Complex Networks Approaches to Supply Chain Management

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Glasgow

Outline

PART I

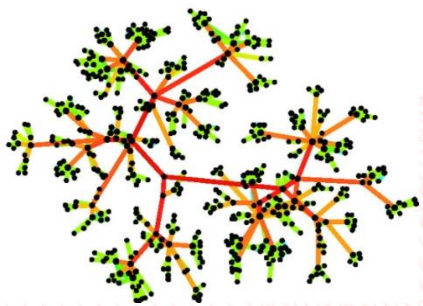
- Why complex networks approaches for supply chains?
- Network metrics and supply chain interpretation

PART II

- Illustration with secondary supply chain data
- Percolation process and resilience of supply networks
- Other approaches and key sources of information
- Summary and Discussion

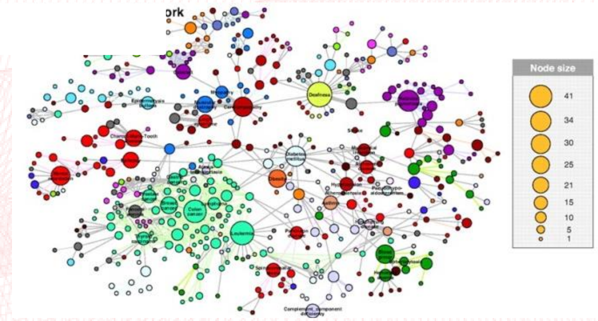
Complex networks are everywhere

mobile communication networks



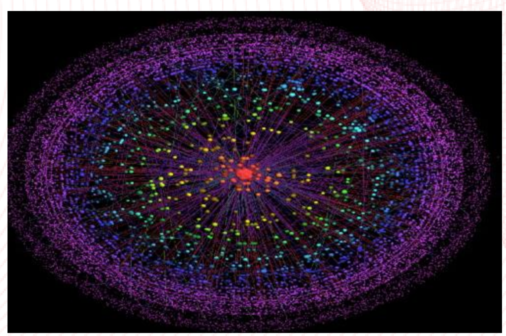
J.-P. Onnela et al. PNAS 2007;104:7332-7336

human disease network



Kwang-Il Goh et al. PNAS 2007;104:8685-8690

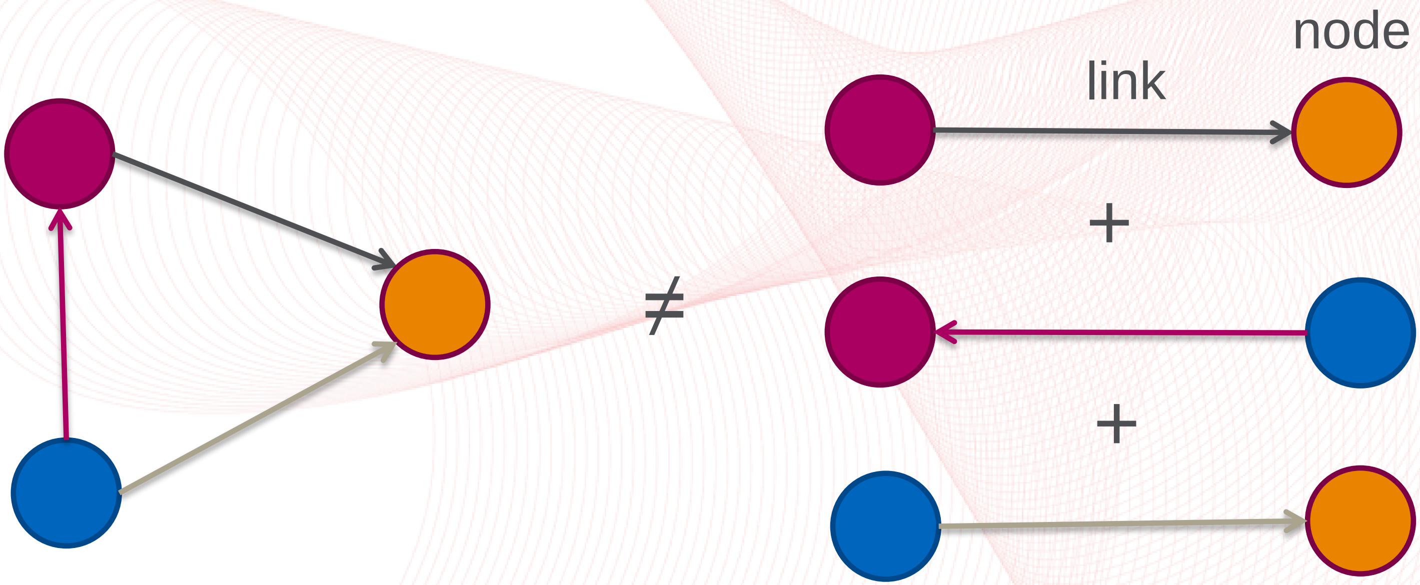
internet



Shai Carmi et al. PNAS 2007;104:11150-11154

Complex networks approach

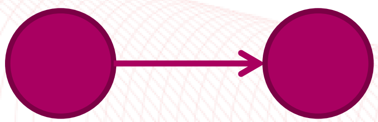
“More is different”



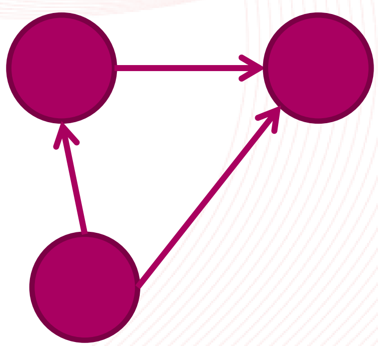
Anderson, P. W. More is different: Broken symmetry and the nature of the hierarchical structure of science. *Science*, **177**: 393–396, 1992.

Complex networks approach to supply chains (SCs)

Dyadic focus in supplier relationship management



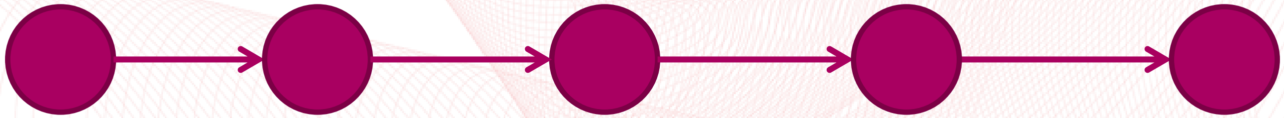
Importance of larger motifs, at least triads



