenegro and Turkey: not available.
(2) 2013.
(3) National data.
(4) Provisional.

# Network Structures and Vulnerability

- ***Hub/SF* networks** are ***highly resistant to random failures*** *(*substantial number of links can fail and still not affect the performance of the network as a whole)

- ***Hub/SF* networks** are ***very vulnerable to a deliberate attack directed against the major hubs***

**Relevance of hub hierarchy**

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**Emerging Policy Issue: to design Random networks**
**or how to design 'resilient' Hubs/SF networks?**

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**Resilience -> Measures of Hub Resilience?**

# *4. The Architecture of Connectivity:* Resilience in Spatial and Transport Economics

## A) Towards Network Resilience

# Resilience Background

In USA: Adoption of **Resilience as Policy Objective, mainly after Sept. 2001**

↓

UK Report **"Network Resilience and Adaptation"** (Highways Agency, **2010**):

↓

EU-JRC **"Building a Scientific Narrative Towards a More Resilient EU Society" (2017)**

**Role of resilience in the US National Academies strategic actions**

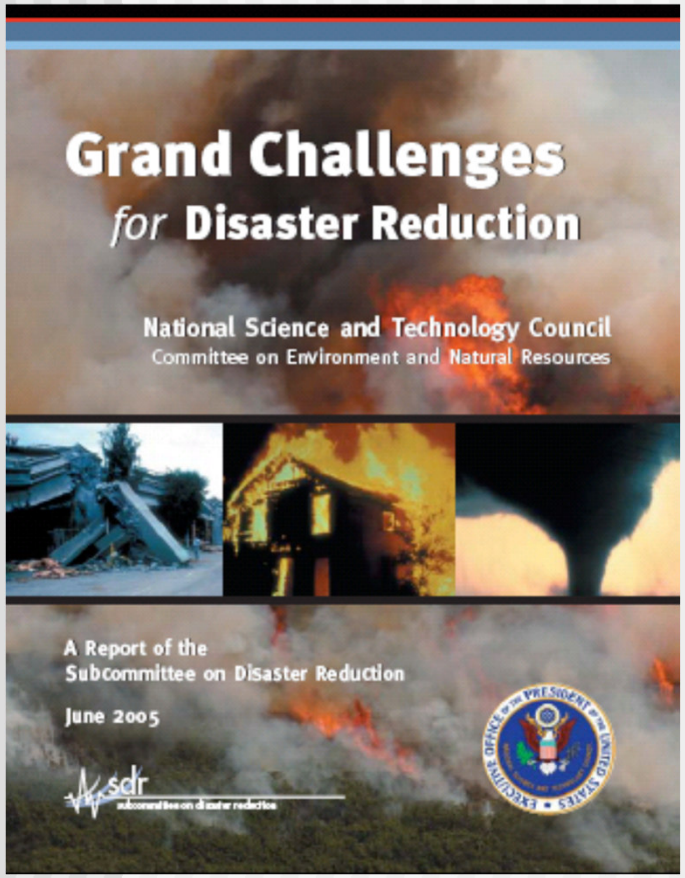
↓

***What is Resilience?***

# Disasters Roundtables of the National Academy of Sciences in The United States January 2001 (http://dels-old.nas.edu/dr/)

25: Children, Youth and Disasters (Thursday, June 25, 2009)
24: Cascading Disasters: How Disasters Unfold
23: Making the World Safer from Disasters: The U.S. Role
22: Disaster Risk Management in an Age of Climate Change
21: Disaster Recovery
20: Creating and Using Multi-Hazards Knowledge and Strategies
19: Protecting Lives and Property at our Coastlines
18: Citizen Engagement in Emergency Planning for a Flu Pandemic
17: Rebuilding for Health, Sustainability, and Disaster Preparedness in the Gulf Coast Region
**16: Community Disaster Resilience**
15: Law, Science, and Disaster
14: The Indian Ocean Tsunami Disaster: Implications for U.S. and Global Disaster Reduction and Preparedness
13: Lessons Learned Between Hurricanes: From Hugo to Charley, Frances, Ivan, and Jean
**12: Creating a Disaster Resilient America: Grand Challenges in Science and Technology (Workshop in 2004; National Research Council)**

# *Six Grand Challenges for Disaster Reduction Identified by the National Science and Technology Council (2005)*




1. Provide hazard and disaster information where and when it is needed.
2. Understand the natural processes that produce hazards.
3. Develop hazard mitigation strategies and technologies.
4. Recognize and reduce **vulnerability** of interdependent critical infrastructure
5. Assess disaster **resilience** using standard methods.
6. Promote risk-wise behavior.

