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Supply Chain Management and Network Science – the Foundation of an Innovative Synthesis

Doctoral Dissertation

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Content

1. Introduction

The emerging network complexity of the supply chains nearly in all industries requires more sophisticated differentiation in inventory, supply chain and operations managements and raising the supply chain management to the strategic level in business management [Monczka and Petersen 2012]. As the network complexity has increased and the links, dependences between the nodes of supply chain network have tightened, the anticipated risks and possible disruptions have increased significantly [Aberdeen Group 2012; Gregory et al 2012; Sheffi et al 2012; Melnyk et al 2014; Bardoscia et al 2016]. A more sophisticated safety stock management needs to be combined with more end-to-end inventory optimization alongside the value chain. Both the business processes and the related IT applications have developed radically in the last decades to meet those challenges. Although, the advanced business processes like Sales and Operations Planning (S&OP) can be implemented in companies of any business size, the related advanced IT solutions often require involvement of external experts and substantial capital investments. Furthermore, economic power and strong influence on the environment are prerequisites for utilizing such solutions as Multi Echelon Inventory Optimization [Snyder and Shen 2011] or S&OP [Karrenbauer 2015] or Distributed Order Management [Supply Chain Digest 2011] with relevant IT application. Therefore, the effectiveness of those proven methods turns to be questionable for small and mid-sized enterprises (SME's). Simultaneously, SME's have limited choices to pave the path for their success:

- Align their business to one of the large (multinational) players – usually OEM's – and becoming a 'Tier-n' subordinated company of that OEM [Brányi et al 2015].
- Rarely the so called 'Blue Ocean Strategy' can be created [Chan Kim and Mauborgne 2004, 2005] giving extraordinary opportunities to that company.
- Finally, the company may try to build a more balanced portfolio, diverse enough not to be fully reliant on one OEM's success or decision [Morvai and Szegedi 2015].

These above business aspects and challenges have determined my research focus.

The demand supply network, supply chain network, logistics supply chain network, supply chain termini have different definitions in the literature [Snyder and Shen 2011; Vitasek at CSCMP 2013; CSCMP 2015], sometimes overlapping each other. I will use **demand supply**

network (DSN) terminus when I would like to emphasize the entire 'super-organism' – important subnetwork of the entire top-network, i.e. world trade web [Serrano and Boguna 2008; Csermely 2009], where the **organization** (company) with its entire complexity is the **network-element**. On the other hand, I will use **logistics supply chain network** (LSCN) terminus when I **focus on material conversion and transport process** in complex networked systems of companies.

Unless the source is explicitly stated under a figure, all **figures** have been **created by me** and the visualized intellectual content is also **generated by me**.

1.1. My research goals, hypotheses and methods

The application of the network science approach has delivered significant breakthroughs in several disciplines, e.g. the drug design, the fight against terrorism and against cancer, the cognitive sciences, the linguistics, etc. [Newman 2011; Barabási 2012]. It helped also in better understanding the resilience, adaptability, evolvability, robustness in the complex nested networked systems. Therefore, at the beginning of my PhD studies and investigations I have defined **my research goals**, as to **build up the network model** of the logistics supply chain network by using the network science approach and to define **new solution alternatives** against the cascading failures, making the supply chain network more resilient and adaptive.

My initial **hypotheses** were:

1. The **network science approach can deliver** new insights in supply chain analysis enabling us to **model** the logistics supply chain as complex viable network.
2. The logistics supply chain network is also complex network with number of **analogies – like scale-freeness, small-worldness, nestedness –** with other viable networks, especially of the biochemical and biological ones.
3. The **network stabilizing weak-linkedness** of the successful biochemical and biological networks can be created also in the logistics supply chain network through network (meta-level) defined **freedom of Red-Amber-Green-Kanbans**.
4. I expected such discoveries concerning the **differences** of the logistics supply chain network compared to other viable networks, what we can **adapt** to the logistics supply chain network and increase its resilience and adaptability.

I have processed a great number of **publications from two large disciplines**, i.e. from supply chain management/theory and from network science.

In **Section 2** I introduce some pivotal **laws of the supply chain theory**, what have important network science interpretation.

In **Section 3** I introduce the important network science termini and bring a number of proven network examples from different disciplines. From a wide range of investigated networks, I could determine a few ones which show **significant analogy** with DSN or LSCN. Those viable networks of billion-year success are the metabolic networks, the protein networks (e.g. interactome, chaperome), the neural network and the food web.

In **Section 4** I make a synthesis of **the two different disciplines** (network science and supply chain theory). In some cases, I make disambiguation, since the same terminus is used with completely different meaning in the two disciplines (e.g. component, module, hub). Apart from the **analogies** between DSN/LSCN and those viable networks I highlight the **differentiating factors**, why those viable networks are far more resilient, robust, and adaptive with high evolvability, compared to DSN/LSCN. Furthermore, I have evaluated the **network science analytical** methods, tools, characteristics and I have defined what we can use, what do we have to adjust to the specifics of DSN/LSCN structure. At the end of that section, I make an inventory of the supply chain and operations management solutions. I highlight the specific aspects, the pro's and con's of those solutions, and I put them into network science context.

In **Section 5** I introduce two analytical tools and methods what were developed by me, for defining the network structure of an organization (the network-element of DSN/LSCN). I give detailed reasoning and series of mathematical equations how to gather the demand data, how to process them and to create the required derivatives for delivering the characteristic parameters about the networked structure of the investigated organization.

Based on the discovered differentiating factors of the viable networks, I could develop **innovative solutions to increase the resilience and adaptability** of the organization. Due to the space limitation of the dissertation, I introduce **two solutions in Section 6**, which were deployed in different industries with breakthrough success.

2. Supply chain mathematics investigated in network science context

Snyder and Shen give a full set of important models. In this section I follow their symbolling and give the relevant page number from their book, supporting the ease of comparison [Snyder and Shen 2011]. I focus on the mathematical modelling of those main supply chain processes to which **I show the network science connotation** subsequently. So we can evaluate the effect of a topological change either we plan (e.g. supply chain design) or resulted from the environmental changes (e.g. topological phase transition, cascading failure).

2.1. Standardization with power-of-two policy

The power-of-two policy follows from the deterministic continuous review optimization, i.e. EOQ [Snyder and Shen, 2011 pp. 37-41]. Therefore, I show just the cost function (Eq. 2-1) and the well/known EOQ formula (Eq. 2-2) for optimal order quantity calculation, where K= fixed cost per order, Q= order quantity, λ= demand per period, h= holding cost per unit in one period:

$$g(Q) = \frac{K\lambda}{Q} + \frac{hQ}{2} \qquad \textit{(Equation 2-1)}$$

$$Q^* = \sqrt{\frac{2K\lambda}{h}} \qquad \textit{(Equation 2-2)}$$

Utilizing the power-of-two policy the distribution of the orders in time will follow the power law of 2. For us the sensitivity of the cost function – g(T) – to order interval (T) is important which follows from the below formula, since T=Q/ λ [Snyder and Shen, 2011 pp. 42-45]:

$$T^* = \sqrt{\frac{2K}{\lambda h}} \qquad \textit{(Equation 2-3)}$$

Snyder and Shen mathematically prove that clustering the orders into power-of-two order intervals – e.g. every day, every second day, every 4^{th} day etc. – causes maximum about 6% cost increase versus the optimal order interval (T*). The practice shows even smaller sub-optimality driven cost increase just in the range of 2-3%. In other words, the loss due to the slight sub-optimality is negligible compared to the gain on standardization.

2.2. Utilizing the commonality effect

Snyder and Shen call demand **risk pooling** when the demand signals from the downstream customers come randomly in a non-correlated way for the identical finished product item [Snyder and Shen, 2011 pp. 143-147]. So a commonality effect will reduce the overall fluctuation especially relative to the totaled demand. The discrete demand as random variable of D_i can be represented with $D_i \sim N(\mu_i , \sigma_i^2)$. Assuming that all customers follow the base stock policy under periodic review with the same holding cost (h) and penalty cost for backordered excess demands (p), and p > h, the optimal solution on base stock level will be then as follows:

$$S_i^* = F_i^{-1} \left(\frac{p}{p+h}\right) = \mu_i + z_\alpha \sigma_i \qquad \textit{(Equation 2-4)}$$

where $\alpha = p/(p+h)$ and z_α is the α-th fractile of the standard normal distribution.

When evaluating the possible magnitude of risk pooling effect (or the magnitude of synchronization driven demand waves at cascading failures) we need to compare the variances of centralized scenario versus of the decentralized scenarios of Snyder and Shen:

$$\boldsymbol{\sigma_C} = \sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N}\sigma_{ij}} = \sqrt{\sum_{i=1}^{N}\sigma_i^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\sigma_i\,\sigma_j\rho_{ij}} \;\; versus \;\; \boldsymbol{\sigma_D} = \sum_{i=1}^{N}\sigma_i = \sqrt{\left(\sum_{i=1}^{N}\sigma_i\right)^2}$$

(Equation 2-5)

In the real world the very unlikely negatively correlated demands would lead to a theoretical $\sigma_C = 0$. In case of uncorrelated demands, the centralized scenario is a fraction of the decentralized one (sum of squares vs square of sum). The fully correlated demands would result high variability, $\sigma_C = \sigma_D$. [Snyder and Shen, 2011 p. 147].

Postponement or late customization create an effect similar to demand pooling. The closer is the lead time (t) for producing the intermediate generic semi-finished product to the total lead time (T) for producing the 'customized' finished products, the lower is the total cost of producing that entire finished product portfolio of N SKU's, thanks to postponement of the proliferation in the variety funnel:

$$C(t) = z_{\propto}\left[h_0\sqrt{t}\sqrt{\sum_{i=1}^{N}\sigma_i^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\sigma_i\,\sigma_j\rho_{ij}} + \sqrt{T-t}\sum_{i=1}^{N}h_i\sigma_i\right]$$

(Equation 2-6)

where h_0 is the holding cost of the intermediate semi-finished product and h_i are the holding costs for resulted finished products and – evidently $h_0 < h_i$. Snyder and Shen give a calculation where the finished product demands are non-correlated [Snyder and Shen 2011, pp. 148-151].

2.3. Process flexibility

Autry highlights that **abnormally disruptive radical changes** are expected in the macroeconomic, social, and physical environments in the 21th century [Geissbauer and Householder 2011; Autry 2012]. Those disruptions require demand-supply integration and **radically increased flexibility in the supply chain**. Melnyk et al highlight some resilience oriented investments for improving the supply chain flexibility, while Trent gives an abundant list of possible built-in flexibilities of supply chain [Melnyk et al 2014; Trent 2015].

According to Snyder and Shen, one extreme is to dedicate one product to one machine or one cluster to one factory without any overlaps. Here the product-machine or cluster-factory node pairs have no other links with other node pairs. The representation of such structure is a bi-partite graph of N product nodes/vertices and N machine nodes with N links/edges. The full dedication supports the heavy specialization, focus and optimization. The other extreme is when all products can be produced in all machines (all clusters in all factories). That is a fully flexible allocation, represented by a connected bi-partite graph of N-N nodes of products and of machines and N^2 links/edges connecting them. That gives maximal flexibility to the enterprise on the price of very high degree of redundancy in tools, machines, etc. According to Snyder and Shen, the full flexibility may grant approximately 12% sales and utilization increase [Snyder and Shen 2011 p. 243]. An optimum solution – called chaining – is the partial flexibility, when each machine, factory has a back-up option. Longer chaining better suits to protecting the network from node's failure (organization), since then a larger portion of the network will dissipate the disruption. However, the dissipation requires some extra capacity in the chaining, otherwise the lost capacity due to network-element's failure has to be anticipated by lost sales. The shorter chaining is more appropriate against link's destabilization, not to disrupt the other part of the network. Balanced, evenly distributed redundant load allocation is the best for disruption dissipation [Snyder and Shen 2011 pp. 241-251; Geissbauer and Householder 2011; Lim et al 2011; Madadi et al 2012].

3. Complex viable systems and the network science approach

Beer introduced the viable system terminus including not only the biochemical and biological systems but those growing, evolving ones what show similar characteristics to the one of the classical living systems – i.e. societal systems, including technological networks like the railways network [Beer 1979]. Applying his terminology in network science, the **viable networks** are the biochemical, biological, societal, and ecological networks. Those inherit **common properties** like: small-worldness – short pathways between nodes; over-represented existence of hubs [Amaral et al 2000; Dodds et al 2004; Bianconi et al 2008; Chattopadhyay 2010]; modular structure; existence of network skeleton; different ratio of so-called weak links and strong links. These above properties I will explain in the coming sections.

Barabási and Csermely pointed out that the network theory seems to be a very powerful approach to link vastly different systems, and show the general aspects of their organization, dynamism and stability [Barabási 2012; Csermely 2009, p.316]. There is a **large literature** available **about different networks.** Because of the limited size of my dissertation I avoid the introduction of all networks, here I just **mention some pivotal references** accordingly: River drainage network [Pelletier 1999]. In group of technological networks including the Internet [Broido and Claffy 2001; Dorogovtsev and Mendes 2001; Pastor-Satorras et al 2001; Ghim et al 2004], power grids [Amaral et al 2000; Carreras et al 2004; Dobson et al 2007], transportation networks [Sen et al 2002; Ducruet and Lugo 2013]. In group of information networks, the World Wide Web [Dorogovtsev and Mendes 2001; Ghim et al 2004], citation and peer-to-peer networks [Price 1965; Amaral et al 2000; Barabási 2003; Newman 2010]. In group of social networks, the network of firms, world trade web [Axtel 2001; Serrano and Boguna 2008]. In group of ecological networks, the food webs are usually small-world small-mid-order directed networks [Martinez 1993; Dorogovtsev and Mendes 2001]. Further references are stated in the body of my dissertation with specific focus on the discussed topic.

