Vulnerability and disruption analysis in supply chain networks: A layered networks perspective

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Background

- Many **real world systems** may be **represented as networks**.
- Consisting of hundreds and more of **entities** (e.g. manufacturing facilities, suppliers etc.) denoting the **nodes** and
- the **interactions** (flows of material, flows of information, financial flows) among them **representing the links**
- **Supply chain** system can be seen as a group of **layers of different interdependent networks**
- As such **disruptions** occurring **in one layer** may have **impact** also **on other layers**

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Objective

Analyse vulnerability of a supply chain in case of disruption, i.e. evaluating the impact of transport disruption on the process performance of a generic supply chain supply

thereby

- Focus is on the entire network as "unit of analysis"
- taking a two-layer network perspective
- apply techniques from complex network research
- use a performance metric to quantify the impact of disruption

Disruption and protection of networks

- **OR/MS based approaches** (integer/mixed integer programming)
  - Node removal – link interdiction
  - Consideration of flows
  - Expected cost models – worst-case cost models
- **System dynamics** (simulation approach, e.g. Wilson 2007)
- **Petri-net based approach** (probability based uncertainties, e.g. Blackhurst et al. 2004)
- **Network analysis approach** (interdisciplinary approach: physics, sociology, mathematics, economics, operations research)

Network analysis approach

to analyse vulnerability of supply chains

- **Network robustness**
  - Ability of a network to withstand random failure or intentional attacks on nodes and/or edges in a network
- How many nodes/links does it need to **break up a network**
- **How robust is a network against disruptions** and how does a certain performance measure change in case of disruptive events in a network (**efficiency change)**
- View the supply chains as a **system of interdependent network layers**

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Some measures for network analysis

- **Structural measures** to get a first impression of the network's structure
  - Degree/strength; Degree distribution/strength distribution
  - Average path length, shortest path length
  - Clustering coefficient
  - Betweenness/weighted betweenness
- **Examples of performance measures**
  - Diameter
  - LM-measure: variations in network efficiency efficiency
  - NQ-measure: assess the performance of a transportation network, capturing flows, costs, and travel behaviour information
  - Multiscale measure of vulnerability (based on link betweenness)

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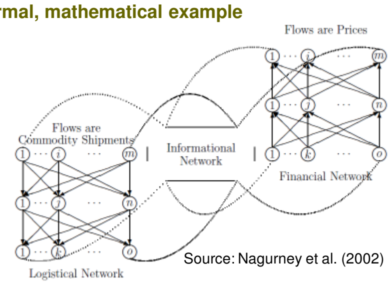
Examples for multi-layer representations of a supply chain system

Formal, mathematical example

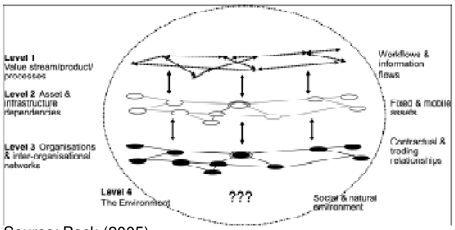


Source: Nagurney et al. (2002)

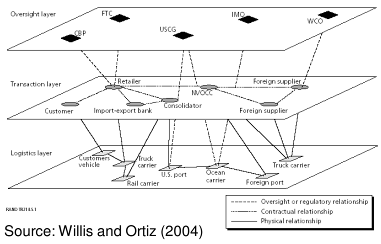
Different network layers in a supply chain

- **Transportation/logistic layer**: physical flow of goods & products
- **Information layer**: information flows & workflow
- **Transaction layer**: contractual & financial flows
- **Organisational layer**: organisations & inter-organisational networks

Two conceptual examples



Source: Peck (2005)



Source: Willis and Ortiz (2004)

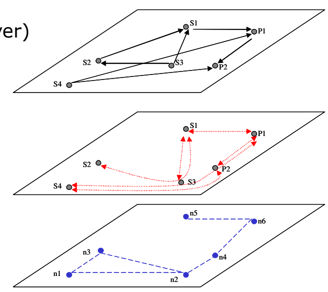
Vulnerability analysis in a two-layer supply chain network: A generic example