Note: In this document, the terms **disasters and hazards encompass events with both natural and technological origins.**

# Resilience Concept: Background

- The etymology of the word **"resilience"** is the Latin verb "**resilio",** meaning to re-bound"(Rose, 2009)

- Starting with **MacArthur (1955),** ecologists have investigated the properties of a number of **different stability-related concepts,** for instance, the concepts of *persistence, resilience, resistance, robustness, etc.*

# Resilience

In general, ***Resilience*** **refers to the "capacity of a system to <u>retain its organisational and functional structure</u> following perturbation of some state variable from a given value" (Perrings, 1994)**

↓

**My RQ: Resilience embedding 'connectivity' features…?**

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**Original definitions in the literature**

# Resilience: Definitions

- ***Engineering Resilience*:** refers to the properties of the system near some stable equilibrium. This definition, due to *Pimm (1984),* takes the **resilience of a system to be a measure of the speed of its return to equilibrium**

- ***Ecological Resilience*:** refers to the **perturbation/shock that can be absorbed** before the system is displaced from one state to another. This definition, due to *Holling (1973, 1986, 1992),* **does not depend on whether a system is at or near some equilibrium**

(see, among others, Gibson, **Ostrom**, Ahn, 2000; Reggiani et al., 2002; 2015)

↓

***Role of network connectivity not emphasized…***

# Engineering Resilience vs. Ecological Resilience

- **Engineering resilience:** more feasible
- The assessment of a single equilibrium – when dealing with simple dynamic systems – can be achieved by means of differential/difference equations
- **Ecological resilience** refers to extent of shock that a local domain is able to absorb before it is induced **into some other equilibrium** (**adaptivity**) (for the adaptivity concept: Levins et al., 1998; **Ron Martin, 2012**)
- **Ron Martin (2012**): Resilience **indicator** based on the dynamics of **regional employment (Unique Variable)**

↓

**Network considerations are missing here…**

**Table 3.** Different interpretations for spatial economic resilience

| Author(s) | Year | Main Field | Definition | Kind of Resilience |
|---|---|---|---|---|
| Adger | 2000 | Community | 'the ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change' (p. 347) | Ecological resilience |
| Ashby et al. | 2008 | Local places | 'the extent to which local places and local government are capable of riding the global economic punches, working within environmental limits, dealing with external changes, bouncing back quickly, and having high levels of social inclusion' | Both kinds of resilience |
| Bristow | 2010 | Places | 'Resilience emphasises the importance of healthy, dynamic local businesses—businesses which are 'competitive' and successful—and yet it does so in a manner which sees virtuous interrelationships between competition, environment and distribution' (p.156) | Ecological resilience |
| Bruneau et al. | 2003 | Community | 'the ability of social units […]to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes' (p. 735) | Engineering resilience |
| Coles and Buckle | 2004 | Community | 'the total of the individual elements that thorough capacities, skills, and knowledge are able to participate fully in recovery from disasters and to cope with wider social, economic and political communities' (p. 6) | Engineering resilience |
| Davies | 2011 | Region | 'the capacity of a regional economy to withstand change or to retain its core functions despite external upheaval', (p.370) | Both kinds of resilience |
| Foster | 2007 | Region | 'the ability of a region to anticipate, prepare for, respond to and recover from a disturbance' (p.14) | Both kinds of resilience |
| Hill et al. | 2011 | Region | '[regional resilience] is the ability of a regional economy to maintain or return to a pre-existing state (typically assumed to be an equilibrium state) in the presence of some type of exogenous (i.e., externally generated) shock' (p. 1) | Engineering resilience |
| Martin | 2012 | Region | 'the capacity of a regional economy to reconfigure, that is adapt, its structure (firms, industries, technologies and institutions) so as to maintain an acceptable growth path in output, employment and wealth over time' (p.10) | Ecological (adaptive) resilience |
| Paton and Johnston | 2001 | Community | 'the capability to "bounce back" and to use physical and economic resources effectively to aid recovery following exposure to hazard activity' (p. 158) | Engineering resilience |
| Pendall et al. | 2010 | City | 'Resilient city would be one that resumed its previous [economic/population/built form] growth trajectory after a lag' (p. 73) | Engineering resilience |
| Pendall et al. | 2012 | Region | 'A resilient region, is one whose governance decisions identify and anticipate stresses, avoid those that can be avoided, and mitigate those that cannot, thereby protecting individuals and households from many harms and helping them recover from others' (p. 272) | Both kinds of resilience |
| Pfefferbaum et al. | 2005 | Community | 'the ability of community members to take meaningful, deliberate, collective action to remedy the effect of a problem, including the ability to interpret the environment, intervene, and move on' (p. 349) | Ecological resilience |
| Rose and Liao | 2005 | Firm and region | 'inherent ability and adaptive response that enables firms and regions to avoid maximum potential losses' (p.76) | Engineering resilience |
| Swanstrom | 2008 | Region | 'a resilient region would be one in which markets and local political structures continually adapt to changing environmental conditions and only when these processes fail, often due to misguided intervention by higher level authorities which stifle their ability to innovate, is the system forced to alter the big structures' (p. 10) | Ecological resilience |
| Wolfe | 2010 | Region | 'how a particular economy gets locked into a specific pattern of growth through a cumulative series of decisions over time. This perspective is also concerned with how new paths are launched and regions alter their trajectory of development' (p.140) | Ecological resilience |