The **key definitions of the network science** are found in the **fundamental monographies** of Newman and Csermely [Csermely 2003, 2009; Newman 2010]. Csermely supports the reader with a separate Glossary at the end of his book. Shorter summarizing article of Dorogovtsev and Mendes is also useful starting literature [Dorogovtsev and Mendes 2001]. Here I give the most fundamental definitions.

Network:
is a set of nodes connected by links. Often many non-identical nodes are connected by different interactions.

Node:
is the single building block of a network. The node is also called vertex, network-element, site, actor [Newman 2010]. The number of nodes defines the **order of the network**.

Link:
connects two nodes of the network. In other disciplines, further termini are applied like edge, bond, tie [Newman 2010]. The number of links determines the **size of the network**. Links may have direction building a **directed graph** (or digraph). In real networks we have complex structure often represented by both symmetric (undirected) links and directed ones. Both links and nodes may have weight forming **weighted networks** [Newman 2003, 2010].

Path:
is the number of links (edges) we pass along for reaching one node from another one – linkes can be part of a path only once. **Diameter of the network** is the longest geodesic path [Newman 2010], or the maximal length of shortest paths between any pair of nodes of the network. A network is **small-world** if its **characteristic path length** is close to the path length of Erdős-Rényi random graph but its clustering coefficient is much higher than that of Erdős-Rényi random graph [Milgram 1967; Watts and Strogatz 1998; Dorogovtsev and Mendes 2001; Dodds et al 2003].

Complex systems can be represented by **different networked structure**. Dementeyev distinguished partialitic, attributive, processual, and functional structures of the complex systems. Partialitic structure describes the physical elements and their links, while the attributive one emphasizes the spatial arrangement and interdependences of the characteristic attributes. Both the processual and functional structures model the interactions of the elements. While in former representation we have no human induced interactions in the latter the interacting elements are of both natural and human natures [Dementeyev 1988]. In the modern network theory, the structural network covers the first two structures of Dementeyev and the functional network covers both the processual and functional structures of Dementeyev [Csermely et al 2008b; Antal et al 2009; Newman 2010].

The network formation delivers such **emergent properties** which can not be deducted from the properties of the elements, nodes. E.g. the swarm intelligence emerges at the meta-level from very simple interaction rules of the ants or bees at a level below [Bonabeau and Meyer 2001, 2002].

3.1. Grouping of links and nodes

Subnetwork:
is used by Newman to characterize the different granularity [Newman 2010 p. 24], while Csermely employs it to dissect the network into weak and strong ones [Csermely 2009 pp. 309-312]. Lim et al disconnect the network into subnetworks [Lim et al 2011].

Degree:
of a node is the number of links the node has. In directed network the nodes have in-degree and out-degree as well. The average degree $\langle k \rangle$ and the degree distribution P(k) are characteristic values of a network.

$$\langle k \rangle \equiv \frac{1}{N}\sum_{i=1}^{N} k_i \ = \ \frac{2E}{N} \qquad (Equation\ 3-1)$$

Degree distribution:
is a histogram of the total number of nodes of the network with a given degree. Barabási in his groundbreaking monography of Linked [Barabási 2003] brings several examples of **scale-free degree distribution** (according to power law). He shows also the role of **preferential attachment**, especially with fitness effect, in the development of scale-free networks. If the fitness effect is too strong – the winner takes all – then the network gradually develops into star net [Albert and Barabási 2002]. A subsequent duplication of a network and divergence leads also to scale-free distribution [Sole et al 2003]. There are evidences that the scale-free networks can be simplified to self-similar, fractal-like hierarchy of network motifs [Song 2005; Goh et al 2006]. The rich are getting richer wisdom, or the Matthew-effect in sociology

means also the same. The, well known **in supply chain society**, Pareto law is also an epiphenomenon of the dynamics discovered by Barabási and Albert with saturation effect [Pareto 1897; Albert et al 2000; Axtel 2001; Wilhelm and Hanggi 2003; Barabási et al 2004].

$$P(k) = ck^{(1-\alpha)} \qquad \textit{(Equation 3-2)},$$

where *P(k)* is the cumulative degree distribution probability, *c* is a characteristic constant to that network, k is the nodes' degree and α is the scaling exponent. The cumulative scale-free degree distribution is seen as a declining straight line in log-log representation.

Hubs:
are the highly-connected nodes of the network. Hubs possess around (or more than) 1% of the total connections. They often achieve high ranking stability in scale-free networks [Ghoshai and Barabási 2011]. Typical hubs are the keystone species in food web, the functional words in language, Erdős Pál in the community of the mathematicians, etc. There are so-called date-hubs and party-hubs. A **date-hub** has different subsets of partners at different time [Sole et al 2003; Guimera and Amaral 2005; Csermely 2009, p. 45; Csermely 2012; Kovács 2013], its connections are transient. Typical date-hubs are the molecular chaperones like Hsp90. **Party-hub** interacts with the connected nodes simultaneously. In other words, those links are in transversal sync [Strogatz 2003; Antal et al 2009; Csermely et al 2013].

Component:
in network science, is the sum of all nodes and links a given node is connected with. In directed networks a node has both in-component and out-component [Newman 2010, p. 142-145]. It is worth to mention that the dissection of the component of a node from the rest of the network is less ambiguous than of a module. For **avoiding ambiguity**, in my dissertation **I do not use the 'component' terminus** from supply chain/operations **for describing material part** built into the product [Vitasek CSCMP 2013], rather apply the material or raw material terms.

Motif:
is a small group of nodes with characteristic linkage pattern. Typical motifs are the feed-back loop, feed-forward loop, bi-fan, bi-parallel [Broido and Claffy 2001; Barrat et al 2004].

Assortativity:
means that similar nodes of the network are preferentially linked. Assortativity may be both positive and negative. Latter called also as disassortativity. The assortativity leads to clustering while the disassortativity is one of the drivers of multipartite structure creation in

the networks. [Sole et al 2003; Newman 2010 pp. 220-225]. Clustering occurs if neighbors of a node are most probably also neighbors. It is measured by clustering coefficient, a ratio resulted from the existing number of links among all the neighboring nodes divided by the theoretically possible ones [Newman 2010, pp. 199-203].

Betweenness centrality:

is another centrality of high importance characterizing the central position of a node in spite of its lower degree. By removing the links of a node of high betweenness centrality the connected network falls into smaller isolated components [Kirschner and Gerhart 2007; Antal et al 2009; Newman 2010]. Nodes of this type are accountable for global connectivity. Often those take central position between network modules. Betweenness centrality of x_i is calculated as follows:

$$x_i = \frac{1}{N^2-N+1} \sum_{st} \frac{n_{st}^i}{g_{st}} \qquad \textit{(Equation 3-3)}$$

$(Eq. 3-3)$ where n_{st}^i is the number of geodesic paths from node s to node t through node i; g_{st} is the total number of geodesic paths from node s to node t; N is the number of nodes in the network. Consequently, the betweenness is normalized both by the total number of geodesic paths between the node s and node t, and by the theoretically maximum betweennes, i.e. when the node *i* would be the center of a star net [Newman 2010, pp. 185-192]. **In Section 5.2** I introduce the **betweennes centrality calculation adopted to supply chain** specifics in material conversion process what is based on bi-parallel characteristics.

Giant component:

is the largest part of the network, where all the nodes are connected to each other. In complex real networks the dissection of the giant component is heavily dependent on what kind of links and link-strengths we take into account [Newman 2003, 2010; Csermely 2009].

Module:

is the group of nodes that are relatively more densely linked to each other than to other nodes of the network and are relatively isolated from the rest of the network. Modules may arise from segregation of a larger network or from integration of smaller networks. As modules have overwhelmingly more intra-modular links than inter-modular ones, their structure enables them to behave as perturbation traps – isolating a perturbation from other part of the network and dissipating it [Ravasz et al 2002; Ravasz and Barabási 2003; Vázquez et al 2004; Antal et al 2009; Palotai and Csermely 2009]. The overlap of two modules or two independent networks is called **fringe area**. It may promote or prevent the communication/interactions between the two connected modules or networks.

Network skeleton:
is a subgraph of the network containing strong links and nodes of high weight and/or importance. In conversion and transport networks the network skeleton is the set of directed highways. The usual optimization is focusing on that [Han et al 2013; Dzupire et al 2014].

3.2. Perturbation and relaxation – the optimality criteria

Perturbation:
is the interactions between the network and its environment and among the different parts of the network (nodes/network-elements, modules, motifs, etc.).

Relaxation:
means that the perturbation is distributed over various parts of the network causing change in their state and by time the network returns to its equilibrium (original or new one).

Perturbations must be dissipated through relaxation, otherwise the network faces netquake [Ansari et al 1985; Carreras et al 2004; Serrano and Boguna 2008; Csermely 2009]. The perturbations generated internally in the network are called intrinsic noise/perturbation – corresponding to processual structure of Dementeyev, while those of external origin are called extrinsic – reflecting to the functional structure of Dementeyev [Dementeyev 1988; Barabási et al 2004; Csermely 2009, p. 55].

The spectral density of **noise** follows the power law:

$$P = cD^{-\alpha} \qquad \textit{(Equation 3-4)}$$

, where P is the spectral density, c is a constant, D is the frequency and α is the scaling exponent. **Pink** noise/perturbation corresponds to scale-free distribution in spectral density distribution and is widespread in the nature: earthquakes, rain, music, etc. Pink noise is good, it supports also the learning and the survival of the network [Carreras et al 2004; Csermely 2009]. At **brown** noise the scaling exponent is equal to 2.

Stress:
occurs when the network either does not have the adaptive response to a large, disruptive

perturbation or does not have enough time to mobilize the already existing adaptive response. There is a negative correlation in energy and stress levels. That is, as the available energy decreases in the network the stress level increases [Csermely 2009, pp. 81-83]. If the perturbations in the network can not be dissipated smoothly then the relaxation of the network becomes restricted. Due to that the tension in the network builds up, and it will reach the status of **self-organized criticality** [Scheinkman and Woodford 1994; Sornette 2002; Carreras et al 2004; Johansen and Sornette 2008], after which an **avalanche-like** relaxation and/or cascading failure take place. Csermely calls this phenomenon as '**netqauke'** – on the analogy of earthquakes, as the earthquakes and often other 'netquakes' also follow scale-free distribution both in terms of probability and spatiotemporal extent [Gutenberg and Richter 1956; Ganopolski and Rahmstorf 2002; Fronczak et al 2005; Dobson et al 2007; Csermely 2009].

3.2.1. The optimality in the strength of links, in synchronicity and in noise level

For effective relaxation a **balanced** combination of **efficient local noise dissipation** and **global communication** are required. In other words, the unspecific perturbations are to be confined and kept in restricted segments of the network (noise), while the signal (information), what arrives often enough to develop learned response, is to be transmitted. Such confined relaxation with global connection is strongly supported by **scale-freeness** and **small-worldness** [Alstyne 1997; Janssen and Jager 2003; Fronczak et al 2005; Goh et al 2006; Csermely 2009, p. 64].

The **weight of a link** can be represented by its **affinity, intensity** or **probability**. In **highly regulated networks** of biological systems the link strength is more **switching** from no-affinity to high-affinity and vice versa [Barrat et al 2004; Antal et al 2009; Csermely 2009; Newman 2010]. **Scale-free distribution** occurs in real complex networks in several aspects, like degrees, event probability, weight of the links, weight of the nodes. Those have also evolutionary reasons. Csermely proves in his monography that the **optimal ratio of weak links stabilizes the network**. A **link** is considered to be **weak** if its removal or addition does not change the network's behavior – measured usually by an emergent property of the network – in a statistically discernable way [Csermely 2009, p. 107]. Relatively large number of weak links compared to strong-links detected in Pareto distribution. Csermely suggests similar approach: top 20% of the links, through which about 80% of the interactions go, could be considered as strong links. In his fundamental work, he brings a great number of evidences (some of them in 2006 were only assumptions and have been already proven in the last years), where the weak links stabilize the network from molecular reign up to global networks. Beer highlighted already in the late seventies that cutting the tail in Pareto distribution destabilizes the system (network) and by weakening some of its the links – e.g. the railway branch lines in the UK – the system 're-creates' its stabilizing tail [Beer 1979]. It is worth to mention the indirectly induced weak linkage as well, when the neighbor's neighbor effect of even strong links results in weak linkage [Csermely 2009, p. 108]. The **long inter-modular links** are the 'classical weak links' of Granovetter. Those bridging contacts between communities are transient. Those long-range links play important roles in finding alternative solutions on unprecedented perturbations. [Granovetter 1973; Alstyne 1997; Csermely 2009, p. 44]. When including relatively simple, common molecules in the biochemical networks like H_2O and ATP large number of weak links and small-worldness will occur [Antal et al 2009; Csermely 2009, p. 11; Szalay and Csermely 2013]. Dunbar underlines that in social groups the language (as socio-cultural system/network) and the vocal grooming (gossiping) generate the system stabilizing weak links between humans. Those are essential for keeping the integrity of larger network parts, larger groups, modules. On the other hand, the strong links form the small groups of humans [Dunbar 1993; Kovács 2013]. Furthermore, the **weak regulatory linkage** of core processes (hubs) in biochemical networks **supports** the **evolvability**. The linkage between the core process and the regulated process is of high affinity in the one hand. On the other hand, those links are versatile and transient. Good examples of such phenomenon are the interactions of calmodulin, where calmodulin is a flexible versatile inhibitor of inhibitors, so decreasing the requirements of the mutational changes and supporting the evolvability [Kirschner and Gerhart 2007].