- **supply chain as a layered network:** one layer reflecting the interactions among supply chain entities (suppliers, manufacturer) (**transaction or logical layer**)
- mapped onto the physical **transport infrastructure layer** based on these supplier-manufacturer relationships
- layered view **accounts for the interdependence** of different layers

(a) Logical layer (Transaction layer)

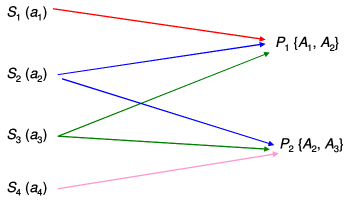
(b) Mapping of the transaction layer into the physical layer

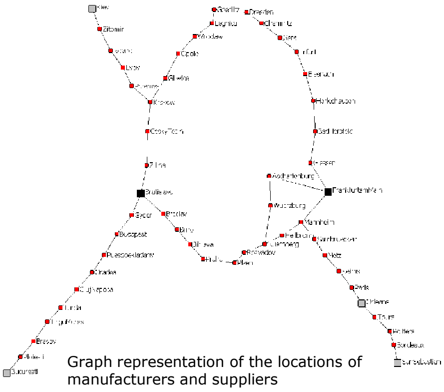
(c) Physical layer (here the transportation network)



The logical supply chain (transaction layer)

- Manufacturer with two plants (P_i) and four tier-1 suppliers (S_i)
- Three different products (A_i); material requirements: Each product (A_i) is made from two of four different components (a_i): $A_1 = \{a_1, a_2\}, A_2 = \{a_2, a_3\}, A_3 = \{a_3, a_4\}$
- Assume: threshold value: 24 (36) hours max. for in time delivery (otherwise production stop), no backup inventory
- Supplier-manufacturer relationships (material flows):





Graph representation of the locations of manufacturers and suppliers

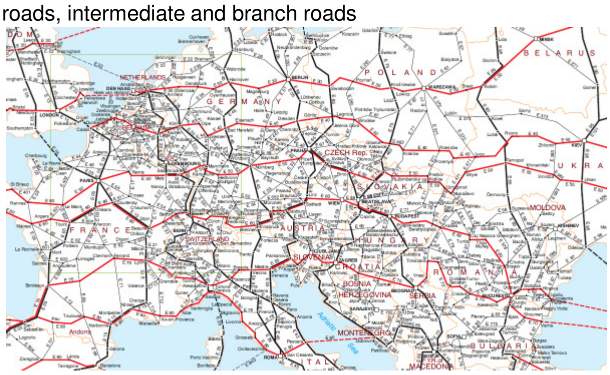
Average transportation lead times (in hours) from suppliers to manufacturers' plant times based on weighted shortest paths

Supplier	Plant P_1 (Frankfort)	Plant P_2 (Bratislava)
S_1 (San Sebastian)	21.99	–
S_2 (Orleans)	11.73	22.47
S_3 (Kiev)	28.84	19.68
S_4 (Bucaresti)	–	14.92
Products	TLT^{P_1}	TLT^{P_2}
A_1	21.99	–
A_2	28.84	22.47
A_3	–	19.68

Note: transportation times are based on weighted shortest paths

The transportation layer (physical layer)

- Physical network: Part of the continental European road network – the so-called E-Roads
- The physical transportation infrastructure network consists of N=725 nodes (reference cities) and E=963 edges (road tracks).
- Three types of roads: main roads, intermediate and branch roads



Assumptions

- Single transport mode: road transport, no ferries, no railroad
- Weights: average transportation time

Disruption strategies

- **three different scenarios** for illustrating disruptions and its impact on the supply chain performance:
  - Scenario 1: **Edge deletion** based on weighted betweenness (e.g. road closure, “bridging function”)
  - Scenario 2: **Selective multiple node/link removal** (e.g. bordure closure)
  - Scenario 3: **Iterative node deletion** along shortest routes (e.g. that causes the highest increase in the TLT)
- **disruptions** occur at the **transportation layer**
- time/duration of the disruption is not considered here
- **transportation lead time (TLT)** as **performance measure** for the supply chain (indicator for the networks’ vulnerability)