| Authors, year | Sub-division | No. of vars. | Variables | Weighting |
|---|---|---|---|---|
| Graziano, 2013 | Infrastructure<br>Innovation and technology<br>Socio-economic | 19 | Broadband services<br>Electrical network<br>Energy networks<br>Rail infrastructure<br>Application of designs<br>Application of models<br>European application of designs<br>European application of models<br>Patents<br>Bank deposits<br>Business density<br>Housing<br>Liquidity ratio<br>Loans to firms<br>Non food consumption/total consumption<br>Pensions per capita<br>Population growth rate<br>Return on equity<br>Value added per capita | Factor analysis |
| Martin, 2012 | Socio-economic | 1 | Employment | - |
| Resilience Alliance, 2009 | Infrastructure<br>Natural environment<br>Socio-economic | 10 | Water table depth<br>Water table equilibrium<br>Biodiversity measure<br>River condition<br>Riverine ecosystem condition<br>Soil acidity<br>Water infrastructure<br>Balance among values held<br>Farm income<br>Presence of high multiplier economic sectors | Equal weight |
| University at Buffalo Regional Institute, 2011 | Community<br>Socio-economic | 12 | Civic infrastructure<br>Home ownership<br>Without disability<br>Business environment<br>Economic diversification<br>Educational attainment<br>Health insured<br>Income equality<br>Metropolitan stability<br>Regional affordability<br>Out of poverty<br>Voter participation | Equal weight |

# Spatial Economic Resilience
## (*Review Paper* by Modica and Reggiani, *NETS*, 2015)

- Recessionary, industry and disaster shocks
- **Both engineering and ecological/adaptivity resilience** of a region/community/urban area

- ***No theoretical study!***
- Multiplicity of applications in USA, EU, UK and Italy
- **Scale of analysis**: local/urban/region->**no network!**

- *Different* **socio-economic indicators** (**mobility/interaction factors are rarely present)**
- *Different* methods and measures (econometric models, regression analyses, performance indices)

***No connectivity or network considerations!***

# Transport Resilience
## (*Review Paper* by Reggiani, Nijkamp, Lanzi, *TRA*, 2015)

- ***Similar*** *concepts:* **Robustness** (Engineering resilience); **Reliability** (Ecological resilience):
  - *Operability* of the network under strenuous conditions
  - *Ability to continue to function after shocks* (Husdal, 2005)

- **Rare empirical applications of resilience** in transport:
  - *Change in modal split after terrorist attack* on the London subway and bus bombing in 2005 (Cox et al., 2011)

- **Several simulations of network robustness/reliability** (Nagurney and O'Kelly in the USA; Knoop in Holland)

- **Only recently**: transport resilience (Gonçalves & Ribeiro, 2020)