Three levels of synchronicity:
are distinguished by Blasius: first level of synchronicity is, when only the frequencies of the oscillators are synced; second level corresponds to sync of both the frequencies and the phases; and the strongest sync is, when apart from the two first, the amplitudes are also synced [Blasius 1999]. Strogatz brings a number of good examples on sync phenomenon in his monography [Strogatz 2003]. As Bianconi et al highlighted, the short loops in the directed networks are underrepresented compared to their random models what leads to stability and optimal synchronization of the directed network [Bianconi et al 2008]. The synchronization is

supported by an optimal ratio of weak links in the network, i.e. scale-freeness both in the degree distribution and in the distribution of link weights [Csermely 2009, p. 93]. The optimal level of synchronization, on the other hand, supports the optimal performance of the network, e.g. an intermediate level of motor unit synchronization is needed to achieve maximal movement precision of the muscles [Csermely 2009, pp. 169-172].

Syntalansis:
is an extensive synchronization of the oscillators (of the network-elements), often preceding the phase transition and culminated in self-organized criticality, a strong sync in the 'entire' network. Strong overall sync causes the epilepsy [Chavez 2010] what shows several analogies with cascading failures occurring in overstretched supply chain networks (See Section 6.1.2).

Optimality in noise level:
is also crucial in the network. Even more, the viable networks regulate themselves by changing their noise level through very different processes [Csermely 2009; Szalay and Csermely 2013]. **Stochastic resonance** takes place when the small signal can exceed the detection threshold only with the help of noise interfering with it [Ganopolski and Rahmstorf 2002; Csermely 2009, pp. 59-60]. It is functioning also as an early warning.

3.3. Network topologies and the topological phase transition

The detected network topology is a **result of subsequent optimizations and adaptive responses during the network's life**. It is strongly dependent from the energy level of the network and of its environment. Palla et al modelled the network topology transitions where the energy level serves for network functioning and the temperature represents the overall noise level [Palla et al 2004]. **A topological phase transition** occurs when the network is bombarded by perturbations and/or the available resources are decreasing [Csermely 2009, pp. 80-86]. See Fig. 1. High energy level and plethora of the resources result in **random graph** topology with short paths and plenty of links. The degree distribution is 'single-scale' Poissonian of Erdős-Rényi [Barabási and Oltvai 2004].

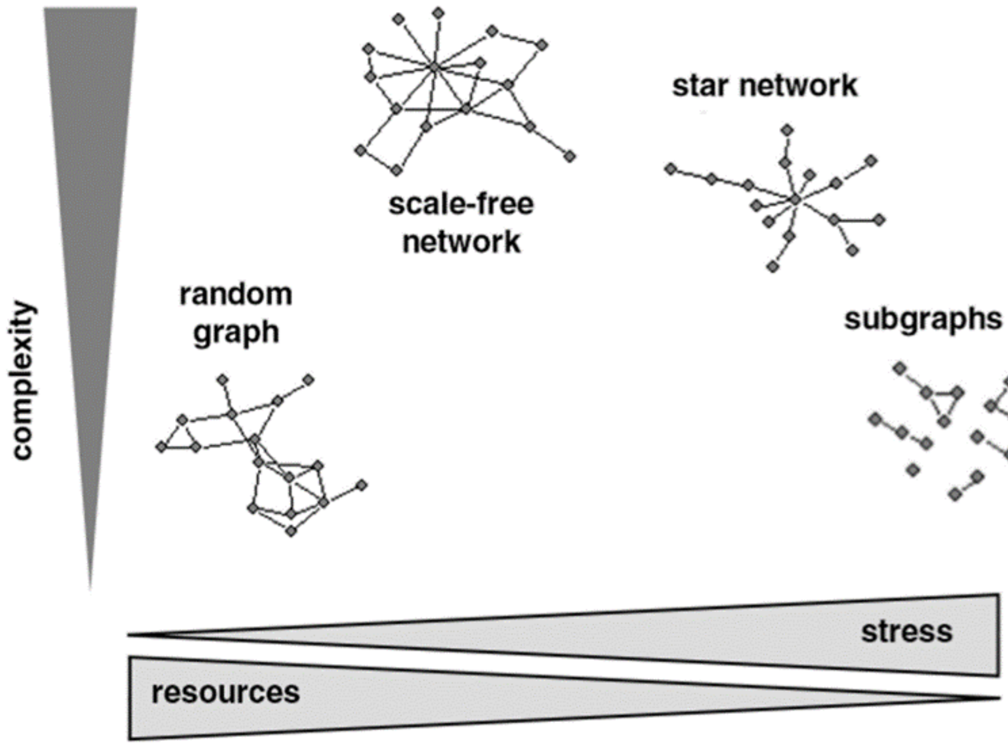


Figure 1. Topological phase transition of networks (with kind permission of Csermely Péter) [Csermely 2009, p. 81]

When the energy level (available resources) decreases the network maintains its connectivity through reducing the number of links and developing longer range links to its modules which , in turn, have become relatively more isolated. The network's clustering is increasing shifting from random graph to **small-world** networks [Watts and Strogatz 1998]. The limited resource availability requires more optimal utilization of the available resources leading to further differentiation in the links' strength and the nodes' degree distribution. As a result, the network 'develops' **scale-free** distribution in nodes' degrees and links' weights. The balanced co-existence of both short-range and long-range links enables local search and global reach – Levy flights [Bianconi et al 2008; Csermely 2009]. When the resources decrease further, a radical condensation takes place which leads to decrease of the weaker links and a relative increase of stronger links, as well as to less hubs but with more links concentrated to them. The compactness of the network increases further and it turns to **star net**. That corresponds to dictatorship. Further increase in perturbations and stress and/or decrease in resources cause the collapse of the network which falls into disconnected subgraphs – it dies. During the above described topological phase transition the scaling exponent α of degree distribution changes. Just a reminder, the degree distribution function is:

$$p(k) = ck^{-\alpha} \qquad \textit{(Equation 3-5)}$$

The α increases from 1 (random graph) to the range of 2-3 to max 4 (scale-free networks). When turning to star net, the degree distribution shifts to exponential cut-off. [Amaral et al 2000].

3.4. Recursive modularization and nestedness of the complex networks

Thanks to **hierarchical organization** of the material we can distinguish quite clear systems levels in living and non-living reigns [Fekete 1992; Csermely et al 2008; Antal et al 2009; Csermely 2009; Szathmáry and Smith 2012]. In network science terminology, the network level is equivalent to system level. The element of a system, or network-element of a network in finer resolution often turns to be a system, or network itself as well, with its relevant internal and external structure; and so on. Due to this nested structure, it is reasonable to highlight the relationship as **top network and bottom network**. Csermely, Kirschner and Gerhart bring several examples on nested, embedded structure of complex networks. Here I show only one **chain of nestedness** from top to bottom: eco web consists of different organisms. Organisms are also complex networks, which are built up by cells as network-elements and having further modularization like organs, and several subnetworks like neural (sub-)network. Cells are also complex networks containing overlapping bottom networks, like protein-protein interaction networks (interactome), etc. Interactome contains also a subnetwork of molecular chaperone interaction networks (chaperome) of similar extent, and so on [Kirschner and Gerhart 2007; Csermely 2009, pp. 130-133; Csermely 2012].

Nested modularization:
may occur in two directions: bottom-up through **symbiosis, cooperation** or top-down through **segregation** [Csermely 2009, p. 35]. Cooperation leads to forming the higher level of the system/network. Cooperation means joint actions between participating partners for common goals facilitated through their communication and strategy adjustment. Competitive behavior at given hierarchical level may lead to cooperation at a level higher. At cooperation, the interacting partners may limit, sacrifice their interest and benefit from the maximized benefit,

better fitness and survival chances of the group [Csányi 2003; Fekete 2003; Csermely et al 2008; Szathmáry and Smith 2012].

3.5. Signaling pathways and transport routes in viable networks

In viable networks there is a need for regulation and communication (partner driven, condition dependent regulation of behavior) as well as for transfer of resources. In non-social viable networks the local routing mechanisms tend to be more stochastic while the global ones are more deterministic.

The lower level strong interactions can generate/be perceived as 'soft-interactions', as communication at the higher, meta-level [Fekete 2003]. Weak linkage characterizes the information flow (signal transduction, regulatory networks) in the biological networks, while at bottom network level it is represented by a switch-like capability [Kirschner and Gerhart 2007; Antal et al 2009]. As Csermely et al highlighted, signaling pathway is a special transport process. I will prove later that it shows analogy with demand network. The signaling cascades lead to development of signaling pathways what effectively filter noise and help the network to adapt to frequently occurring new stimuli, i.e. signals [Palotai and Csermely 2009]. The overlapping modules and the internal redundancy, on the other hand, create perturbation traps in the interactomes [Palotai and Csermely 2009; Csermely 2012]. The unusual strong persistent signal may slightly disassemble the protein modules temporarily reducing the inter-modular links. After the disruption, the network **re-assembles but in slightly different way**. That is called learning by Csermely.

3.5.1. Some relevant elementary motifs of the biochemical and biological networks

The biochemical networks have complex nested structure of overlapping subnetworks. Here I highlight two fundamental motifs that have strong analogy with motifs of LSCN. In **metabolic** reactions material A (substrate) turns to material B (product) – Fig. 2 left. The conversion is supported by enzyme(s) which catalyze(s) the reaction but themselves do not change. The coenzymes on the other hand change their state – coenzyme Z changes to Y. There may be more substrates in the reaction – in that case instead of A→B we have A+B→C reaction like in protein-protein interaction in Fig. 3. The reactions are often reversible (↔), however the use of the 'end products' triggers the reactions more into one direction. The dynamically changing concentration of the different materials in the network, especially of coenzymes, results in an emergent complex self-regulation of the running chemical reactions. Those regulative interactions are typical weak-linked ones. Such feedback regulation may happen either so that the regulating coenzyme concentration Z (Fig. 2 right) changes in a completely different metabolic pathway (A→B; C→D) or in the same pathway (A→B→C).

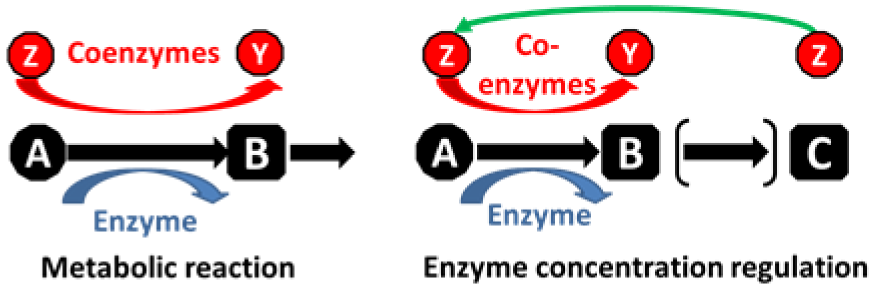


Figure 2. Two fundamental motifs of metabolic networks

In case of **protein-protein interaction network** we have already covered the A+B→C motif, that models the protein complex formation from (two) different proteins (Fig. 3 right). The other important motif of the corrective interaction involves the protein chaperones. The protein folding process would be a low fidelity process without the corrective support of the molecular chaperones which unfold the protein, enabling it to restart the folding process – not inevitably from the very beginning [Csermely 2009].

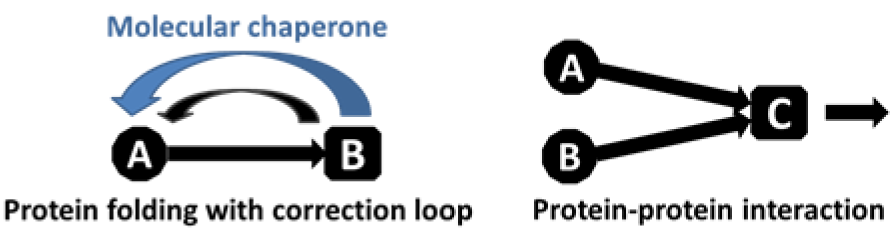


Figure 3. Two important motifs of protein-protein interaction networks

As we will see in Section 4 and 5, the the LSCN is predominantly a directed network where the **stratification** of the network is less effective with such centrality analyses like clustering coefficient [Newman 2010]. In such situation the discovery of the **bi-fan**s and **bi-parallel**s

(See Fig. 4) in our networks are the focus motives to determine the indirect transversal dependences.

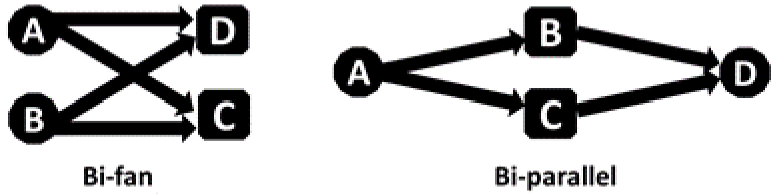


Figure 4. Two important motifs of stratification in digraphs

Those motifs are well detectable with the help of the **co-citation and bibliographic coupling matrices** discussed in Section 5.2, and support the determination of latent modular structure of the investigated organization.