Topological analysis of the physical network

Table 1 Some basic statistics for the unweighted network

Metric	Value
Max. degree k_{max}	8
Min degree k_{min}	1
Average degree k	2.65
Diameter d	48.00
Radius	25.00
Average clustering coefficient C	0.02922

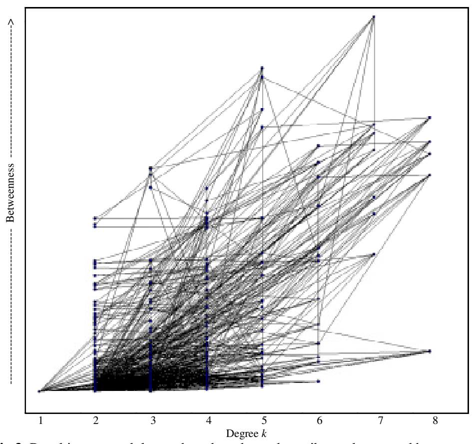


Fig 3. Resulting network layout based on the node attributes degree and betweenness as coordinates

Table 2 Results for largest connected component (LCC) after degree based node removal

Nodes removed with k	Number of nodes with degree k	LCC (No. of nodes)	Number of components after node removal
$k = 8$	5	720	1
$k = 7$	7	718	1
$k = 6$	14	700	5
$k = 5$	31	680	5
$k = 4$	101	280	37
$k \geq 7$	12	710	2
$k \geq 6$	26	653	8
$k \geq 5$	57	478	22

Table 3 Average transportation lead times (in hours) from suppliers to manufacturers’ plant times based on weighted shortest paths

Supplier	Plant P_1 (Frankfort)	Plant P_2 (Bratislava)
S_1 (San Sebastian)	21.99	–
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Note: transportation times are based on weighted shortest paths

Results of the disruption scenarios

Scenario 1 - Edge deletion:
at plant P1 threshold value not met → production halt

Table 5 Comparison of the lead times for each component before and after removing edges

	Total transportation lead time TLT			
	Plant P_1		Plant P_2	
Products	before	after	before	after
A_1	21.99	**25.33**	–	–
A_2	28.84	30.43	22.47	22.81
A_3	–	–	19.68	19.88

Scenario 2 - Selective multiple node/link removal:
slight increase in TLT

Table 6 Comparison of the component's lead times before and after border closure

Supplier-plant	Component	$LT_{a_i}^{od}$	$LT_{a_i}^{od}$
S1-P1	(a1)	21.99	21.99
S2-P1	(a2)	11.73	11.73
S3-P1	(a3)	28.84	28.84
S2-P2	(a2)	22.47	**22.81**
S3-P2	(a3)	19.68	**21.97**
S4-P2	(a4)	14.92	14.92

Scenario 3 - Iterative node deletion:
after second iterationthe chain is broken

Table 7 Results of iterative node removals for supplier

Supplier-plant	Component [Products]	${}^{orig}LT_{a_i}^{od}$	${}^{disr1}LT_{a_i}^{od}$	${}^{disr2}LT_{a_i}^{od}$
S3-P1	(a_3) [A_2]	28.84	**54.98**	∞
S3-P2	(a_3) [A_2, A_3]	19.68	**45.66**	∞

Concluding remarks

Conclusions

- Network analysis allows a quick look for the „big picture“
- Apparently „little“ disruptions may have severe impacts (Scenario 3)
- Interdependence among networks layers
- What are the critical components of „my“ supply chain
- Network structure plays a crucial role for efficiency and robustness

Further research issues and extensions

- Analysis of a real world multi-modal transportation network (eg. three layer network representation, two transport modes, cost of mode change)
- Account for dynamics by modelling duration of disruption
- Comparison to OR approaches (different, complementary)
- Simulation of scenarios with other disruption strategies