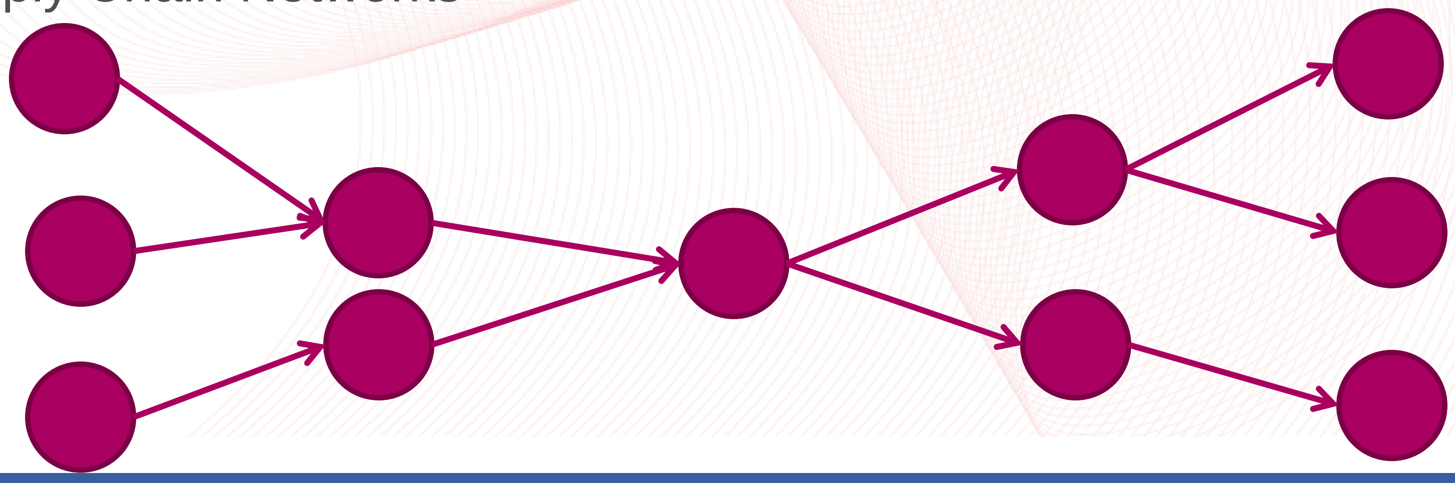
T. Y. Choi and Z. Wu. Taking the leap from dyads to triads: buyer-supplier relationships in supply networks. *Journal of Purchasing & Supply Management*, 15:263-266, 2009.

Complex networks approach to supply chains (SCs)

Supply Chains

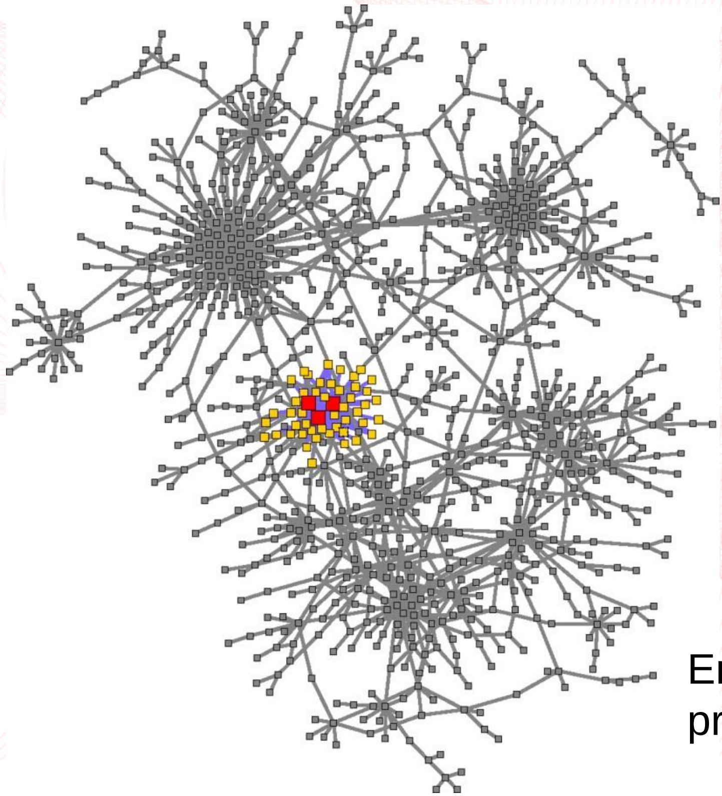


Supply Chain Networks



Complex networks approach to supply chains (SCs)

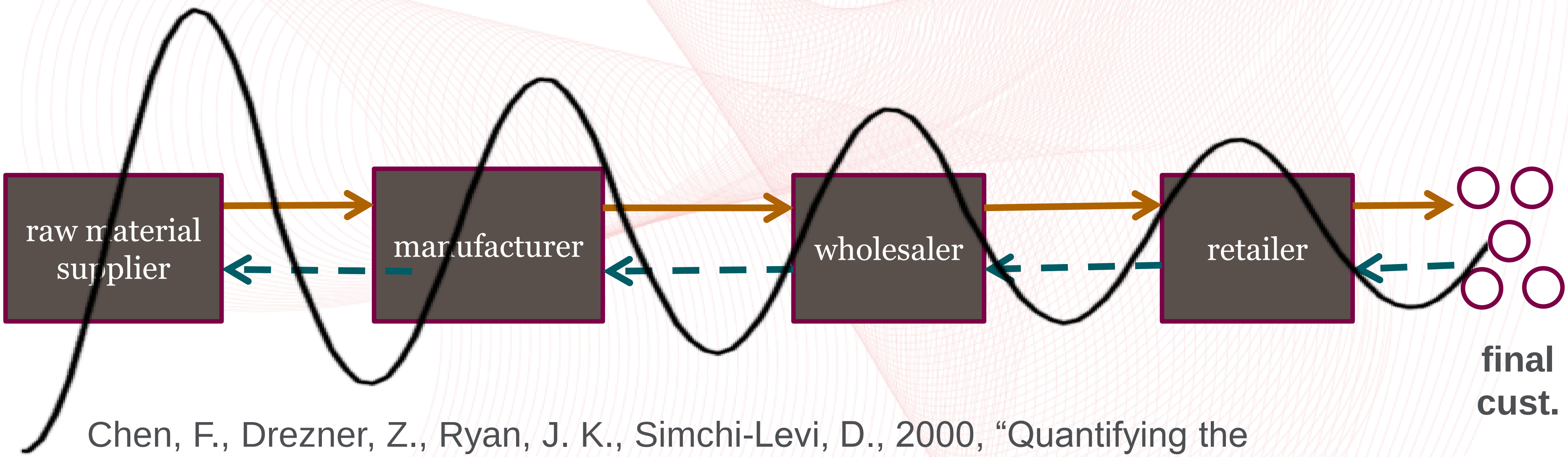
Production Networks or Industrial Ecosystems



Enghin Atalay et al. Network structure of production. PNAS ,108:5199-5202, 2011.

Systemic Effects: Why is it relevant?