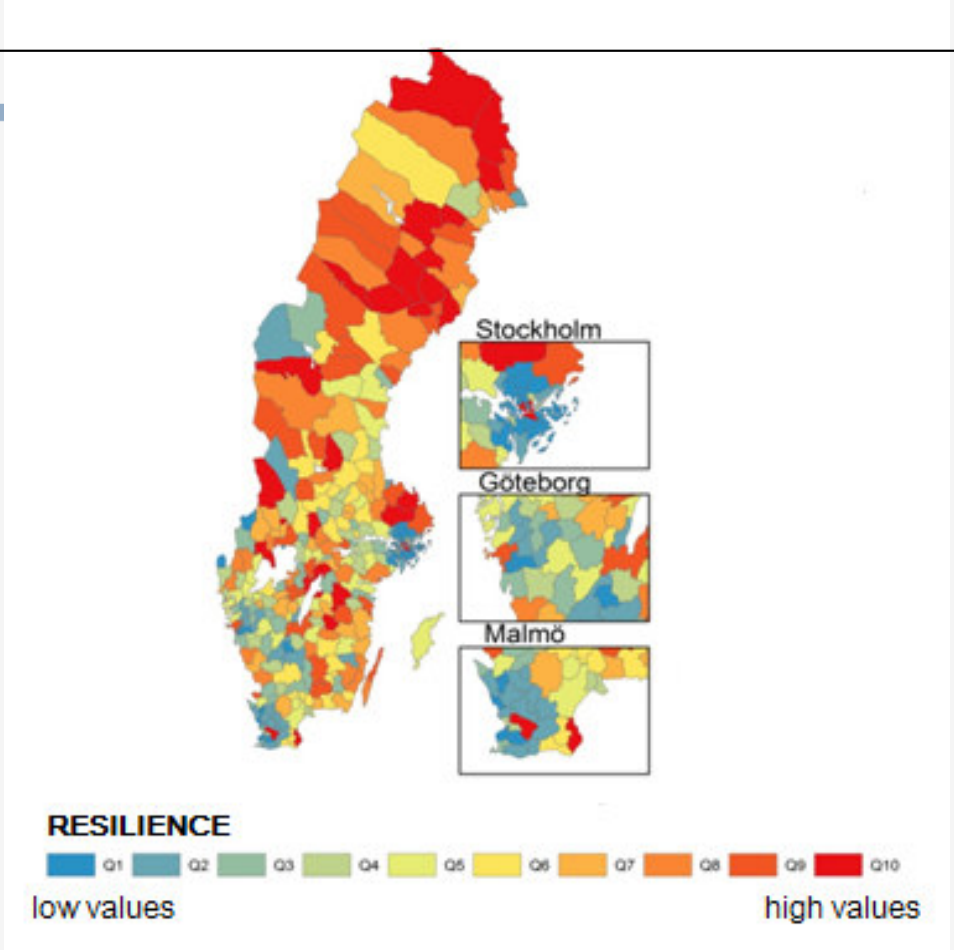
# Measuring Resilience in Urban Areas in Sweden
## (Osth, Reggiani, Galiazzo, CEUS, 2015)

**RCI (Resilience Capacity Index)** (Foster & Cowell, 2013): http://brr.berkeley.edu/rci/

- **12 Socio-economic (*not mobility*) indicators**
- Three components (at municipality level in Sweden)
  - **Economic Capacity (4 indicators)**
    - income equality (income distr. Gini), economic diversity (deviation from national industrial mix), affordability (housing market – related to income in SE), and business environment (ranking of local business climate)
  - **Socio-demographic capacity (4 indicators)**
    - Educational attainment (% 25+ with Bachelor's degree), 'Without disability' (share of pop without need of care), 'out of poverty' (% pop above the poverty-line) and health insured (sick leave in Sweden)
  - **Community capacity (4 indicators)**
    - Civic infrastructure (share of '*NGO*' workers), metropolitan stability (Stability of pop), Homeownership (residing in owned home), and Voter participation (share voting)

# Resilience and Hubs

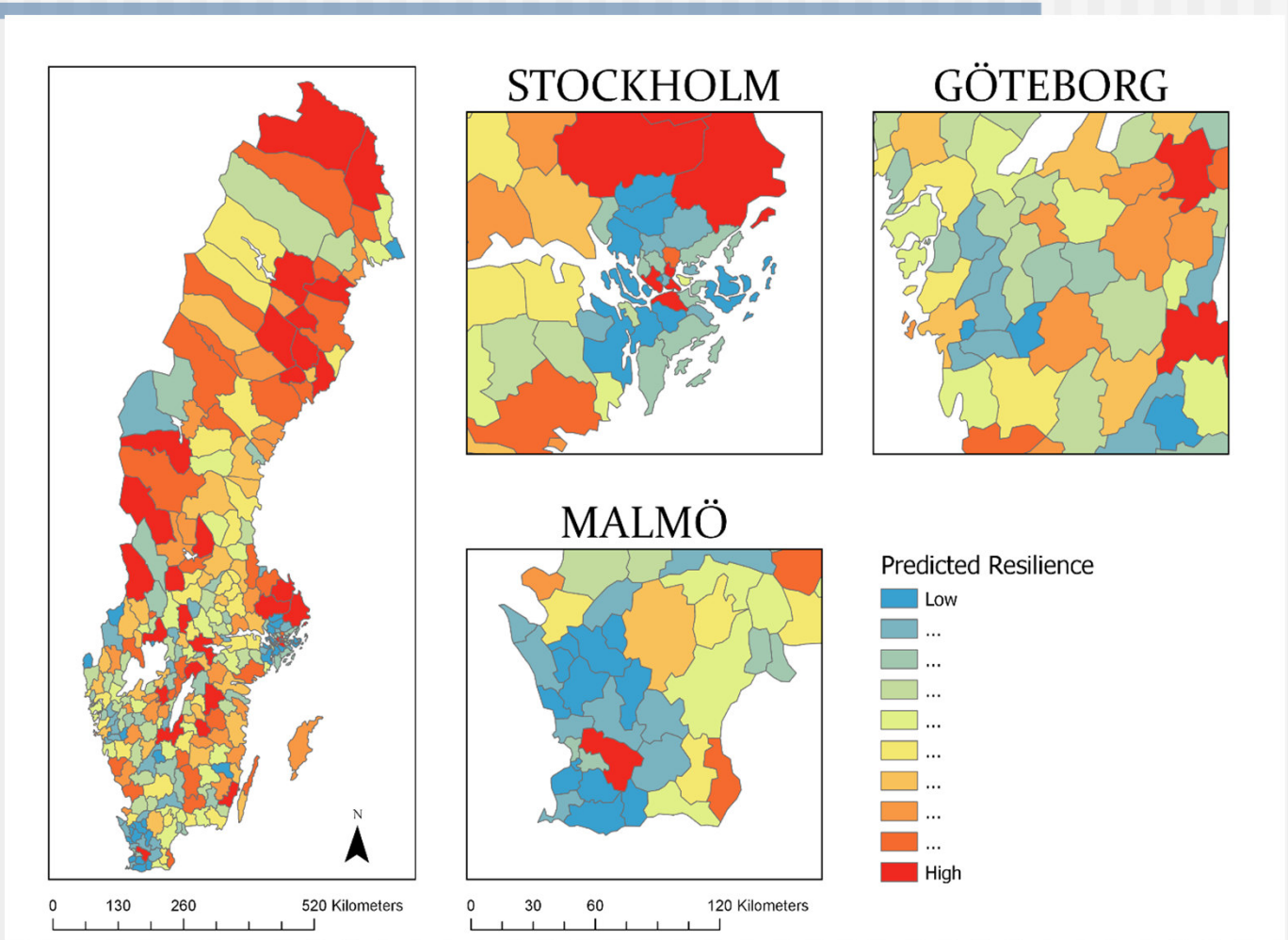
## (Östh, Dolciotti, Reggiani, Nijkamp, 2018)