3.6. Plasticity-rigidity cycles in complex networks

Adaptation to environmental changes is a prerequisite of the system's (network's) survival. The **recursive cycles of more plastic** exploring behavior and of **more rigid** focusing exploiting behavior create the adaptation. Both extremes of rigidity and of plasticity lead to destabilization of the system [Csermely 2015]. In supply chain terminology we use more the **flexibility term for plasticity** [Geissbauer and Householder 2011. Pure flexibility means that the system returns to its equilibrium after the perturbation, like a spring, i.e. fast and reversible response from the network to known/well defined environmental changes, perturbations. Therefore, **in my view, plasticity** is more like the chewing gum, i.e. long and/or large enough environmental change will lead to system's alignment to the change (developed adaptive response with a new equilibrium), while smaller and/or shorter-term perturbations change the system's state only temporarily and it will return to its original equilibrium. Such plasticity-rigidity cycles are detected in all types of networks from the protein folding, through birds' song learning, in the cycles of brain storming, to the economic cycles [Csermely 2015].

While the **hubs** of very high degree situated more **in** the **giant component** and in the **modules** contributing to high connectedness, the **bridges of high betweeness centrality** connect the modules to each other and to the possible central giant component. Due to the large number of links of hubs, the portion of weak links are high in their portfolio. **Bridges**, as a rule, have **low degree** and their low number of links are also more of **weak links with transient** behavior. The strongly connected, stronger linked central component is usually over-constrained and rigid, while the peripheries are under-constrained and flexible [Newman 2003, 2010; Antal et al 2009; Csermely 2015].

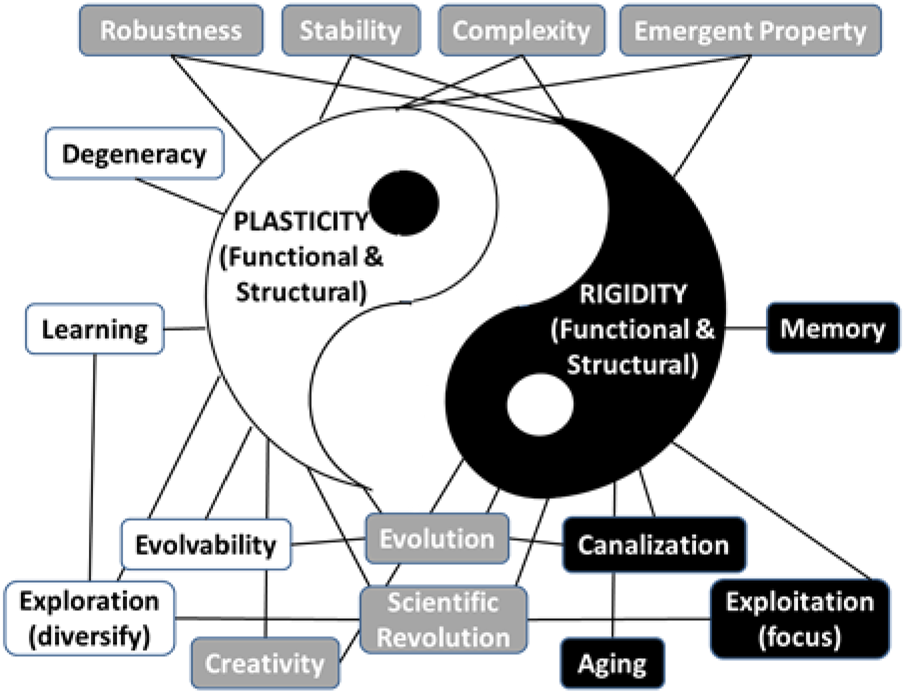


Figure 5. Plasticity-rigidity cycle and its connection with key network characteristics (reconstructed with kind permission of Csermely Péter) [Csermely 2012]

As it is seen in Fig. 5 (reconstructed with kind permission of Peter Csermely) in plasticity-rigidity cycles the **contributing properties are interlinked** and support each other in complex relationship. The opposite position of the property pairs in the picture reflects to their opposite and complementary relationship as well – like learning and memory, evolvability and canalization, exploration and exploitation [Csermely 2012]. Aspects in white box support the system's functional and structural plasticity, while properties in black box contribute to its rigidity. The attributes in grey box support both plasticity and rigidity. The plasticity-rigidity cycles form an overlapping embedded complex structure. Therefore, I use the symbol of yin and yang what symbolizes that embeddedness.

Degeneracy:

means that functionally identical but structurally different network-elements are in the network. In other words, the same function, product, outcome, solution may be a result of (slightly) different processes, reactions, entities, ways [Edelman and Gally 2001; Liker 2004; Csermely 2009, p. 115; Whitacre and Bender 2009; Whitacre 2010]. The evolvability of the complex networks/systems – the capacity of generating wide variation of outputs, responses, products, solutions [Plotkin and Wolyne 2003; Kirschner and Gerhart 2007; Csermely et al 2008; Gáspár and Csermely 2012; Csermely 2015] – is strongly supported by degenerative redundancy, in other words degeneracy.

Evolvability:

of the organisms (**biological** networks) largely depends on the existence of **highly stable** conserved comparted processes coded by rigid DNA sequences. These stable hubs with proliferated large number of links de-constrain the other processes so generating the **epigenetic variation to be selected** [Darwin 1859; Kirschner and Gerhart 2007]. So, they are co-selected with those successful processes which latter were selected through those successful functions they regulate [Darwin 1859; Kirschner and Gerhart 2007; Csermely et al 2008; Csermely 2015].

Resilience and **stability:**

have (slightly) different meanings and definitions in the literature, but describing similar capability leading to successful survival of the network. The network's stability may be manifested in its structural, functional and parameter stabilities. Resilience is the capability of the network to preserve its integrity, giant component, and percolation. That is the system's structural stability, since it does not fall apart to subgraphs. The **functional** network **stability** (homeostasis) means that the network is able to keep its functionality, the changes are statistically negligible when removing nodes/network-elements or links from the network. That manifested often in parameter stability as well. In his definition of '**netsistance'**, Csermely gives a dynamic and generally usable definition on stability and resilience: The network keeps its integrity against minor structural changes caused by environmental and network perturbations. The network is able to dissipate the large perturbations through fast and efficient relaxation and returns to its previous equilibrium state or goes into a new one [Sole et al 2003; Csermely 2009, p. 333; Geissbauer and Householder 2011; Melnyk et al 2014].

Stability landscape:

To better understand the different behavior of the simple system/network and of complex nested networks it is advisable to visualize the network's state space by stability landscape. That is similar to topographical maps and visualizes the possible states of the network characterized by its 'goodness'. The 'goodness' may be energy, fitness, **market value of the company**, etc. The local optimal minima are separated by ridges and saddles of different height causing rougher or smoother landscape. Rough stability landscapes make the transition from one state (local minimum) to another more difficult, often resulting in so-called punctuated equilibrium. When the environment changes and the network is unable to smoothly change its state according to the new requirement, then self-organized criticality may occur, causing avalanche-type relaxation, netquake [Ansari et al 1985; Csermely 2009, pp. 121-130]. For simple systems, the **Lyapunov** stability is sufficient to show how quickly the system returns to its original equilibrium state after the perturbation – a shallow landscape corresponds to less stable behavior, while a steep minimum leads to quick return and high stability. Extremely plastic simple systems are highly adaptive, exploring large number of possible solutions, but they are unable to generate stable standardized optimized reliable responses to repeated environmental stimulus – those learn and forget quickly. The extremely rigid simple systems respond very reliably efficiently and quickly to repeated stimulus. They transmit the perturbations well but dissipate them poorly. On the contrary, after perturbations the complex systems/networks may return to the same stability or another than of prior to the perturbation. Consequently, the classical Le Chatelier principle of systems stability is not fully satisfactory. The **complex systems have more complex stability landscape with several local minima**. The system/network may drift among those minima until it reaches the stable state [Plotkin and Wolyne 2003; Csermely, 2015]. Such behavior is typical in protein folding process. The roughness of the stability landscape can be smoothened by adding weak links to the network, like water in biochemical networks, chaperon proteins in protein-protein interaction networks [Kovács et al 2005; Antal et al 2009; Csermely et al, 2013]. By cycling between more plastic and more rigid states the complex networks find the maximal structural and functional stability in a changing environment.

Csermely brings several examples from non-viable systems up to societal networks on **plasticity-rigidity cycle-driven adaptation** and **evolution** [Csermely 2015]. The **plasticity-rigidity cycles of different spatiotemporal extent stabilize** the networks against perturbations of different magnitudes, and that significantly helps the success and survival of the network. Such **nested plasticity-rigidity cycles** must be developed in DSN and LSCN – see Section 6. Csermely underlines that the plasticity-rigidity cycles of various time-scales and ranges help the evolution in general [Csermely 2015].

3.6.1. The role of the creative elements

The creativity is a 'luxury' in stable predictable environment, and is the insurance in highly volatile disruptive environment. Creativity of a system is represented and delivered by so-called creative elements, which have transient, weak links leading to important positions (often to hubs). Csermely has generalized the presence of 'creative elements' in protein, cellular and social networks. Creative elements are active centers in the network with free energy, so-called hot spots. Those help the complex systems in their survival when unprecedented challenges occur. Network analyses of protein networks show that creative elements occupy central position, giving unique links, integrating the communication (highways, inter-modular position), do not take part in dissipative motions, but collect energy (Csermely 2008, 2009). Therefore, creative elements play key role in the development, survival, and evolvability of the complex systems.

4. Synthesizing the supply chain and the network sciences

Based on my research and investigations, as well as my own experience in several industrial segments, in this section I make a synthesis of the two large disciplines, i.e. of the network science and of the supply chain theory. In some cases, there was a need of disambiguation, since same terminus is used with completely different meaning in the two disciplines (e.g. component, module, hub). Apart from the analogies between the supply chain networks and the above discussed viable networks, I highlight the differentiating factors as well.

4.1. Supply chain mathematics in the context of network science

The **power-of-to policy**, explained in Section 2.1, is of high significance. In the real networks, including supply chain networks, we often detect power low distribution with scaling exponent between 2-3. The power-of-to policy is utilized differently in the western culture and at Toyota. In the western culture a typical case is the 'one warehouse multi-retailer structure'. The order fulfilment will be e.g. for large orders every day, for smaller ones every second day, and so on. In this case the timing (sequence) is standardized while the fulfilled quantities are not – as they correspond to particular customer demands. The other latent risk is the interference of the demands, causing 'super-waves' in the activity load of the warehouse. What does Toyota differently? Liker and Meier underline, Toyota also standardizes the frequencies as to be produced e.g. every day, 2nd day, 4th day, and the rest 'to order'. But Toyota standardizes the produced quantities as well, i.e. level loading with heijunka as ABACABAD, etc. This double standardization creates stable flow of demands (both volume and mix wise) upstream towards the suppliers and supplier processes. The fluctuation between the so standardized flow of supply and the demand fluctuation is either absorbed by the de-coupling finished product inventories and/or covered by the increased flexibility in supply, in production [Liker and Meier 2006]. That is a philosophical difference.

Uncorrelated demands, described in Section 2.2, reflect to the **lower limit of weakly synced outgoing links**, while **fully correlated demands reflect to strongly synced outgoing links of a node**. The latter occurrs during cascading failure, what I will explain later in Section 6.1.2. Therefore, I suggest to use the abovementioned Function 2.5 with correlating demands of the finished products (weaker or stronger synchronicity), i.e. σ_C or σ_D depending on the strength of correlation, the strength of sync.

Postponement or late customization create an effect similar to demand pooling. However, please note: in real life, especially when serving an OEM or in environment of mass customization [Salvador et al 2002, 2004; Logility 2010], more than just one proliferation steps are in the variety funnel. Consequently, we may have other intermediate (less generic/more customized) items between the generic semi-finished product and the final customized finished products. That leads to certain sync (correlation in demand) of those intermediate items. See also Fig. 19.

Apart from the benefits highlighted in the mathematics of chaining in Section 2.3, the **chaining structure** may **create** implicit **degenerative redundancy,** since the different factories may produce the same product with slightly different processes. As we saw, in the biological and biochemical networks the wide-spread degeneracy – structurally different network-elements may serve identical function and that may change in spatiotemporal space –

results in extraordinary robustness [Sole et al 2003]. In biological networks the degenerative redundancy occurs at more than just one hierarchical level, which heavily contributes to the robustness and resilience of the network [Albert et al 2000; Sole et al 2003]. In Section 6.2.2 I show how we could create such multi-level degeneracy resulting in extraordinary adaptability and flexibility in a large organization.

4.2. Symbols to visually grasp the main network characteristics of DSN/LSCN

In LSCN the modularization takes place both alongside the material flow of the supply chain (like value streams) and perpendicular to it (like echelons). The former direction I call longitudinal, while the latter is the transversal direction. **I distinguish transversal and longitudinal sync** accordingly, depending on whether the sync takes place between links or nodes alongside the material flow or perpendicular to it. Transversal sync of out-links causes perturbation increase of that node – e.g. piece-picking of different materials into kit of a production order causes such perturbation increase in the picking process. On the contrary, when creating weak sync and/or weak links in material-subnetwork of the organization at different hierarchical levels we can establish the netsistance (network resistance) of the organization. The links of a node or network-element may have different strength or weight as well as they may behave with different level of synchronicity. In Section 5 I will show the correlation between node's behavior and the linkage and sync patterns in its out-component.

When creating common understanding about an organization's networked structure it is inevitable to visualize it. Although there are simple and powerful visualization approaches on links of different weight (thickness of the lines/arrows or full-dashed-dotted lines), the level of synchronicity is either latent or its visualization is cumbersome (i.e. links circled around). During my investigations, I have developed **simple symbols** by what we can easily **visualize the key characteristics of a complex networked structure** both by hand or in printed form – in text or e.g. in PowerPoint. I could use those symbols in different countries and cultures with great success [Fekete 2003; Fekete and Hartványi 2015; Fekete and Hartványi 2016a].