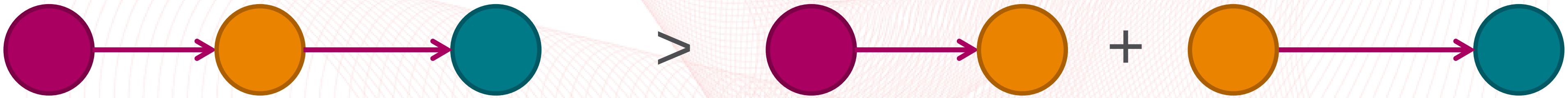
Example I: Bullwhip Effect



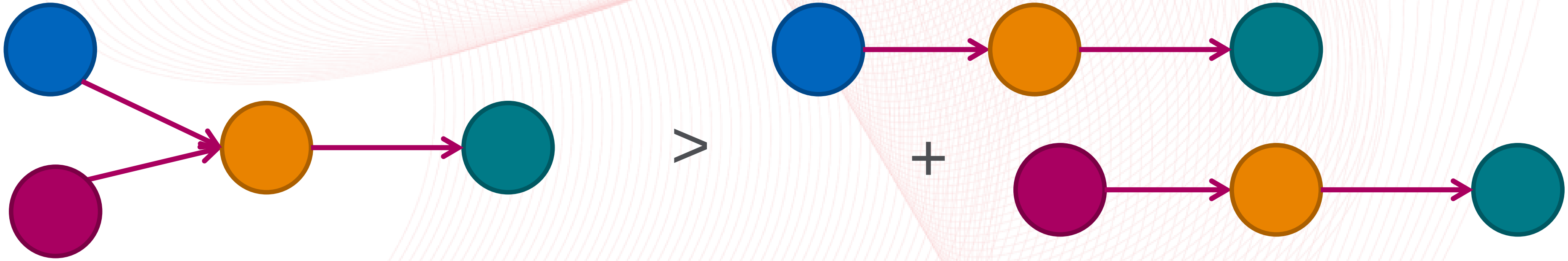
Chen, F., Drezner, Z., Ryan, J. K., Simchi-Levi, D., 2000, “Quantifying the Bullwhip Effect in a Simple Supply Chain: The Impact of Forecasting, Lead Times, and Information”, Management Science, 46(3), 436-443

Systemic Effects: Why is it relevant?

Example I: Bullwhip Effect



D. C. Chatfield. Underestimating the bullwhip effect: a simulation study of the decomposability assumption. *International Journal of Production Research*, 51(1):230244, 2013.

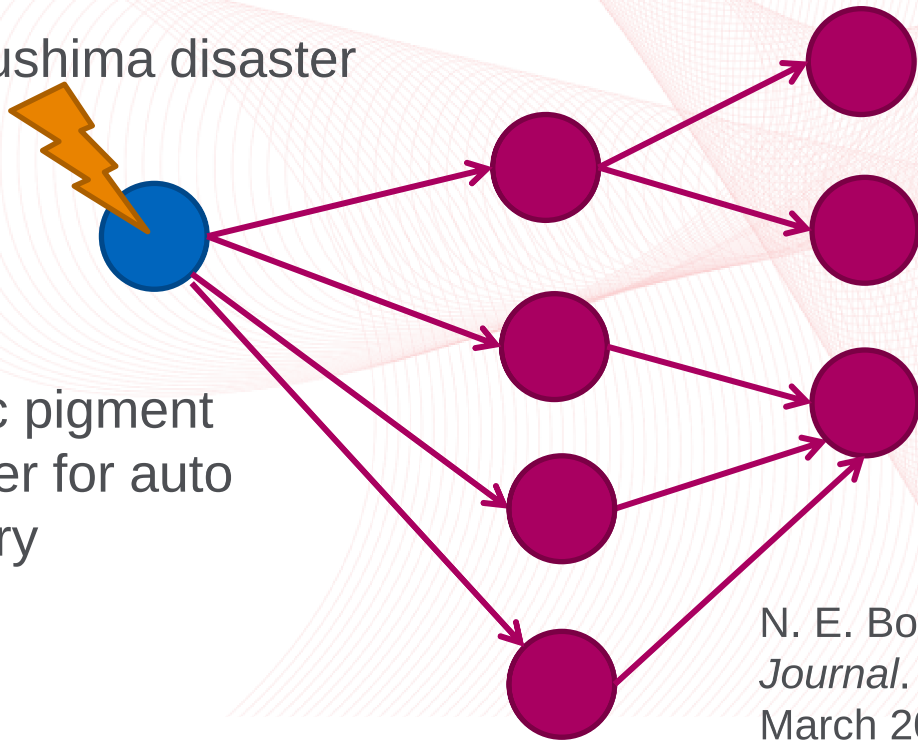


R. Dominguez, J. M. Framinan, and S. Cannella. Serial vs. divergent supply chain networks: a comparative analysis of the bullwhip effect. *International Journal of Production Research*, 52(7): 21942210, 2014.

Systemic Effects: Why is it relevant?

Example II: Reliance on single source at upper tiers

Fukushima disaster

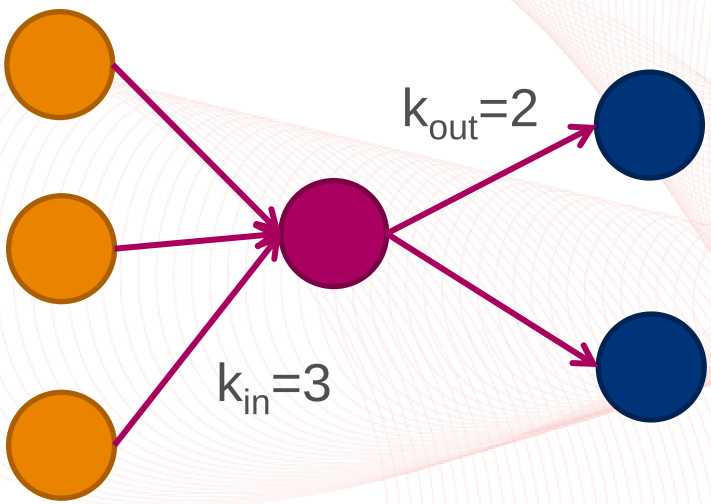


Xirallic pigment supplier for auto industry

N. E. Boudette and J. Bennett. *Wall Street Journal*. Pigment shortage hits auto makers, 26 March 2011.

Network Metrics

Degree Centrality



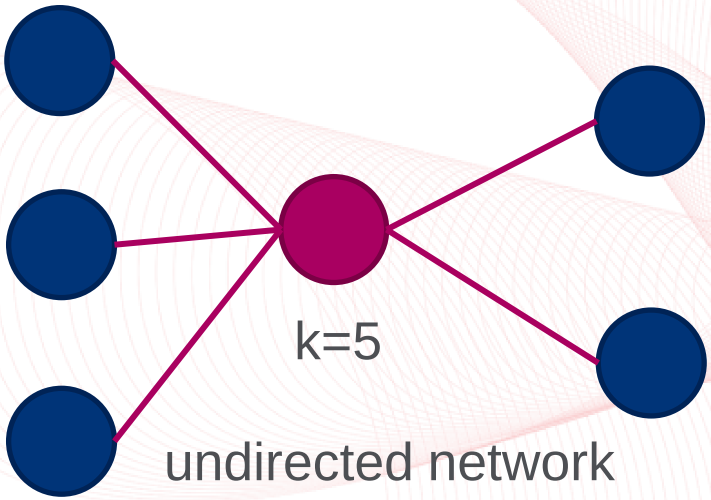
directed network

Degree: number of neighbours / connections (in/out)

SC context (material flow network)
In-degree centrality: supply load
Out-degree centrality: demand load
Managerial / operational difficulty [1]

Network Metrics

Degree Centrality



Degree: number of neighbours / connections

SC context (contractual network)