**The most resilient municipalities are the biggest and are also knowledge cities (Stockolm, Göteborg, Malmö)**

***More network opportunities for social engagements and recreative and intellectual activities (social capital)***

# Resilience and Network Connectivity
## (Östh, Dolciotti, Reggiani, 2020)




**Positive impact of (topological) network connectivity on socio-economic resilience**

# Towards Network Resilience: Reflections

- **Spatial economics: Connectivity or network indicators have rarely been considered in the economic analysis of resilience** (Boschma, 2015; Caschili et al, 2015)

- **Transport: only recently first attempts of considering network connectivity indicators of resilience** (Bešinović, 2020)

**<u>Towards Network Resilience</u> -> Role of Hubs/Hierarchy**

↓

***Hubs can be very resilient, but also very critical for the network***

↓

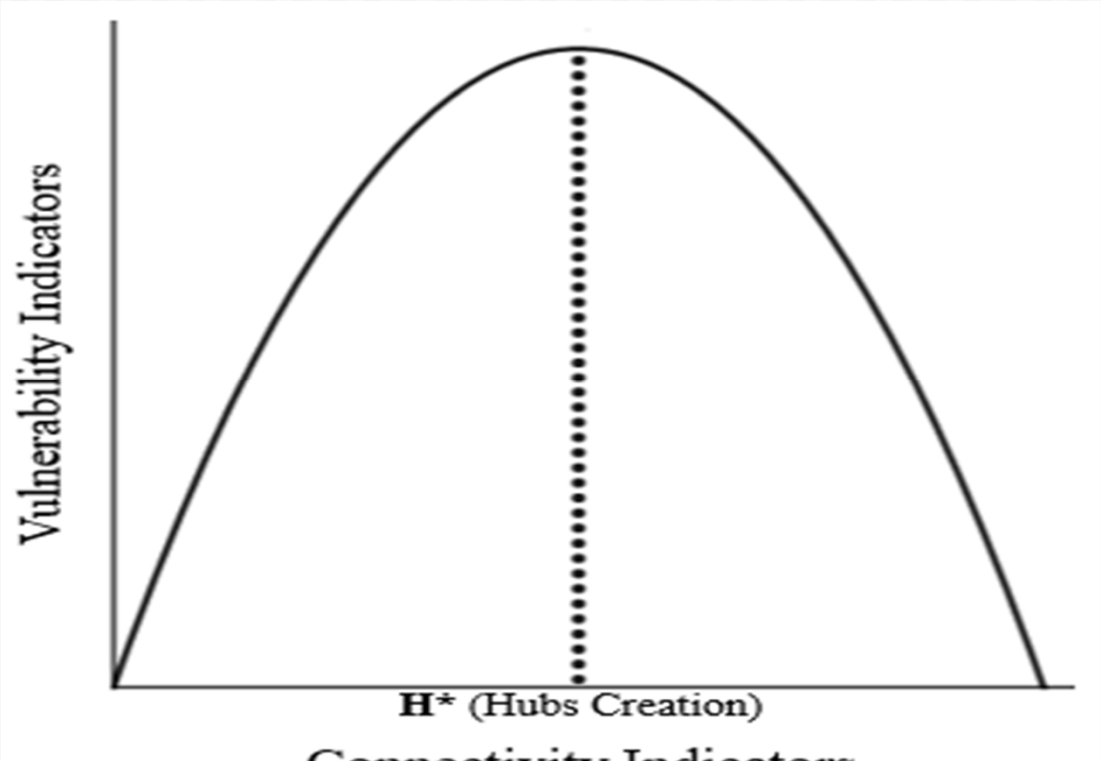
**Connectivity architecture-> hubs -> vulnerability -> connectivity -> resilience**