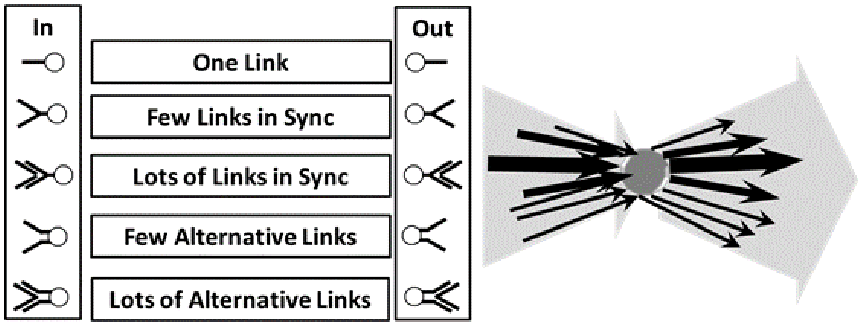


Figure 6. Group behavior of links – with different level of transversal synchronicity

In Fig. 6 I show the symbols of prevalent link's behavior for both in-links and out-links. In LSCN the "few" means half to one dozen (rarely a few dozens), the "lots of" corresponds to several dozens to several hundred (sometimes several thousand). In all cases we read the digraphs built by these symbols from left to right which assures clarity about in and out directions.

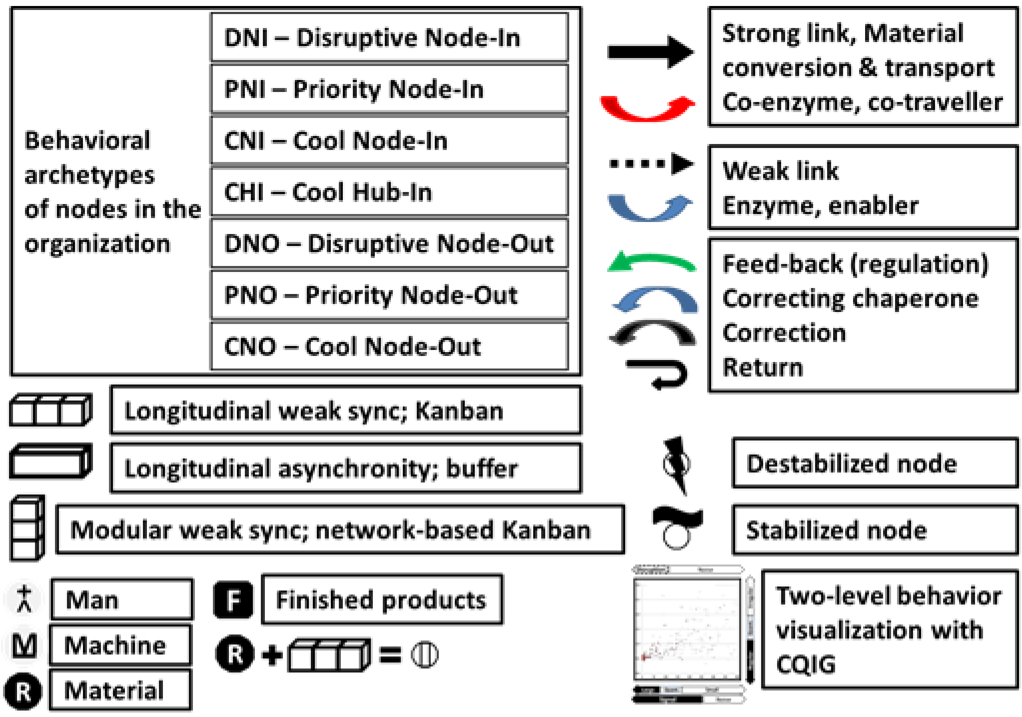


Figure 7. Symbols to visualize the main network characteristics of the bottom network

In Fig. 7 are seen those **symbols** which **I use in my dissertation to visualize the motifs in viable networks and in DSN/LSCN**.

4.3. The network characteristics of the DSN and LSCN

Node:

DSN and LSCN are characterized by many non-identical nodes what are connected by different interactions. Nodes in our investigations can be: different material forms, machines of different complexity (from a tool up to a complex production line, etc.), men (or teams, etc.), larger complex network-elements, like entire factories, organizations, etc. That is more dependent on the goals of our investigation. I use node terminus in general terms, while the **network-element term** when I would like to **emphasize its further networked structure** at one hierarchical level lower. A raw material or finished product, or machine is treated more as a node while the organization can be perceived more as a network-element with own complex networked structure. The number of nodes in an organization, what defines the **order of the network**, may vary from dozens to tens of thousands. The material nodes in different organizations are seen as follows: close to 7000 on Fig. 19, 400 on Fig. 27, 3500 on Fig. 29.

Link:

The number of links determines the **size of the network**. The size of the network of an organization is usually a magnitude higher that of the order – see Fig. 19. Links may have direction building a **directed graph** (or digraph). In DSN and LSCN we have complex structure often represented by both **symmetric (undirected) links and directed ones**. Both links and nodes may have weight forming **weighted networks.**

Diameter of the network:

the maximal length of shortest paths between any pair of network-elements/nodes of the network is heavily dependent from the set of links what we take into account in DSN or LSCN. In DSN we have a great number of undirected links between men what shortens the path-length to few steps. If we take into account only the directed links of material conversion and transport process in the organization, then the path length tends to be indefinite, e.g. the path of a node-pair of two well isolated from each other value streams. However, in case of cascading failures those directed links turn to symmetrical ones what immediately change the diameter to few steps – see the case in Section 6.1.2.

Subnetwork:

We could see in Section 3, that different scientists apply subnetwork terminus with different meaning. I use the **subnetwork** terminus as the **connected subgraph part** of the network usually **of similar spatial extent** and **containing** (mostly) only **one type of nodes/network-elements**. E.g. the entire eco web contains the subnetwork of human beings what contains the man-subnetwork of demand supply network. The spatial extent of those (sub)networks is the same, i.e. global. A subnetwork has usually similar nested, complex structure as of its network. According to the man-machine-material triad in the supply chain management, an organization consists of man-, machine-, material-subnetworks, at least. That structural systematization will play fundamental role in **right-sizing the organization's modular structure** when creating robustness against perturbations of different spatiotemporal extent and magnitude (Section 6.2).

Degree distribution:

In DSN the preferential attachment, the optimum driven design and (self)organization are important drivers as well. The successful component is preferred in further/new products, successful partner wins more benefits and businesses. The optimum in dealing with complexity (late customization, postponement), the optimum in economic order quantity, the optimization driven by the physical distance caused costs, etc. All those are **drivers of scale-free degree and weight distribution** in DSN [Salvador et al 2002, 2004; Serrano and Boguna 2008; Lim et al 2011; Petridis et al 2015]. However, there may be **different degree distribution in different parts**/clusters of the multipartite complex networks [Csermely 2009, p. 17; Chattopadhyay 2010]. My investigations show, that is especially **characteristic to the LSCN**:

1. **Poisson** (if any) **in-degree** distribution **of** material **sources** (overwhelmingly single supplier structures);
2. **Exponential in-degree** distribution **of** finished **products** (bill of material driven);
3. **Scale-free out-degree** distribution **of both** (material) **resources** and of finished **products** following power law. That latter phenomenon plays crucial role in designing more robust LSCN I describe later.

In Fig. 8 the **cumulative degree distributions** of in-degree and out-degree of the nodes are shown from a Tier-1-3 automotive supplier.

$$P(k) = ck^{(1-\alpha)} \qquad \textit{(Equation 4-1)},$$

where *P(k)* is the cumulative degree distribution probability, *c* is a characteristic constant to that network, *k* is the nodes' degree and α is the scaling exponent. The cumulative scale-free degree distribution is seen as a declining straight line in log-log representation.

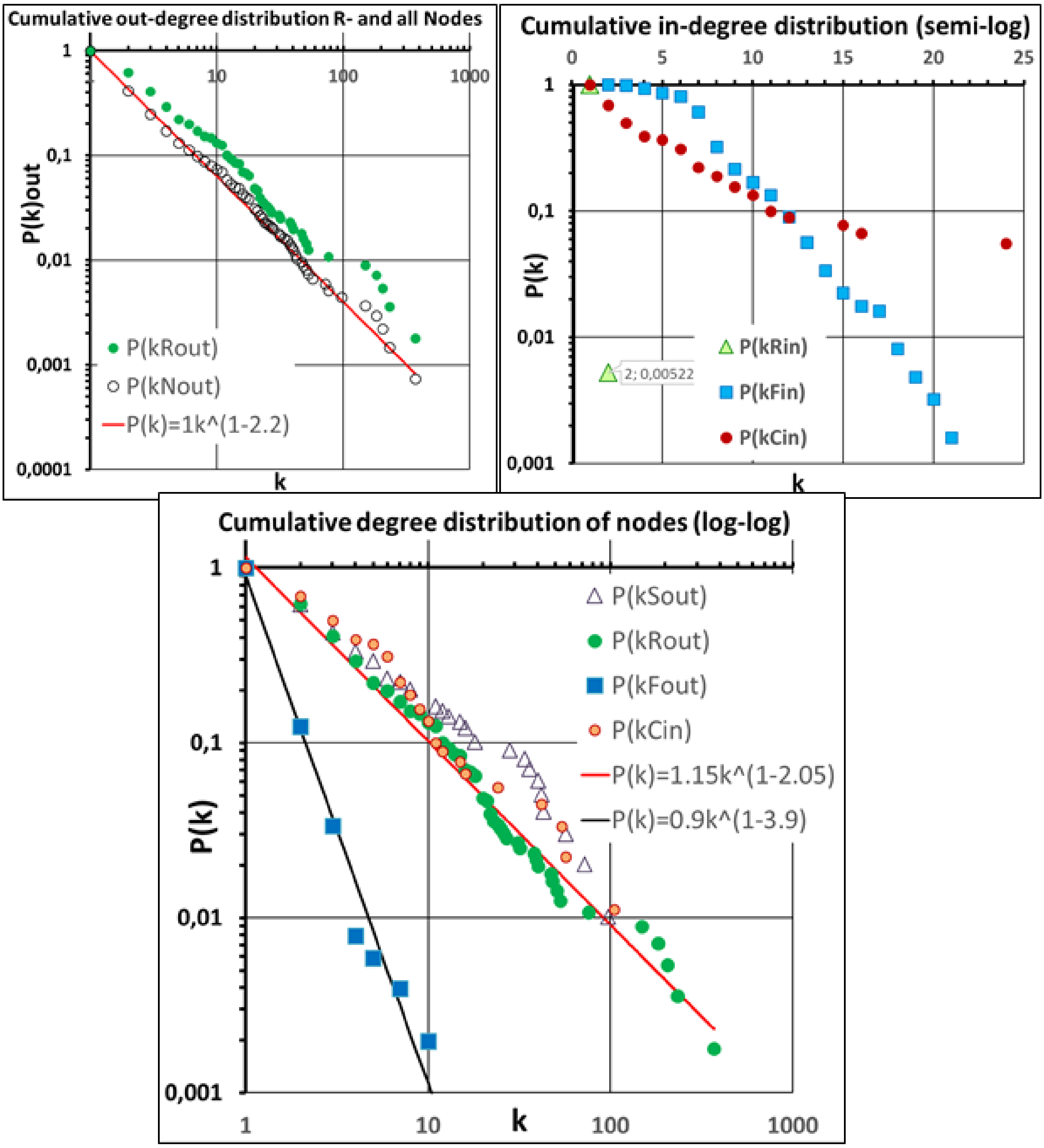


Figure 8. Cumulative degree distribution in Tier-1-3 automotive organization

Top left graph shows the cumulative **out-degree distribution of the raw material nodes** (Rout) and of **all nodes** of the organization (i.e. suppliers, resources and finished products). For the latter the scaling exponent of the scale-free distribution is 2.2 (Fig. 8 top left). The **bottom graph shows** the particular cumulative **out degree** distributions of the **supplier nodes** (Sout), **material resource nodes** (Rout) and **finished product nodes** (Fout) – all are **scale free**. The scaling coefficient of the finished products is around 3.9, i.e. quite high, closer to star net topology. In case of Tier-n suppliers that is expected as they have limited number of customers and usually there is/are 1-2 customer/s in very strong, dictating position in the organization's portfolio. The cumulative **in-degree** distribution of the **customer nodes** (with links only from our organization) also show scale-free distribution (Fig. 8 bottom). The cumulative **in-degree** distribution of the **finished products** (Fin) shows **exponential** distribution in the top right graph of Fig. 8 – straight line in semi-log representation. The **cut-off at low degrees** (2, 3, 4) is due to semi-finished products, where 2 to 3 components with 1-2 subassembly were assembled together. The **in-degree of the material resources** (Rin) is overwhelmingly 1, and 0.5% of nodes have 2 (dual sourcing). The customer in-degree (Cin) warns us in semi-log chart that it is rather scale-free (Fig. 8 top right).