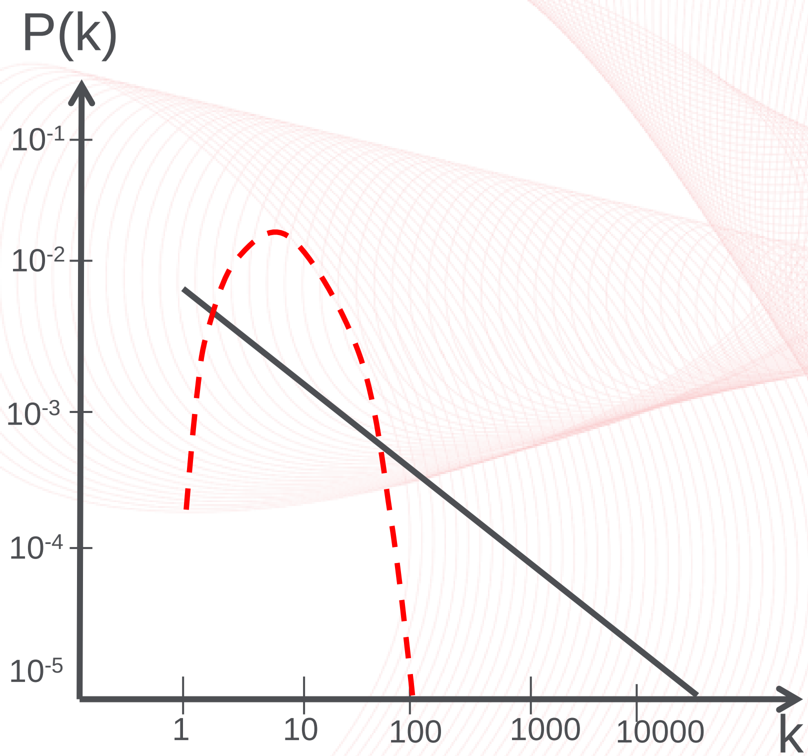
Degree centrality: influential scope

Impact on other firms’ policies

[1-3]

Network Metrics

Degree Distribution



P(k): Fraction of nodes in a network with degree k

Homogeneous (exponential)

$$P(k) \propto \frac{e^{-\langle k \rangle} \langle k \rangle^k}{k!}$$

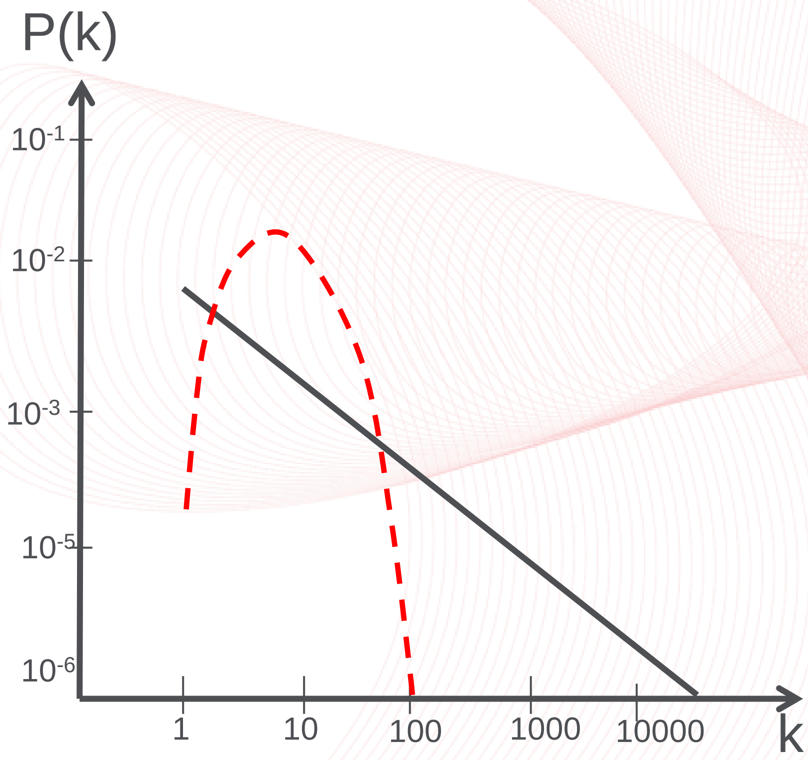
Heterogeneous (scale-free):

$$P(k) \propto k^{-\alpha}$$

Hub nodes

Network Metrics

Degree Distribution

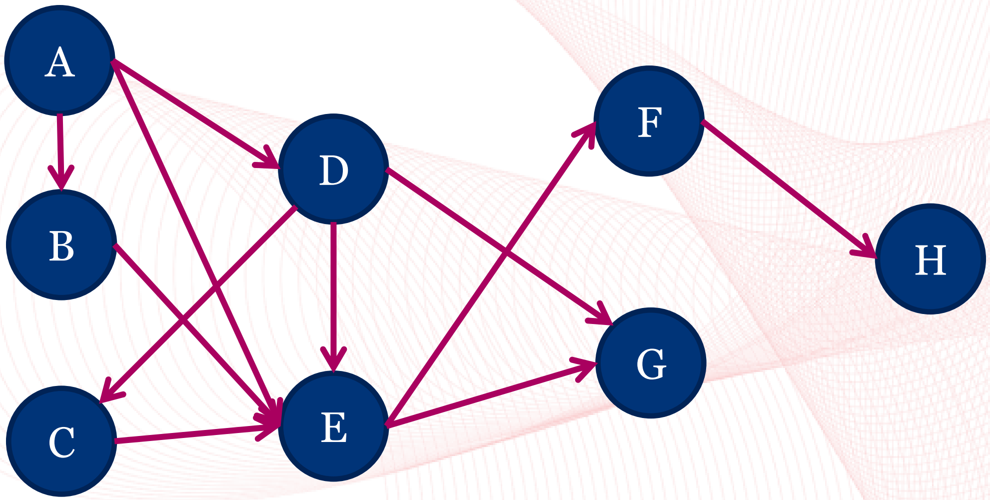


<u>SC context (contractual network)</u>
Control / coordination

Hubs denote centralisation and they can exert control and influence [1,6]

Network Metrics

Shortest Path key for information flow



A-B: AB (1)
A-C: ADC (2)
A-D: AD (1)
A-E: AE (1)
A-F: AEF (2)
A-G: ADG / AEG (2)
A-H: AEFH (3)

Betweenness centrality

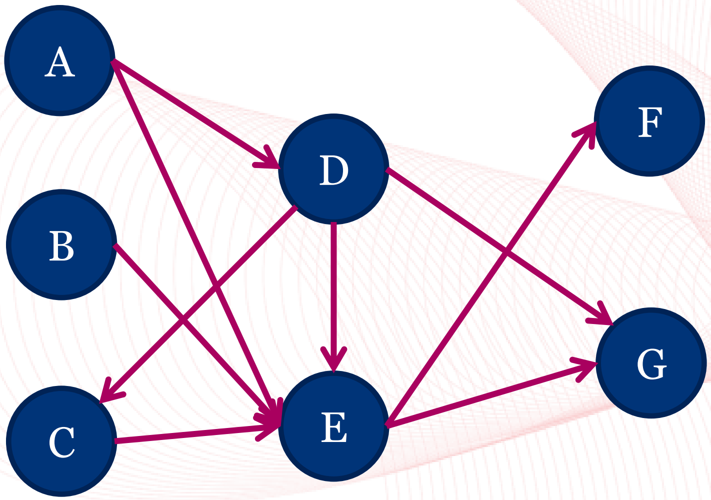
B(X): number of shortest paths that a given node X sits on

Closeness centrality

C(X): 1/average(shortest path lengths from X)