# *4. The Architecture of Connectivity:* Resilience in Spatial and Transport Economics

## B) From Network Vulnerability to Hubs' Resilience

# The Vulnerability-Connectivity Curve (Kuznets Curve)

- **In a complex network, connectivity increases in order to build up the *hubs* (point *H**), which are also *vulnerable nodes* for the network: SF network**
- **Above this value *H* (SF network realization)*, connectivity can be the instrument able to enhance resilience, which is, in turn, a way to reduce vulnerability**



# Some Considerations

- **Connectivity -> fundamental role by creating various network architectures ->** hierarchical networks, hub-and-spoke networks, etc. ->hubs

- **Vulnerability vs. Creative Destruction:** small changes - which can provoke chaos in the hubs - are not necessarily negative, **thanks to the network connectivity architectures leading to resilience**

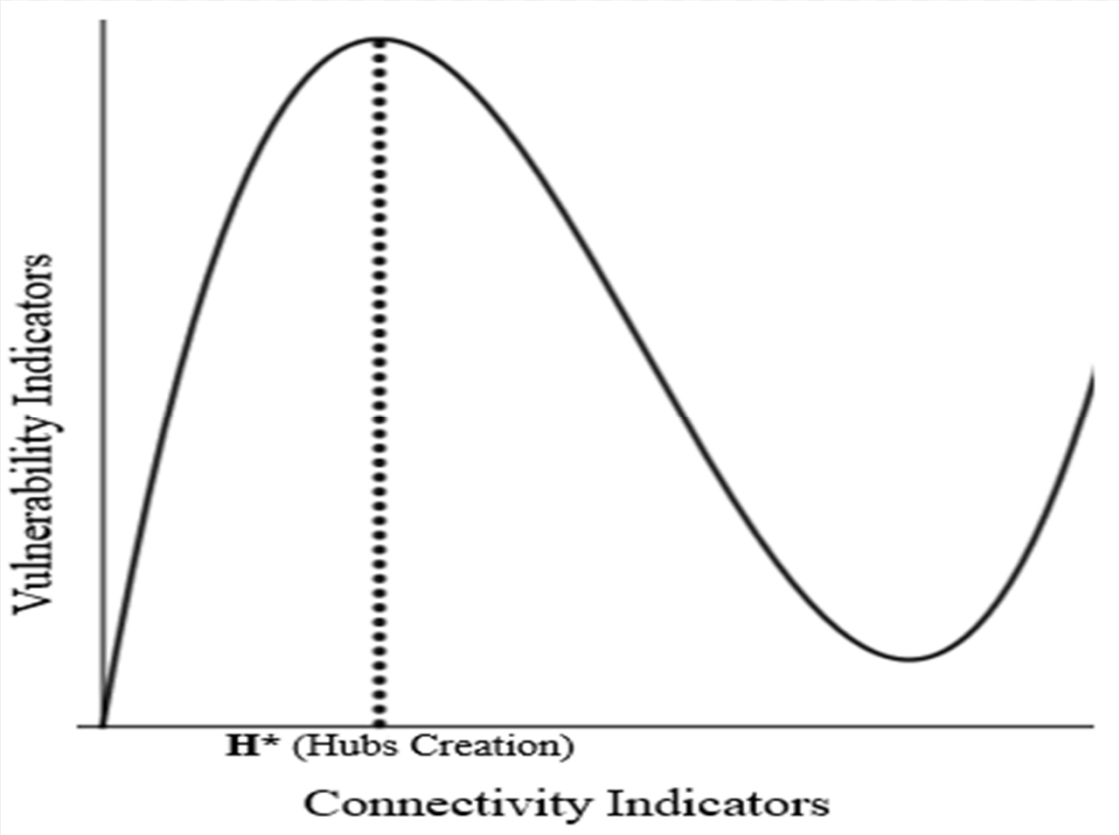
- The new equilibria can create **new opportunities**: ***Socrates: 'Chaos as divinity'; Plato: 'Disordered motion before the divine order'***