Hub:

in **LSCN** can possess also few percentage-weight in the interaction portfolio – see Fig. 27 weights: W 4.8%, 2.3%, 2.1%. The ranking stability of the hubs in LSCN is caused by preferential attachments to the successful hubs described above. Since the material conversion in the LSCN is directed, we have to distinguish **in-hubs and out-hubs**. In-hubs in LSCN often suffer from high dependability and sensitivity due to mandatory sync requirement of their in-links – being party-hubs, while out-hubs benefits from their weakly synced out-links. Therefore, the **finished product hubs** are possessing '**Janus-face**' in LSCN, with asymmetric structure: the in-links are in strong sync (e.g. materials built into a product) corresponding to party-hub behavior, while the out-links may be in weak sync (finished product delivered to large number of customers with non-correlating demands) corresponding to date-hub behavior. Another type of **asymmetry** is described by Morvai and Szegedi **at DSN level**, where the organizations are the network-elements. The large players of food supply chain have large number of more transient links of lower affinity to their suppliers and customers, while the small suppliers – who are more dependable from the large players – try to build and maintain strong and long-lasting links, relationship to their customers. I.e. the dominating players of the food supply chains behave like date-hubs [Morvai and Szegedi 2015].

Assortativity, clustering:

In LSCN either assortativity or clustering have limited meaning as the LSCN is a multipartite directed network with echelons and stratified value streams. The **material-subnetwork** of the **LSCN** is a directed network where the **stratification** of the network is less effective with such centrality analyses like clustering coefficient [Newman 2010]. If two finished products C and D use the same materials (A and B), then they form a **bi-fan** shown in Fig. 4. Since in the

LSCN the finished products have dozens of built-in materials, in fact, we have multi-fans linking all the common materials of that finished product pair. The transversal dependency may occur in even more tightened way through **bi-parallel**s, when two materials have common supplier upstream and common finished product downstream, or the two finished products have common material and common customer respectively. See Fig. 4, right. Therefore, I found the combination of the bibliographic coupling matrices and the co-citation matrices to be more appropriate in LSCN (see Section 5.2).

Component:

An organization represents the giant component if we take into account all the weak links and symmetric links of the multipartite network – especially of man-subnetwork [Chattopadhyay 2010]. On the other hand, the material-subnetwork of the organization is percolated only in case of cascading failures when the links and pathways become symmetrical, undirected.

Skeleton:

In conversion and transport networks like LSCN the network skeleton is the set of directed highways. The usual optimization is focusing on that [Han et al 2013; Dzupire et al 2014]. **I include in the network skeleton** those **high importance nodes** which indirectly will cause large perturbations after their destabilization – see Section 5.

Network topology and attractor in LSCN:

Concerning market value, undoubtedly it is a longer-term indicator of the fitness, as an emergent property of a great number of different parameters and dimensions of its healthiness – the perspective of its owners, customers, suppliers, employees, public partners, etc. However, in operational timescale I have found the complete on-time delivery (COTD) or the quality-delivery-cost to be a better goodness value. At an automotive supplier, we implemented my solution on smoothening the stability landscape (see Section 6). We considered the complete on-time delivery as a strong indicator of our performance, 'goodness', while the so-called 'stock replenishment trigger' (SRT) behaved as the attractor of the organization (entire stock profile, stability landscape). There was a strong **correlation between** COTD's behavior (as '**goodness'** value) and the aggregated attractor (**SRT**) seen in Fig. 9. As the **attractor** (stock replenishment trigger) moved from the safe 1000 man-hours region to 4000, the COTD started fluctuating more and more and decreasing from the stable 98-100% COTD hitting even 90%. When the SRT moved back to healthier region (2600) the COTD fluctuation decreased and the mean raised back to the high nineties.

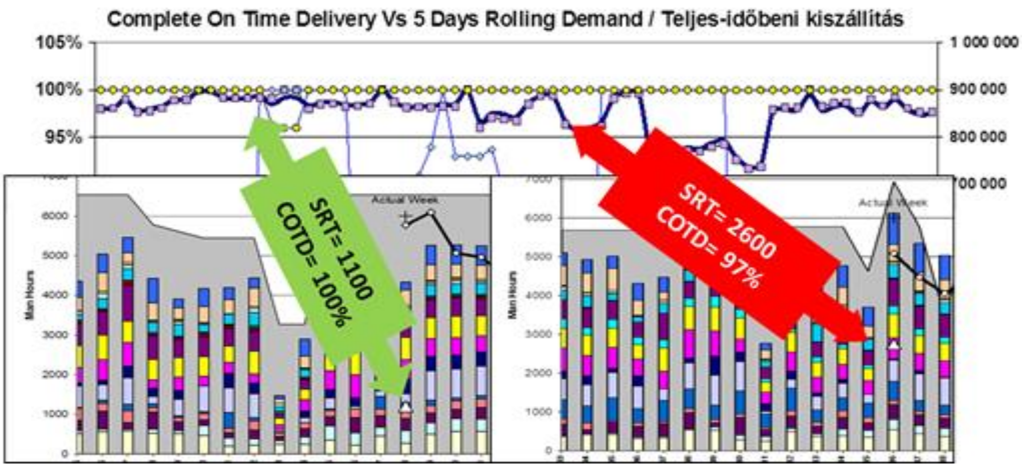


Figure 9. Correlation between the attractor (SRT) and the performance (COTD) of the organization (automotive supplier)

4.4. Perturbation, relaxation and the optimality criteria in DSN/LSCN

In DSN the perturbations are the requirements of material, value, energy, information flow (demand) and the flow itself (supply) – the demand signal, to which we want to match the supply and the resource flow to the need, respectively. The product (value) we supply to our customer can be perceived as accumulated energy frozen in material form as a generalization for all man, machine, and material resources. Following Csermely [Csermely 2009] I use **perturbation in general terms**, while **noise** to describe the large number of distracting small irregular perturbations in an organization.

Signals are the large enough regular usual perturbations, to which the network needs to develop and utilize well defined adaptive responses – to what the organization must/can be optimized, sometimes over-optimized [Dobson et al 2007]. The large irregular perturbations I call **disruptions** against what we want our organization to become more resilient. Trent emphasizes the quick adaptive response of our supply chain to risks/disruptions, though without distinguishing whether those are known or unknown ones [Trent 2015]. Melnyk et al call the unprecedented disruptive events as uncertainty, while the known ones as risks. Based on such distinction they define the investment directions in building resilience at the DSN level [Melnyk et al 2014]. The reigns of signal, noise and disruption are important discriminating factors in the combined quantity-irregularity graphs (see CQIG in Section 5.1).

In supply chain management, the **rule of power-of-two** creates also **brown perturbation** at supplier in order intake [Snyder and Shen 2011 pp. 37-45]. However, it makes the arrival of demand signal to supplier regular, while the amplitude of the total demand signal in that time period will be amplified due to interference and due to sync in frequency and phase of the arrived demands. In other words, the rule of power-of-two is good for the order intake team, while it may generate fluctuation in the total demand.

Another example is the **bin sizes** we designed and implemented in a large Asian IT factory's milk-run process **followed** also **power law** (scale-free) distribution, since the revisit frequency was planned as fixed and the demand distribution of the different materials followed Pareto law. The exceptions were the **rounded-up** items to manage reasonable packaging form size (e.g. to full tray quantity) and the materials with large packaging unit size but with small physical size (e.g. screws). Regarding to latter, the bin size might correspond to multiple of the quantity used during one revisit cycle. Those **deviances from the general principle created further stability** in the total logistics load pattern of milk-run replenishment as the harmful interference of demands described at power-of-two law was diminished.

As we could see, the **weak regulatory linkage** of core processes (hubs) in biochemical networks **supports** the **evolvability**. The linkage between the core process and the regulated process is of high affinity in the one hand. On the other hand, those links are versatile and transient. **Similar dynamism** we can design in an organization where the different levels of planning-execution pairs assure that the execution is more local while the communication is more global, i.e. the information flows more on meta-level. The execution at the higher-level planning creates the frames and conditions for the lower-level, and so cascading down from strategic planning of the entire enterprise to planning and execution in a factory at shift level. Evidently, the plan process in SCOR model [Supply Chain Council 2011] corresponds to long-range weak links between organizations respectively.

Sync:

In LSCN, e.g. the surface mounting technology devices (SMD machines) in a board-assembly production line behave like strongly coupled oscillators, while the internal placing processes in one SMD machine (may) have different partial frequencies compared to each other (embeddedness again). The operators in a balanced production cell with standard WIP behave like weakly coupled oscillators, i.e. only their frequency – in average – is the same. The light

oscillations between their frequencies and phases are evened out by the well-designed standard WIP, which is decoupling and linking the two operators/processes with tolerance – that is the weak linkedness again.

Stochastic resonance:
In DSN similar function fulfills the amber inventory-element in well-designed Kanban-systems or the yellow Andon lights at Service Kanban (designed by me and implemented in a large telecom factory) where increasing number of yellow signals create pre-warning about near-future overload of the supply process.

4.4.1. Strongly linked and synced star net topology around dictating organization

In DSN the dominant enterprises dictate – in a humble or less humble way – to their adjacent suppliers and customers in few-steps distance (Tiers in supply chain terminology). The strong alignment to dominant dictating organization – e.g. OEM – creates star net topology. In such topology the value stream optimization, driven by the dictating organization (DCT in Fig. 10), is very effective and the Multi Echelon Inventory Optimization (MEIO) works also well. The demand signal is transmitted undistorted upstream. Such supply chain is usually called by Gartner as the „Best supply chain of the year" [Aronow et al 2014].

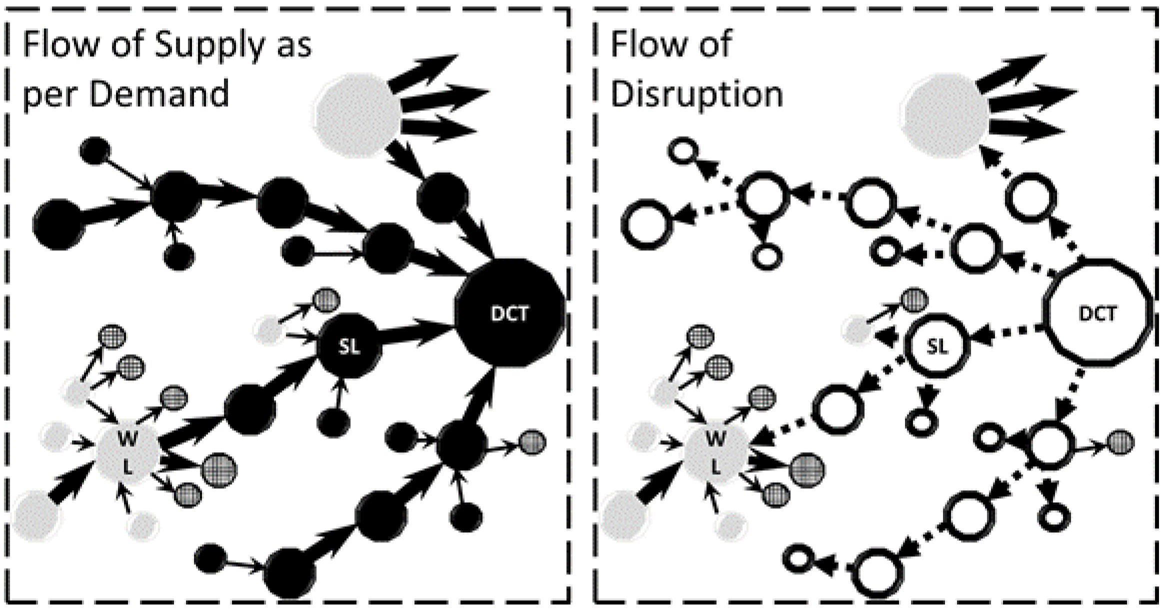


Figure 10. Star net topology in the neighborhood of a dominant organization

However, the star net topology generates also disadvantages. The strongly linked and aligned suppliers (SL in Fig. 10) are heavily dependent on the dictating organization. The fluctuation of the dictating organization disperses through the network as disruption. Often there are digital survival chances for smaller organizations at the end of the chains. If the central dominant dictating organization collapses, then the entire star net will be fragmented and the strongly aligned and linked organizations will be heavily affected. Some weakly linked organizations may survive – WL in Fig. 10 [Fekete and Hartványi 2015].

4.5. Signaling pathways, material conversion and transport process in DSN/LSCN

The general properties of transport processes, determined by Csermely and Palotai, in networked systems are listed below [Palotai and Csermely 2009; Fekete and Hartványi 2014], while after "=" sign in ***Italics*** I bring some **DSN analogies**.

Purpose: goal of transport process, related to fitness or survival of entity = *successful value creation to customers; profitability, prosperity for resource providers: investors, suppliers, employees*. **Sources and sinks**: specific network-elements identified as source or sink of given transported quantity = *analysis dependent in DSN*. **Information need**: routing mechanism of the network-element/s determining which network-element /s they will forward the received quantity what may require local or global knowledge = *e.g. demand signals in DSN*. **Determinism**: routing may be deterministic or stochastic = *routing in most of the cases is deterministic, except for the stochastic order in elementary component use*. **Adaptiveness**: adaptive or static routing process affected or not by dynamic properties of network = *in DSN static routing processes are predominant; the built-in flexibility is also more engineered (supply chain design, S&OP, VSM), rather than of adaptive origin.* **Information preservation**: preserved, distorted or lost transported quantities = *undistorted demand signal shared with the suppliers, while bullwhip-effect as distorted*. **Time**: discrete or continuous time process = e.g. *periodic review or continuous review systems in the inventory optimizations*.

In non-social viable networks the local routing mechanisms tend to be more stochastic while the global ones are more deterministic. In DSN we create more deterministic routings and strong links what may cause cascading failures.