Network Metrics

Betweenness Centrality



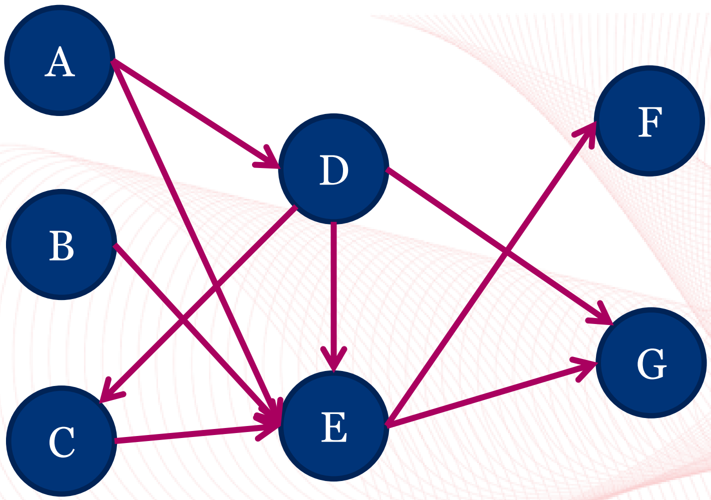
B(X): number of shortest paths that a given node X sits on

SC context (material flow network)
Operational criticality:
Impact on performance objectives such as cost, quality, delivery

SC context (contractual network)
Relational mediation:
The ability to intervene and control interactions; power and network influence

[1-3]

Network Metrics



Closeness Centrality:
C(X): 1/average(shortest path lengths from X)

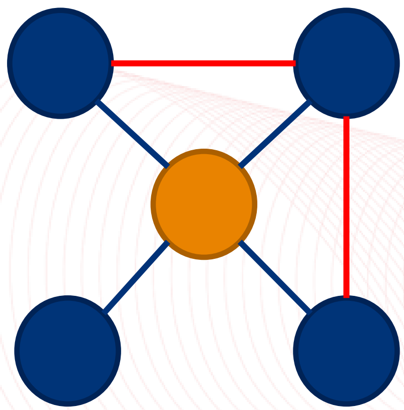
SC context (contractual network)
Informational independence:
Access to information without control and capability of independence [1]

Average shortest path length

SC context
Responsiveness to demand [7]
Efficiency of information flow and ease of material flow control [6]

Network Metrics

Clustering Coefficient



T(X)=2/6

Network transitivity

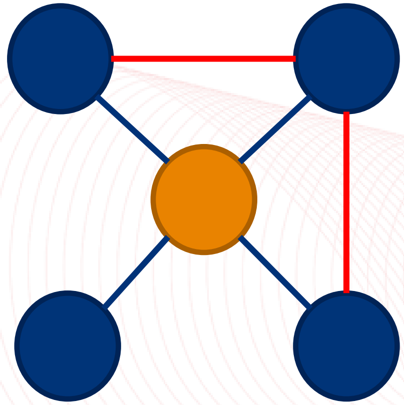
Likelihood of two nodes being connected provided that they have a common neighbour

<u>Local clustering coefficient</u>
T(X) = # of existing links between two neighbours of X / maximum possible

<u>Global clustering coefficient</u>
Average of T(X) over the network

Network Metrics

Global Clustering Coefficient



Network transitivity

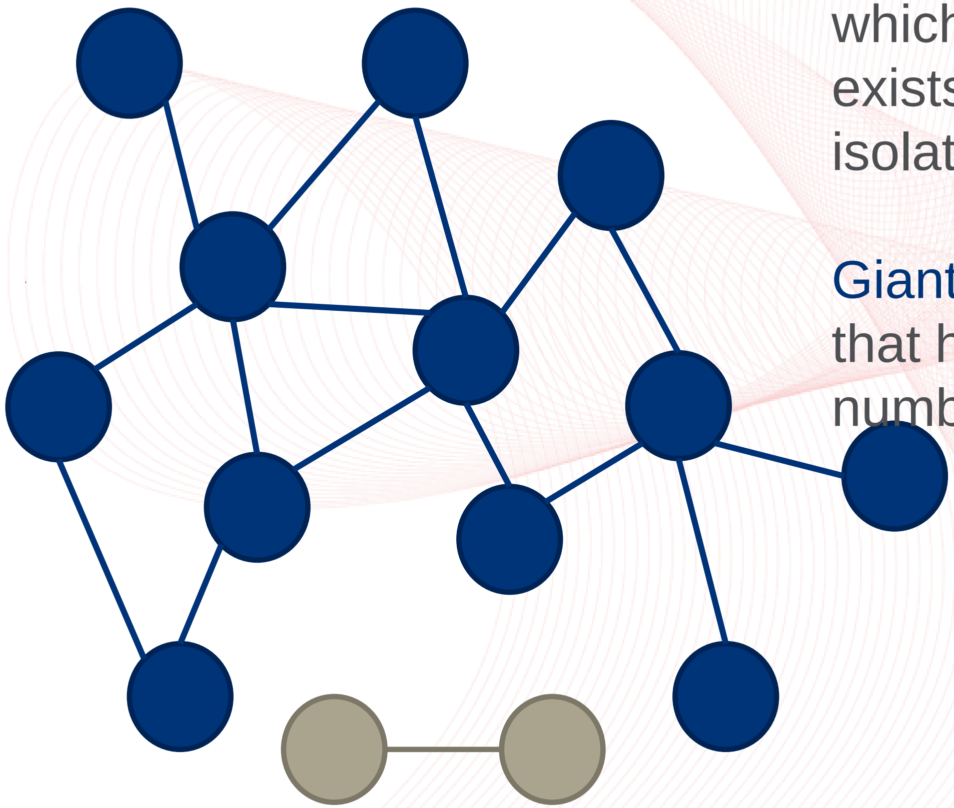
SC context:

Flexibility: Existence of alternate paths, potential for dynamical rerouting and resource pooling
[2,6,7]

Extended information sharing: Promote collaboration and prevent opportunistic behaviour
[2,6,8]

Percolation Process and Resilience

Network Component

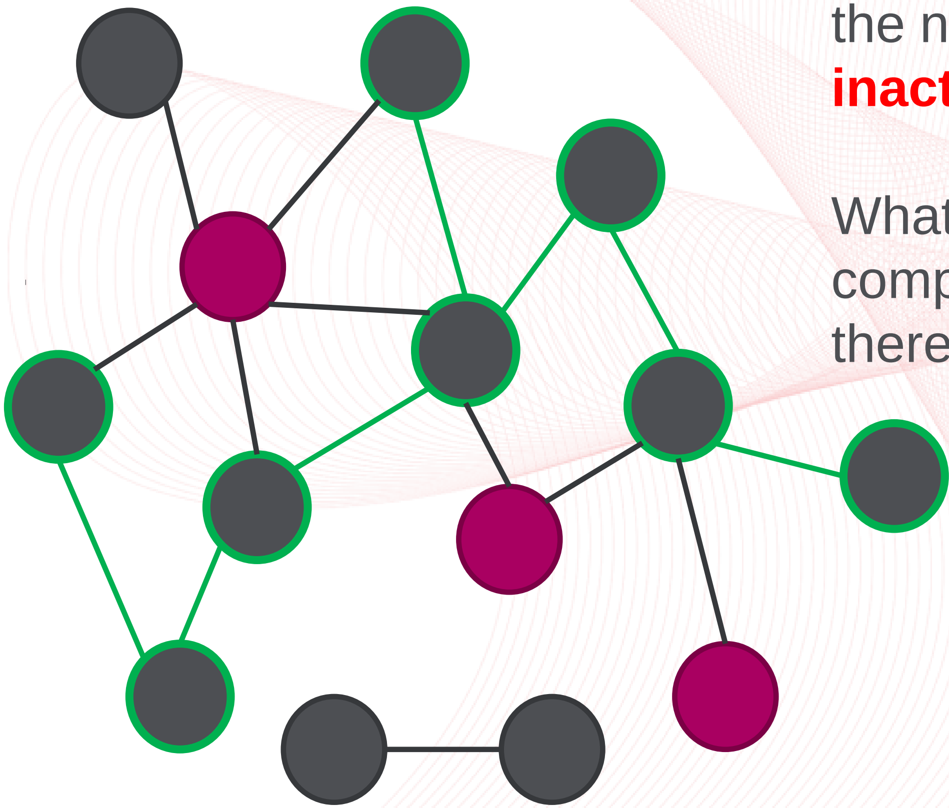


Network component is a subgraph in which all pairs are connected, i.e. there exists a path between two nodes, and is isolated from the rest.