↓

***The architecture of connectivity: a conductive platform for further spatio-temporal vulnerability-resilience domains***

# Possible Evolution of the Vulnerability-Connectivity Curve: N-Shape!

**Possible phases of homogenous (hub)networks depending on the connectivity architecture**



# Conclusions: From Network Vulnerability-Resilience to Hubs' Role

**The Architecture of Connectivity:**

Fundamental for understanding and interpreting vulnerability and resilience of networks and hubs

**Role of various types of Hubs:**

The Vulnerability/Resilience network depends on:

- **Different typologies of hubs/hierarchies of hubs**
- **Relevance of hubs' dynamics**

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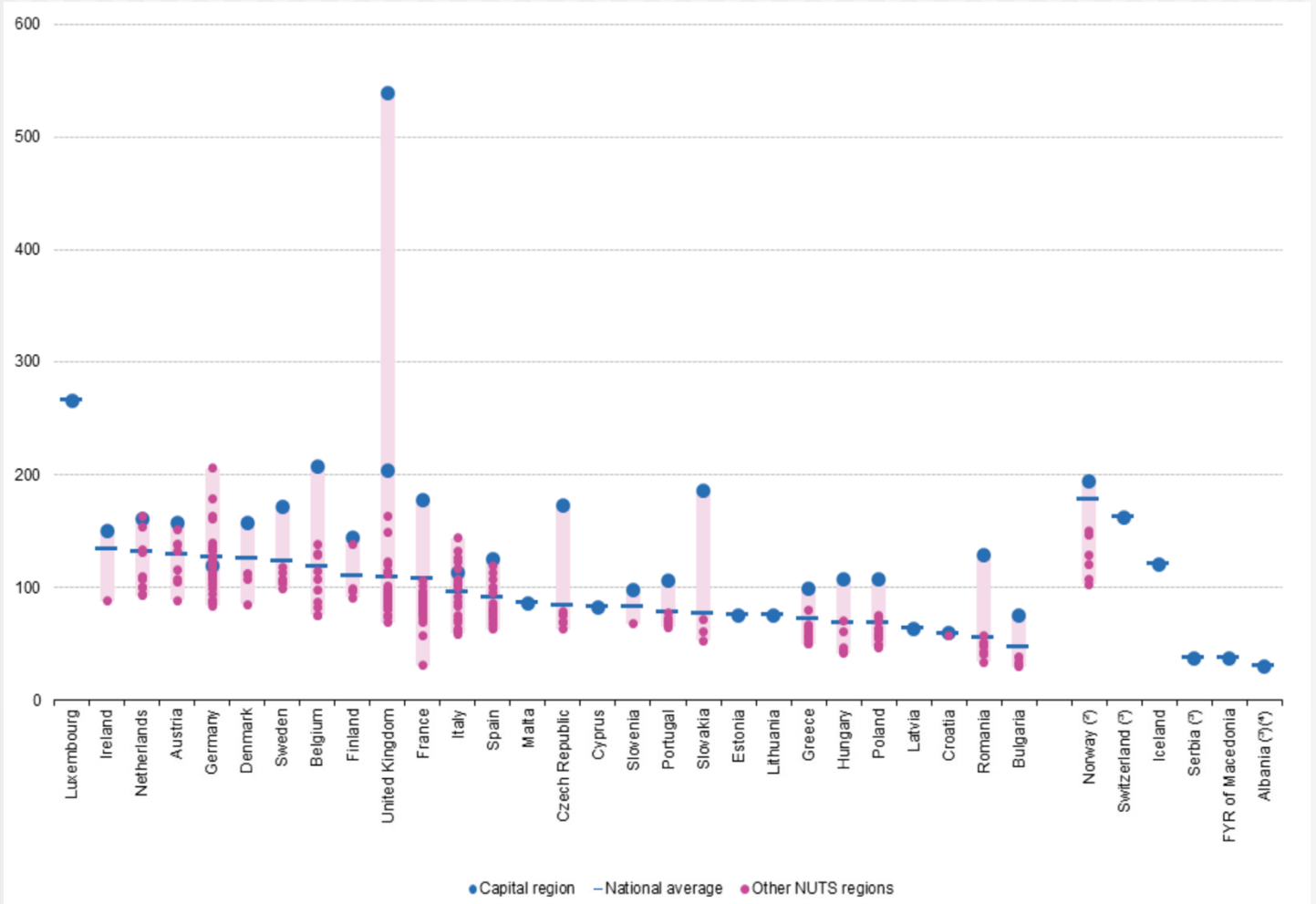
**Relevance of inter-connectivity of hubs!**

**(Non/Nearly decomposable networks?)**

# Network of Hubs: Capital Regions in the EU (GDPpc) -> Convergence?




(1) The light lilac shaded area shows the range of the highest to lowest region for each country. The blue bar shows the national average. The blue circle shows the capital city region. The lilac circles show the other regions. Liechtenstein, Montenegro and Turkey: not available.
(2) 2013.
(3) National data.
(4) Provisional.