4.5.1. The elementary conversion and transport motifs of the LSCN

In accordance with the subnetworks of DSN, the network-elements of the man-, machine-, and material-subnetworks play substantial role in **material conversion and transport process**. Therefore, only those will be shown in the elementary motifs, and other network-elements/nodes like energy or the process steps will not be visualized avoiding the complicatedness. I will describe the elementary motifs of the conversion (incl. packing), of the loading, transportation and unloading, and of the unpacking (incl. preparation for the next conversion). Those elementary motifs often are combined and/or merged in a recursive mode creating the complex hierarchically organized and optimized LSCN. See Fig. 11. Sometimes man or machine is not needed in the interaction. The input links of these motifs are in strong transversal sync, i.e. all the input nodes are required at the same time to get the output.

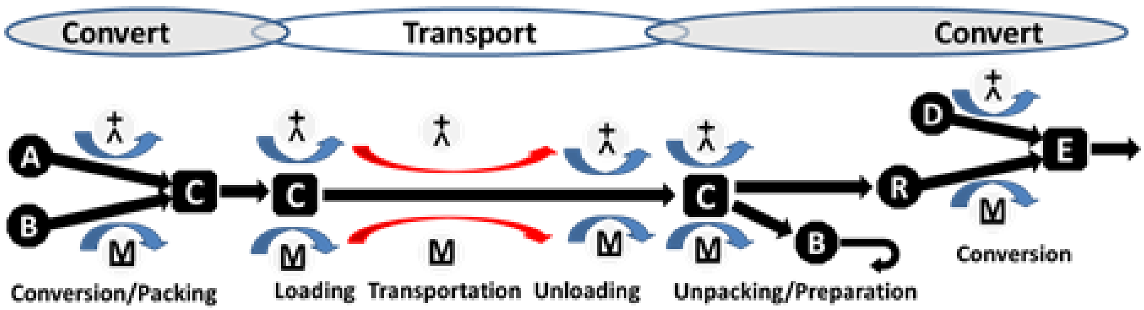


Figure 11. Elementary motifs of the material conversion and transport process

There are three types of input nodes in the **conversion motif** – man, machine and material. We convert usually more than one material (A and B) with the help of man and machine into a new material form (C). As a rule, the material path from raw material(s) of input to (finished) product of output is directed (exceptions are the fractions of returns, only rarely a large ratio of 20-40% of reverse materials in a foundry as an example). The **packing** is similar to conversion, as usually we have the material to be packed (say A) and the packaging material (say B). The packed and consolidated material (say C) predominantly acquires a new identity – e.g. new SKU identification number for a master carton of the packed phones.

In simplistic form the same man and/or machine **loads, transports and unloads** the same material (see Fig. 11). Here the co-travelling man and machine behave like the coenzymes, since they also change their state – at least in space. The loading and unloading may be assisted by other men and/or machines who do not change their state, analogously to the enzymes or molecular chaperones. If there is any consolidation before or during loading, then we have to add the packing motif.

As a result of the **unpacking** and **preparation** the finished product of the supplier turns into raw material of the customer. That may involve physical changes as well, but at least the SKU identification changes according to the customer's ERP system, i.e. from C to R in Fig. 11.

In case of strongly coupled conversion motifs (production line) the series of the intermediate motifs fall off from the process, highlighting the obvious benefit of integrating the material conversion (production) steps into continuous flow.

4.5.2. The conversion and transport route of the LSCN and the structural analogies

Newman emphasizes that in metabolic networks the **right level of investigation** is usually neither the whole network (of extreme complexity) nor the individual reactions, but the metabolic **pathways** [Newman 2010]. Similar aspect is highlighted with regard to transportation networks, i.e. "meso-level" representation at nodal region is to be characterized and of the food webs [Martinez 1993; Ducruet and Lugo 2013]. The previously discussed motifs are combined in the conversion and transport routes, and create an overlapping complex structure. The organization converts the material resources (Fig. 12: RM, R-nodes) from the input module into new material form, i.e. finished product (Fig. 12: FG, F-nodes).

In transport process de-facto the same material is travelling. On the other hand, the same material form is having different coding at the different organizations due to the differences in ERP-systems of the organizations. The customer may require from supplier to mark its finished product with the customer's coding as well stating both 'FG-' and 'RM' or 'FG' and 'RM+' coding respectively. We rarely know the internal structure of the customer or supplier. Therefore, in our network analyses it is sufficient to denote the supplier ($\mathbf{S}$), resource ($\mathbf{R}$), finished goods/product ($\mathbf{F}$) and customer ($\mathbf{C}$) nodes/network-elements.

The combination of Fig. 18 and Fig. 12 clarifies the **overlapping modularity in LSCN**, as we add the supplier nodes ($\mathbf{S}$) and the customer nodes ($\mathbf{C}$) nodes to the input and output modules from Fig. 18: Input Module $\{\mathbf{S}, \mathbf{R}$(A B D F)$\}$, Output Module $\{\mathbf{F}$ (G), $\mathbf{C}\}$. The Conversion Module $\{\mathbf{R}$ (A B D F, C E), $\mathbf{F}$ (G$\}$ remains unchanged. Consequently, with **S-R-**

F-C-paths we cover the material conversion and transport routes, what, in turn, are the building patterns of LSCN.

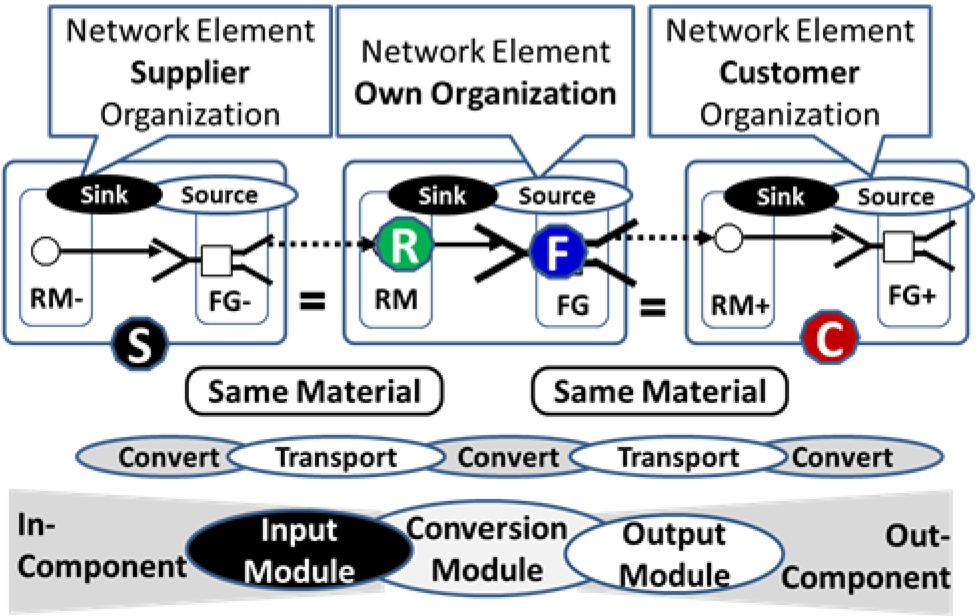


Figure 12. Investigated nodes in material conversion and transport process

The **material conversion process in LSCN** shows **strong analogy** to the **irreversible metabolic chemical reactions**. The man and machine in such material conversion play the enabler's role similar to enzymes of metabolic reactions or the molecular chaperones in the protein networks. The substrate proteins of interactomes (protein-protein interaction network) correspond to materials (to be converted in an organization). The chaperone proteins forming mono-oligomers are analogous to machines of different complexity, what can also be grouped in a production line or cell. Those proteins which are forming hetero-oligomers are more analogous to humans in their interactions. Molecular chaperones form two overlapping subnetworks. The chaperone of one subnetwork help in producing new proteins from protein substrates or other molecules, through assisting in the folding of nascent proteins (e.g. SSB Hsp70), in full analogy to operators working in the production. While the chaperones of the other subnetwork (e.g. SSA Hsp70, Hsp90) check the produced proteins and repair them if required through refolding the damaged proteins, similar to repair and reconfiguration activities of the repair operators. Here the biochemical network achieves the perfection through frequent repair of the damaged products, differing from the right quality first time approach in production. There are chaperones fulfilling both functions, and the degenerative redundancy makes the chaperome robust [Csermely et al 2013]. The mother nature further utilizes any successful process for new completely different purpose as well, e.g. in complex, emergent regulatory processes. Until a molecular chaperone is engaged with protein repair it can not fulfill other tasks – the molecular chaperones are more multitaskers, typical hubs in the interactome (where the chaperome is the subnetwork of the interactome). In case of increasing stress (heat), the defected proteins in heat stress require also repair what takes the capacity away from supporting the folding process of the juvenile proteins. That leads to overload in chaperones' work and the interactome becomes more noisy. The increasing noise level leads to evolvability [Kirschner and Gerhart 2007; Csermely 2009]. Both man and machine nodes are redundant and both – but especially the man – show degeneracy. That means the different knowledge structure, and even slightly different interaction structure with material and machine deliver statistically same output, 'same phenotype'. The degeneracy plays crucial role in evolvability and network resistance in all viable networks [Edelman and Gally 2001; Sole et al 2003; Csermely 2009; Whitacre and Bender 2009; Whitacre 2010]

In **LSCN** the **co-travelling returnable** materials behave **like** the **coenzymes** as they change their state empty→full→empty and they change their state in space supplier→in-transit→customer→in-transit→supplier as well. If we use the returnable materials as Kanban boxes, then similar **self-regulating 'empty-box-concentration'** can control the conversion process, as it shown in Fig. 2 at the right.

In summary, in LSCN the **machines and men** mostly behave **similar to enzymes** as they do not change their status, they drive/enable the conversion, or they enable the loading and unloading process. On the other hand, **at transport the men and machines** may behave also **as the coenzymes**, since they change simultaneously their state together with the material they carry, i.e. they co-travel with the material – e.g. ship crew and the vessel, driver and the fork lift truck, etc.

4.5.3. Analogy in the signaling pathways of DSN and of neural network

There is a striking similarity between the **signaling pathway of DSN** and the signaling pathway of neurons. At demand-supply match the demand network is an **inverse structure** of the supply network – compare Fig. 12 and the top of Fig. 13.

Both in the motif of DSN and in the neuron the input signals are coming from several sources and are in weak sync (the top and bottom graphs in Fig. 13). The input signals are processed by the neuron. When reaching a threshold value, the neuron executes the so-called firing. The signal will be transduced through the axon in large distance and the axon terminals will pass synchronized signals to the receiving neurons in the axon terminals' proximity [Newman 2010]. In case of DSN the demand signaling is also in sync, if no buffering inventories are between the customer and the suppliers. The signaling pathways diverge already at the emitter, as the receivers (suppliers) may be situated quite far from one another.

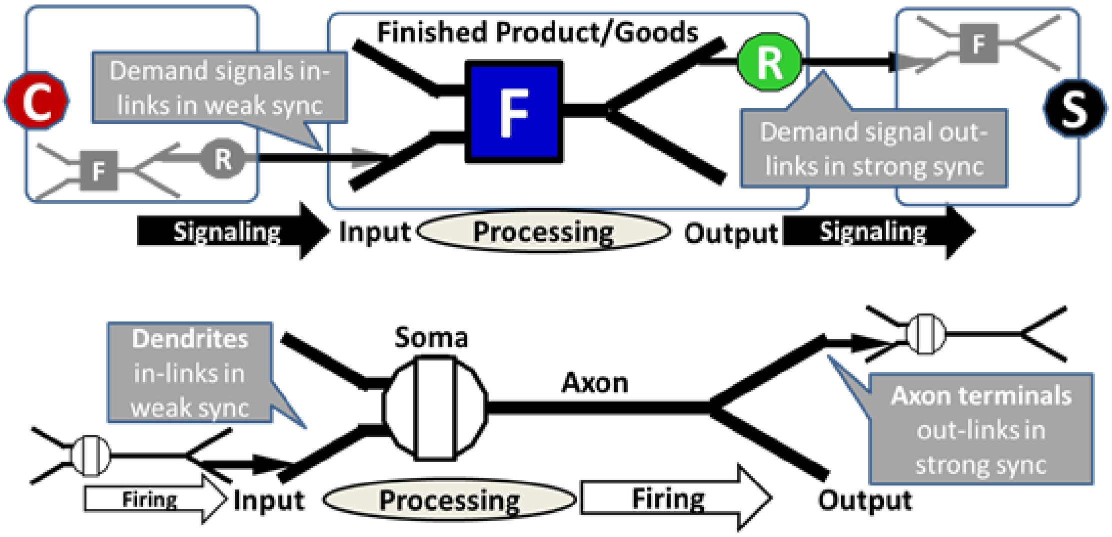


Figure 13. Demand signaling in DSN vs signal transmission of neurons

The **human cerebral cortex** contains several billion **neurons** and tens of trillions connection among them [Csermely 2009, pp. 172-178]. **The neural network** is a small world, and the connection length displays scale-free distribution. It has modular structure and the modules are highly interconnected. The **degeneracy and the i**nter-modular fringe areas either facilitate or occlude the neighboring module. The higher brain functions are emergent properties of the transient synchrony among neural cells and modules. Both loss of neural **synchronization** and over-synchronization (epileptic seizures) lead to unconsciousness [Chavez et al 2010]. In the network-element of DSN we see thousands, tens of thousands of input-nodes (resources) and hundreds to tens of thousands output-nodes (products). The number of links are usually 1-2 magnitudes higher than of the nodes. An analogous functional and structural phenomenon of over-synchronization in DSN will be outlined in Section 6 [Fekete and Hartványi 2015]. The under-synchronization reflects to the demand-supply mismatch [Aberdeen Group 2012].