Giant component is the large component that has a constant fraction of the total number of nodes with increasing size.

Percolation Process and Resilience

Percolation (node percolation)



In a given network, with probability **p** set the nodes active and probability **(1-p) inactivate / remove** the nodes

What are the properties of the network components as nodes are removed? Is there a giant network component?

Errors: removed nodes selected randomly

Targeted attacks: high degree nodes removed with higher probability (p_k)

Percolation Process and Resilience

Exponential (homogeneous) networks

$p < p^*$ ⇒ only small component

$p > p^*$ ⇒ one giant component (and small components)

p^*: **percolation threshold**

Similar for random errors and targeted attacks

Communication breaks down at the percolation threshold

Percolation Process and Resilience

Scale-free networks

p* $\rightarrow$ **0** as networks get bigger for **errors**

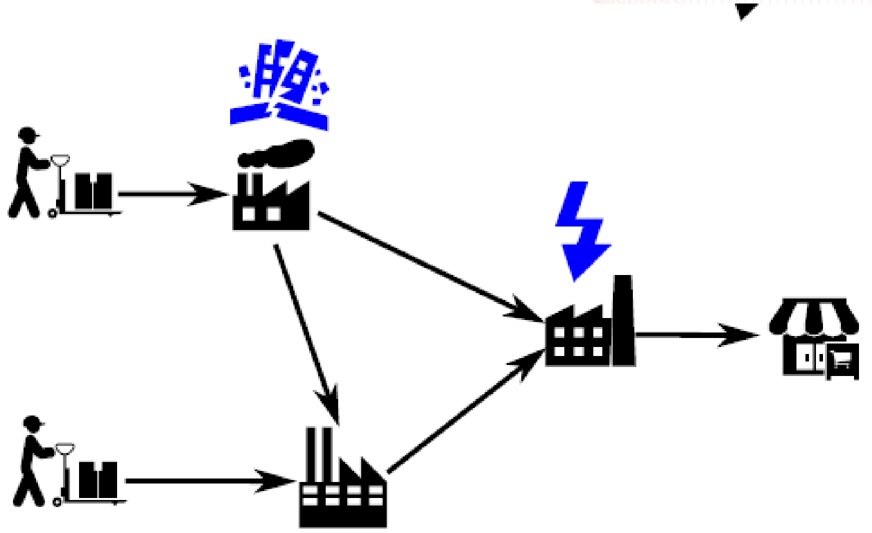
but

p* is **high** for **targeted attacks**

Scale-free networks: extreme tolerance to errors but high vulnerability to targeted attacks!

Percolation Process and Resilience

Supply Networks



Disruptions are common in supply chains

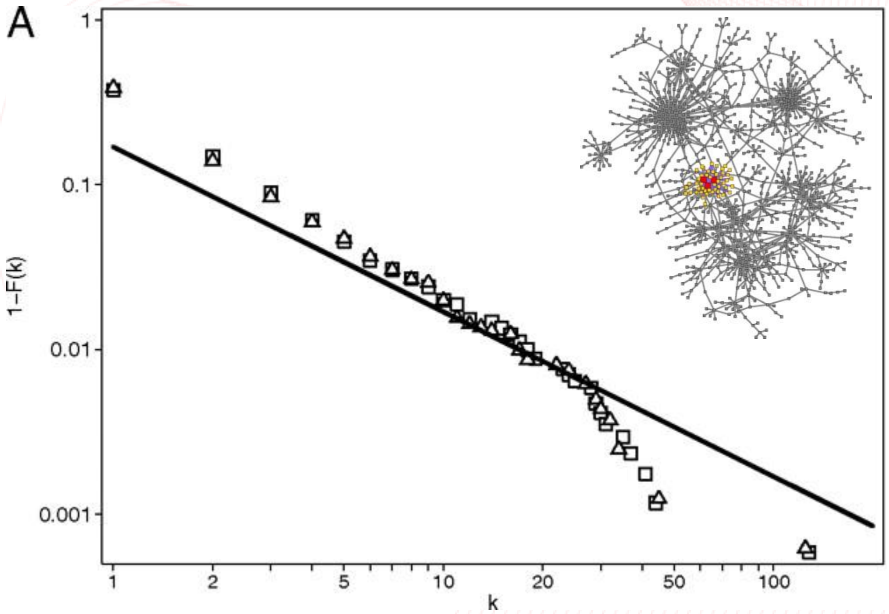
Y. Park, P. Hong, and J. Jungbae Roh. Supply chain lessons from the catastrophic natural disaster in Japan. *Business Horizons*, 56(1):7585, 2013.

How vulnerable are they against disruptions?

Resilience

Percolation Process and Resilience

Supply Networks



Enghin Atalay et al. Network structure of production. PNAS ,108:5199-5202, 2011.

Not scale-free but still high heterogeneity!

Consider that failures may not be totally random but load (degree) related

A potential explanation of high impacts of disruptions

Y. Kim, Y.-S. Chen, and K. Linderman. Supply network disruption and resilience: A network structural perspective. *Journal of Operations Management*, 33-34:43-59, 2015.

Does it hold under the peculiarities of supply chains?

Other Related Modelling Approaches

Complex Systems Approaches

A. Surana, S. Kumar, M. Greaves, and U. N. Raghavan. Supply-chain networks: a complex adaptive systems perspective. *International Journal of Production Research*, 43(20):4235-4265, 2005.

Cellular automata

Nair, R. Narasimhan, and T. Y. Choi. Supply networks as a complex adaptive system: Toward simulation based theory building on evolutionary decision making. *Decision Sciences*, 40(4):783-815, 2009.