# Research Agenda: RQs

**Policy: Tendency towards (non)physical Hub Network organization(s)? (Which architecture(s)?)**

**From the theoretical-operationalisation viewpoint:**

- **More work on dynamic theory…**
- **How to measure the connectivity architecture of networks and hubs,** given the various connectivity indicators and measures? -> Multidimensional analysis?

- **How to identify strong/weak links, i.e., (non)decomposable networks** (Simon)**?**
- **How to measure hubs' resilience levels?**

↓

*(Non)Limits to Growth? -> multidisciplinary perspective!*

# The Smart Hub Concept (Eranet-JPI Project: 11 EU-Partners)

***Smart Mobility Hub:*** a mobility hub which offers **advanced levels of physical, digital, and democratic integration**

***Physical integration***: of *different modes of transportation* in a dedicated and well-visible location, including one shared mobility option (e.g., (e-)shared bike, cargo-bike, e-scooter, carsharing) and one public transportation opportunity

It also incorporates a range of *non-mobility* and urban components, such as waiting spaces, Wi-Fi, phone charging, green areas, etc.

***Digital integration:*** users can easily access information provided by multiple providers in a single digital platform (e.g., plan, book, and pay for mobility services)

***Democratic Integration***: hub implementation allows both stakeholders and users (including the most vulnerable) to participate in the decision-making process.

# *Review Papers* (by AR et al.)

***Inter-connectivity in our research!***

- M. Modica, A. Reggiani (2015), "**Spatial Economic Resilience**: Overview and Perspectives", *Networks and Spatial Economics*

- A. Reggiani, P. Nijkamp, D. Lanzi (2015), "**Transport Resilience and Vulnerability**: the Role of Connectivity", *Transportation Research A*

↓

**Different perspectives on Resilience & Vulnerability:**
**Unifying 'umbrella' is necessary!**

# Special Issues

- I. Cardinale, A. Reggiani, R. Scazzieri (**2022**), Special Issue on "**Resilience, Vulnerability and Complexity in Socio-economic Systems: A Connectivity Approach**", *Networks and Spatial Economics (forthcoming)*
- J.C. Martín, A. Reggiani, J-C. Thill (2018), Special Issue on "**Accessibility, Resilience and Vulnerability**", *Transportation*
- S. Caschili, A. Reggiani, F. Medda (2015), Special Issue on "**Resilience and Vulnerability in Spatial Economic Networks**", *Networks and Spatial Economics*
- S. Caschili, F. Medda, A. Reggiani (2015), Special Issue on "**Resilience and Vulnerability in Transport Networks**", *Transport Research A*

# Methodological/Empirical Papers (by AR et al.)

- O. Hudec, A. Reggiani, M. Šiserová (2018), "Resilience Capacity and Vulnerability: A Joint Analysis with reference to **Slovak** Urban Districts", *Cities,* Vol.73, pp.24-35

- J. Östh, M. Dolciotti, A. Reggiani, P. Nijkamp (2018) "Social Capital, Resilience and Accessibility in Urban Systems: A Study on **Sweden**", *Networks and Spatial Economics,* Vol.18, pp. 313-336

- J. Östh, A. Reggiani, P. Nijkamp (2018) "Resilience and Accessibility of Swedish and **Dutch Municipalities**", *Transportation,* Vol.45, pp. 1051-1073

- A. Reggiani, P. Nijkamp, T. De Graaff (**2002**), "**Resilience: An Evolutionary Approach to Spatial Economic Systems**", *Networks and Spatial Economics*,

# Methodological/Empirical Papers (by AR et al.)

- J. Östh, P. Nijkamp, A. Reggiani (**2022**), "Accessibility, Population Dynamics and Regional Economic Resilience" *(forthcoming*

- A. Reggiani (**2022**) "The Architecture of Connectivity: A Key to Network Vulnerability, Complexity and Resilience", *Networks and Spatial Economics (forthcoming).*

## THANK YOU,

**for your 'interconnectivity' &'resilient' attention!**

***Questions and comments are welcome***

**HANDBOOK on "*Entropy, Complexity and Spatial Dynamics: A Rebirth of Theory*?"**
(Edward Elgar, December 2021)

***Editors*: *A. Reggiani (Italy), L. Schintler (USA), D. Czamanzki (Israel), R. Patuelli (Italy)***

**Necessity to 'revitalise' theory!**
(Anderson, 2008: The End of Theory)