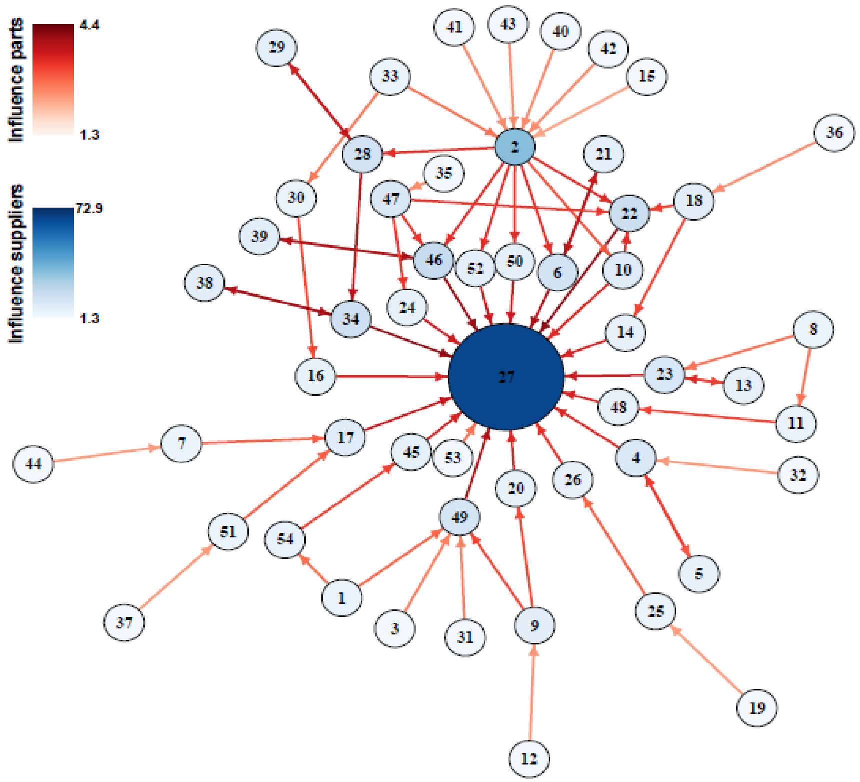
L.-M. Chen, Y. E. Liu, and S.-J. S. Yang. Robust supply chain strategies for recovering from unanticipated disasters. *Transportation Research Part E: Logistics and Transportation Review*, 77:198-214, 2015.

Agent-based modelling

J. M. Swaminathan, S. F. Smith, and N. M. Sadeh. Modeling supply chain dynamics: A multiagent approach. *Decision Sciences*, 29(3):607632, 1998.

C. M. Macal and M. J. North. Tutorial on agent-based modeling and simulation. In *Proceedings of the 37th Conference on Winter Simulation*, WSC'05, pages 2-15. Winter Simulation Conference, 2005. ISBN 0-7803-9519-0.

Generalised Modelling



A complex networks method that has been borrowed from ecology (T. Gross et al. Generalized models reveal stabilizing factors in food webs. *Science*, 325: 747-750, 2009

Dynamical systems theory with a focus on stability

Enables to capture SCM specific flows (inventories and material flows)

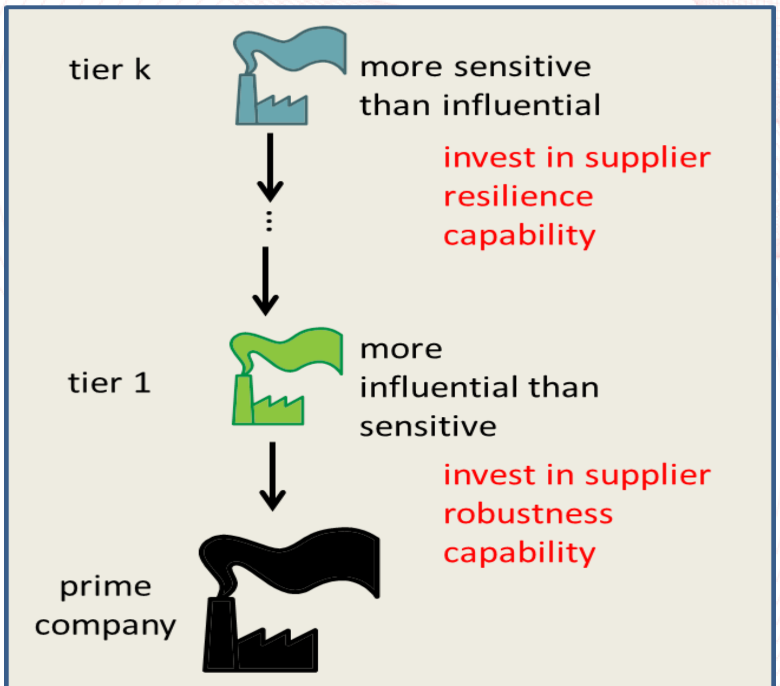
Predicting supply network response to disturbances under general conditions

Which parts of the network are most influential / sensitive?

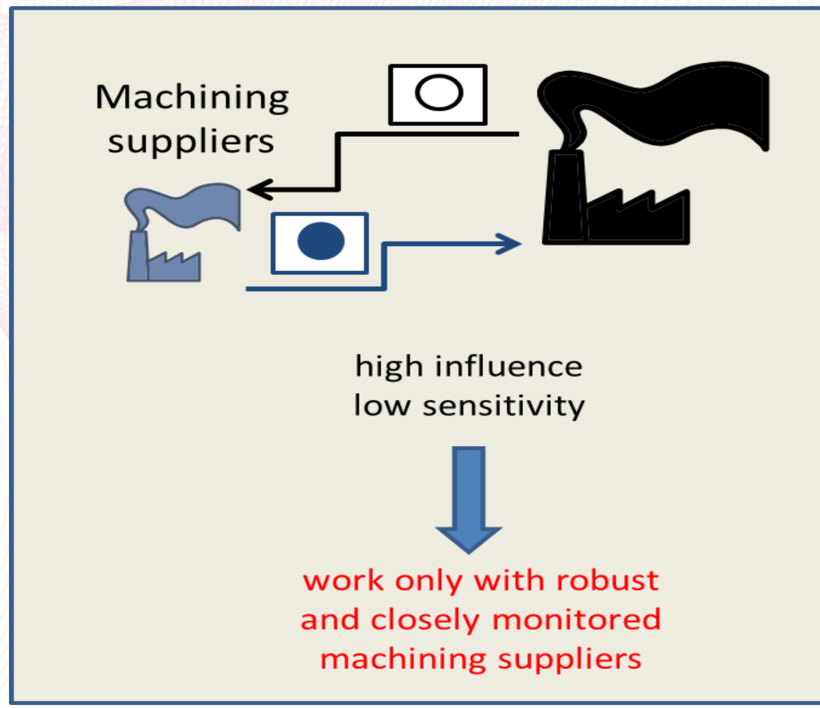
Generalised Modelling

Sensitivity: How strongly is an organisation affected from changes of others?
Influence: How strongly does the change in an organisation affect others?

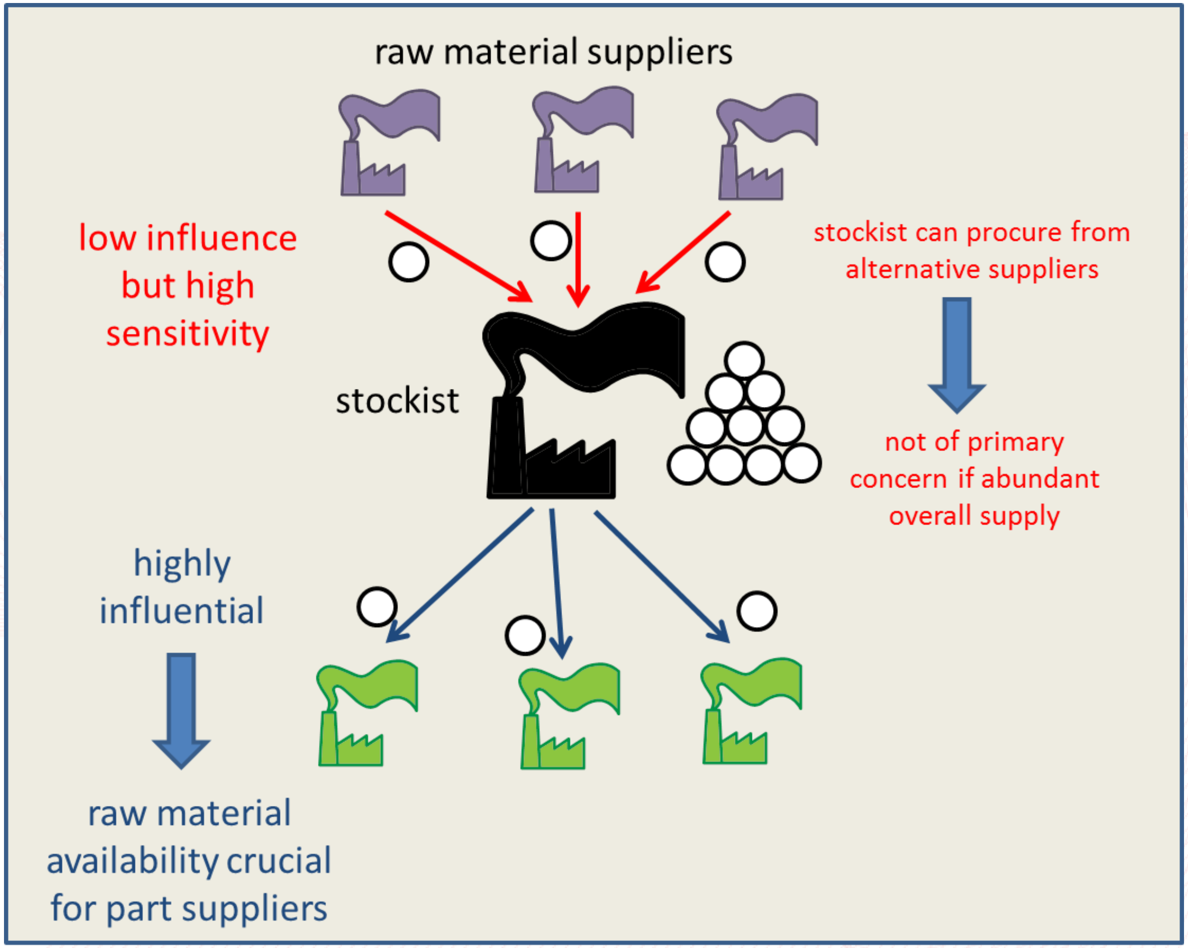
effect of tier



machining suppliers



Generalised Modelling



Useful Resources

Books

Albert-László Barabási, *Linked: How Everything is Connected to Everything Else*, 2004, ISBN 0-452-28439-2

Mark Newman, *Networks: An Introduction*, Oxford University Press, 2010, ISBN 978-0-19-920665-0

Anna Nagurney, *Supply Chain Network Economics: Dynamics of Prices, Flows and Profits,* Edward Elgar, 2006, ISBN 9781845429164

Network visualisation and basic analysis software

Gephi, Pajek, Cytoscape, R

Summary and Conclusions

- Complex networks provides a universal approach for analysing and understanding systems from different domains.
- Supply chains can be modelled as complex networks and network metrics help to understand supply chain properties such as flexibility and responsiveness from a systems perspective.
- Supply chain management needs to be extended to incorporate network aspects rather than focusing on dyadic relations in isolation from one another.

Summary and Conclusions

- Percolation process characterises the attack and error tolerance of complex networks. Heterogeneous networks are tolerant to random errors but vulnerable to targeted attacks.
- Supply networks are fairly heterogeneous but not scale-free in general. Therefore, similar results might hold.
- There exist other methods such as agent-based modelling and generalised modelling that allow to incorporate supply chain processes in more detail, which lead to further insights.
- Generalised modelling provides a systematic screening tool for identifying sensitive and vulnerable firms in supply networks.

Questions

References

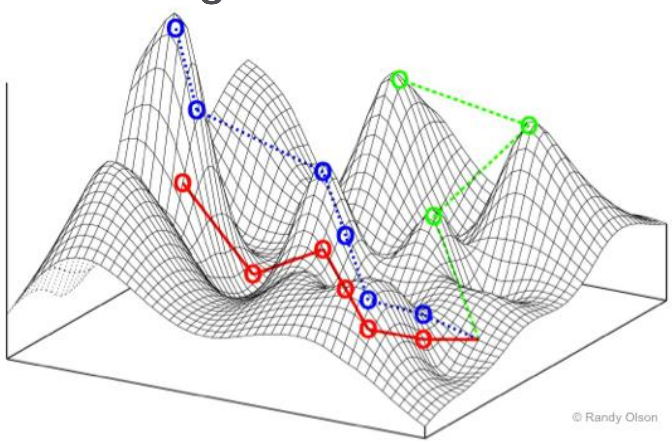
[1] Y. Kim, T.Y. Choi, T. Yan, and T.K. Dooley. Structural investigation of supply networks: A social network analysis approach. Journal of Operations Management, 29(5):194-211, 2011.
[2] M.A. Bellamy and R.C. Basole. Network analysis of supply chain systems: A systematic review and future research. Systems Engineering, 16(2):235-249, 2013.
[3] P. Greening and C. Rutherford. Disruptions and supply networks: a multi-level, multi-theoretical relational perspective. The International Journal of Logistics Management, 22(1):104-126, 2011.
[4] T.Y. Choi and Y. Hong. Unveiling the structure of supply networks: case studies in Honda, Acura, and Daimler-Chrysler. Journal of Operations Management, 20(5):469-493, 2002.
[5] L. Ponnambalam, A. Namatame, X. Fu, R.S.M. Goh, E. Kitamura, and R. De Souza. A study on emergence, vulnerability and resilience of complex supply chain networks using multi-agent based approach. Technical report, AAMAS 2014 Conference Proceedings, 2014.
[6] E.J.S. Hearnshaw and M.M.J. Wilson. A complex network approach to supply chain network theory. International Journal of Operations & Production Management, 33(4):442-469, 2013.
[7] H.P. Thadakamalla, U.N. Raghavan, S. Kumara, and R. Albert. Survivability of multiagent-based supply networks: A topological perspective. IEEE Intelligent Systems In Intelligent Systems, 19:24-31, 2004.
[8] T.Y. Choi and Z. Wu. Taking the leap from dyads and triads: buyer-supplier relationships in supply networks. Journal of Purchasing and Supply Management, 15(4):263-266, 2009.

NK Fitness Landscape Approach

System state

1	0	0	1	0	1	0

Dynamic evolution according to fitness values



A method that has been borrowed from ecology (S. Kauffman and S. Levin. Towards a general theory of adaptive walks on rugged landscapes. *Journal of Theoretical Biology*. 128 (1): 11–45.1987)

Business Strategy:
D. A. Levinthal. Adaptation on Rugged Landscapes. *Management Science*, 43 (7): 934–950.

Supply Chain Strategy:
A. Capaldo and I. Giannoccaro. How does trust affect performance in the supply chain? the moderating role of interdependence. *Int. J. Production Economics*, 166:36-49, 2015.