4.6. Demand supply network (DSN) as subnetwork of the 'eco web'

The highest order network on the Earth contains all the non-viable networks and the viable ones, like biochemical, biological, ecological and man-made networks, including the DSN. That highest order network is the 'eco web', or Gaia [Csermely 2005, 2009], where the **organizations** are one of the **network-element type**s of that top network. The **world trade web**, is the **coarse-grained representation of the DSN**, where the nodes are the **countries** and the directed links are the import and export activities [Serrano and Boguna 2008]. Also at that representation, the DSN shows the characteristics of the complex networks – scale-freeness, small-worldness, with high clustering, as a result of those dynamics what are widespread in viable networks – preferential attachment, network aging, diffusion and resistance, saturation, cooperation and competition driven modularization, etc. [Bass 1969; Axtel 2001; Janssen and Jager 2003; Serrano and Boguna 2008; Wilhelm and Hanggi 2003]. However, the **countries** form more **modules of high interconnectedness** (rather than behaving as network-elements) and include overlapping modules of multinational enterprises – see the distinguishing criteria in Section 4.6.2.

The organization itself is also a network (**bottom network**) with multipartite complex nested structure (see Section 4.6.3). The real networks contain a number of **subnetworks** of the 'same' magnitude/order, which latter are built up by more 'monomer' building elements, e.g. subnetworks of omnipotent men. In my investigation those subnetworks of man, machine, material and processes were important what form the organization (bottom network of our focus) and the higher order DSN (top network of our focus). Similar to complex protein-protein interaction networks, we can find '**oligomer' subnetworks, modules**, and network-elements at different hierarchical levels. The customer-supplier relationship links the two adjacent network-elements into a chain of supply of the resources and a chain of demand signals, similar to self-orientating magnets – Fig. 14. The flow of resources directed from sources to sinks through supplier-customer relationships – called downstream, i.e. from the most upstream natural resources to the final point of consumption of products or services. Since a great portion of the organizations (network-elements of DSN) has more than one upstream and downstream neighbors the formed chains are resulting in a complex networked structure.

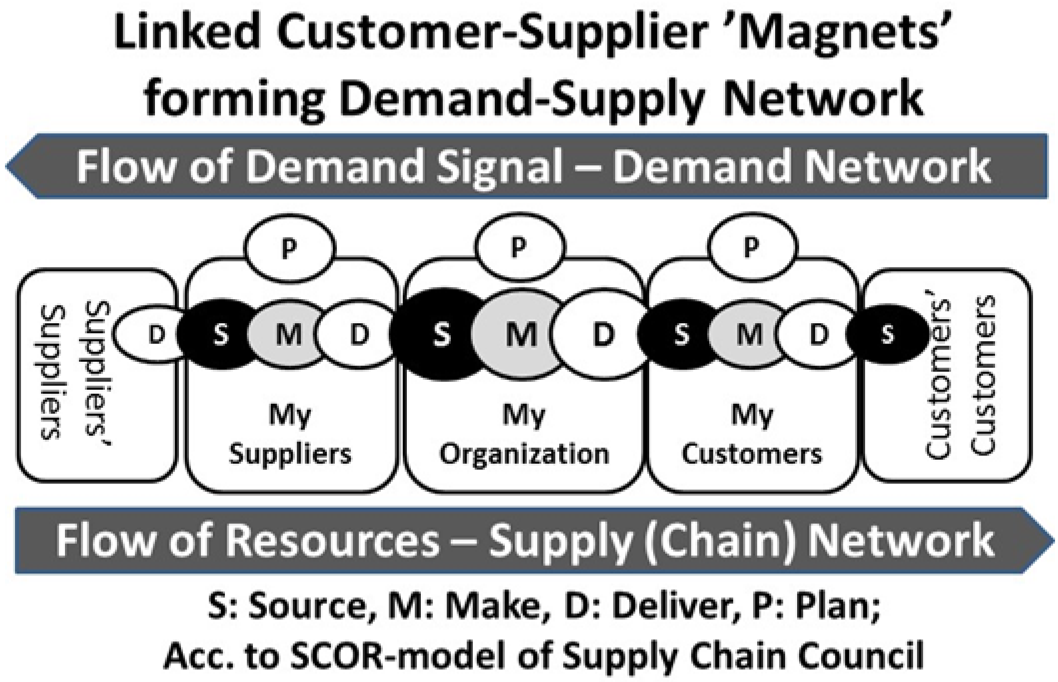


Figure 14. Demand supply network with linking processes of the customer-supplier relationship

The network-element – My Organization in Supply Chain Council's SCOR model – triggers the resources from suppliers through Source-process, what in turn is the Deliver-process for a supplier. After converging the resources into valued finished products (Make-process), the organization delivers it to its customers [Supply Chain Council 2011; Fekete and Hartványi 2016a].

The **organization** is the **network-element of** the 'eco web' and of **DSN** (where DSN is a subnetwork of the 'eco web'). In DSN the **complementing** stronger **cooperation** of the suppliers around a large OEM also leads to modularization of the DSN, where the module-building network-elements are the organizations. The keiretsu in Japan also behave as a network module within the supply chain network. Later I will prove why the organization itself is a (bottom) network rather than a module of DSN, so taking place between the two systems levels of global 'eco web'/DSN and the building network-elements of its subnetworks, like man, machine, material, etc. An example on **segregation driven modularization in DSN** was in a large IT factory, when due to raising complexity in knowledge demand, we had to create further intermediate hierarchical levels (modules) in the human subnetwork of that organization to rightsizing the network structure to those perturbation challenges we faced (see Section 6.2).

Viable networks require **communication and regulatory processes** for optimization and adaptation to changes. The communication and regulatory processes are covered mainly by the Plan-process in SCOR Model. Csermely and Palotai consider network signaling as highly specialized case of transport process [Palotai and Csermely 2009]. The longitudinal synchronization of the demand signals alongside the supply chain may assure that those convey upstream quickly and undistorted [Aberdeen Group 2012]. The demand is represented predominantly by strong links to be fulfilled [Geissbauer and Householder 2011]. Rarely can be flexible, and then is represented by weak link, when the customer is willing or forced to accept the supplier's terms (like consumer versus a novelty-product supplier, e.g. Apple).

Atalay et al investigated the network structure of firms through customer-supplier links. In the model of Atalay et al, the birth, rewiring, and death are also modelled, i.e. growth and decay causing appearance and disappearance of nodes and links. Scale-free degree distribution with exponential cut-off was detected in the models in accordance with the factual data [Albert et al 2000; Atalay et al 2011].

4.6.1. The three levels of granularity when investigating an organization

In most of the cases we can investigate the internal structures of an organization at detailed level (fine-grained representation), while we may have limited access to the organization's external structure. The links of supply from the organization's suppliers and to its customers are usually well known, but the mid-grained or fine-grained structure of the suppliers or customers are usually hardly known – further steps we go bigger are the question marks in Fig. 15. That **asymmetry in our knowledge** will be reflected in our objects of investigation. That approach is similar to systems analytical approach in complex geological mapping developed by me in early nineties [Fekete 1992].

The introduction of the network-element ('complex node') and of the module termini enables us managing the complexity and focusing on the more densely connected network parts, and on the network skeleton of high importance nodes – hubs, bridges, creative elements, high-weight/high-centrality nodes, etc. [Antal et al 2009]. Similar approach we use in DSN, where apart from the longitudinal pathways, it is worthwhile to investigate the transversal groupings called echelons as well [Snyder and Shen 2011; Fekete and Hartványi 2015]. Typical **echelons** in our investigations are of the suppliers and customers at the network-element level of the DSN, and of resources (materials, machines, men, etc.), and finished products at the network-element level of the organization. I suggest to distinguish **input module, conversion module and output module** in the organization. **Input module** is built up by: 1. Supplier nodes (in fact, network-elements, without clear to us internal structure); 2. nodes-in (called sources of the material conversion process, i.e. resources) what organization buys from its suppliers; 3. Links from supplier nodes to nodes-in/sources. **Output module** is built up by: 1. nodes-out (called sinks of the material conversion process, i.e. finished goods/products) what the organization sells to its customers; 2. Customer nodes (in fact, network-elements, without clear to us internal structure); 3. Links from sinks/nodes-out to customer nodes. The **conversion module** overlaps both the input- and output modules, and built up by: 1. Sources/nodes-in; 2. Sinks/nodes-out; 3. Links between those two groups of nodes (Fig. 15.).

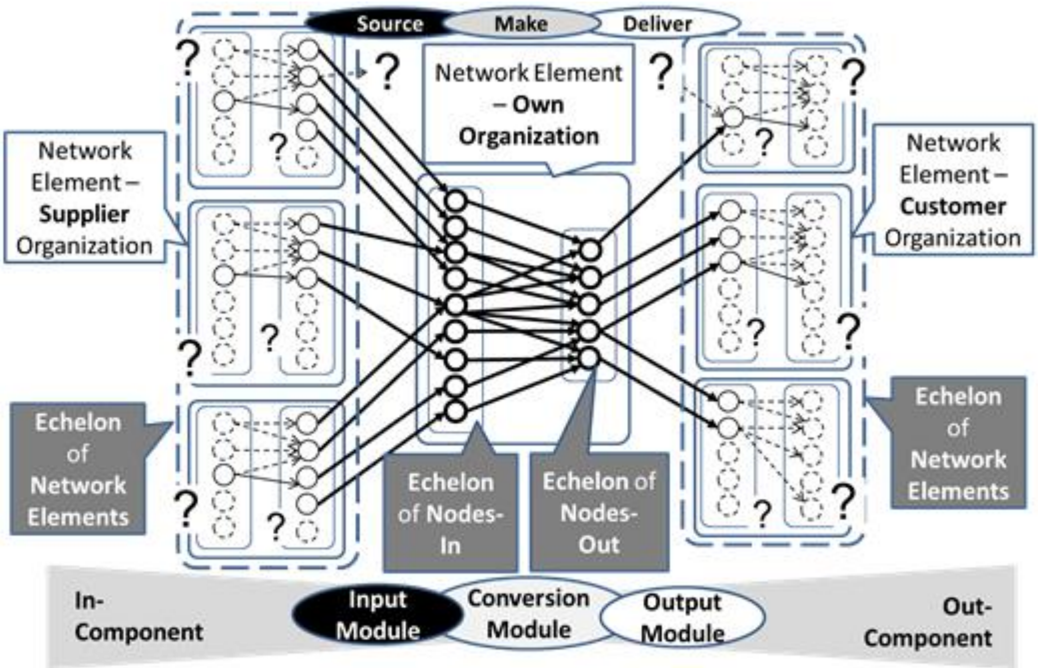


Figure 15. Different resolution of the network space in and around the organization

Further important network science termini are the **in-component and out-component** [Newman 2010]. The in- and out-components of a source node or a sink node and of organization – the two adjacent hierarchic levels – are evidently different. The in-component of organization at meta-level contains all the in-components of sources/nodes-in, while the organization’s out-component is built up by the out-components of sinks/nodes-out respectively.

Please note: the **echelon structure of LSCN shows analogy with food webs** where such groupings transversal to material and energy flow (from prey to predator) are called trophic level [Sole et al 2003]. While at the top-network level of LSCN the in-links are similarly alternative to certain extend, at the bottom-network level (in the organization) the “predator” of LSCN (the finished product need all the “preys” (materials/resources) simultaneously. That is a fundamental difference what underlines the higher vulnerability of the LSCN compared to the food webs.

4.6.2. Organization – network-element of DSN – the bottom network

Let us check if an organization is a network-element of the eco web/DSN or just a module of that through the checklist of Csermely. The larger the value, the more likely the investigated entity is a network-element [Csermely 2009, p. 41].

- ✓ network size vs the size of the entities: eco web/DSN is by several magnitudes larger than an organization
- ✓ number of entities in the network: number of organizations in the entire DSN is in the range of tens of millions
- ✓ difference among different entities: the organizations may differ from one another significantly, e.g. far more than of human beings
- ✓ ratio of intra-entity links vs inter-entity ones: in the material subnetwork of the analyzed organizations the number of intra-organization links is a magnitude higher than of the links with suppliers or customers; when including the men subnetwork as well, then the ratio will be even larger
- ✓ weight (strength) of intra-entity links vs weight of inter-entity ones: the intensity and frequency of interactions through internal links are evidently higher than through the inter-organizational links
- ✓ number of transient and unnecessary inter-entity links: especially the man-subnetwork is full of transient and unnecessary links has wide range of literature of gossiping, and pseudo-grooming [Granovetter 1973; Csányi 2003; Csermely 2009].

- ✓ availability of entity as independent network: an organization (e.g. a factory) is more independent than its module. Although the plant-in-plant mode of operation between customer and supplier could raise questions, in such a case the supplier organization is larger than its plant in the customer's plant, i.e. that is more a module of the supplier organization embedded in the customer organization.

From the above checklist I consider the **organization** to be the **network-element of the DSN/LSCN** with high confidence. All the cultural differences between organizations further support that consideration – e.g. company culture, own language, especially of the 3-letter abbreviations, the separation as legal entities, the segregation in the IT-systems (e.g. different SAP code for the same material), etc.

4.6.3. Multipartite structure of the organization

The main **resources form** the most important **subnetworks of the organization**. Fig. 16 illustrates the key node types (network-elements) of the organization and their inter-relationship. The materials are converted into finished products with the help of men and machines. Therefore, the links between the material and finished products nodes are directed, while between the latter and the man and machine nodes are symmetrical. Sometimes it is reasonable to distinguish separately the more generic equipment from the more product specific tools in our investigations.

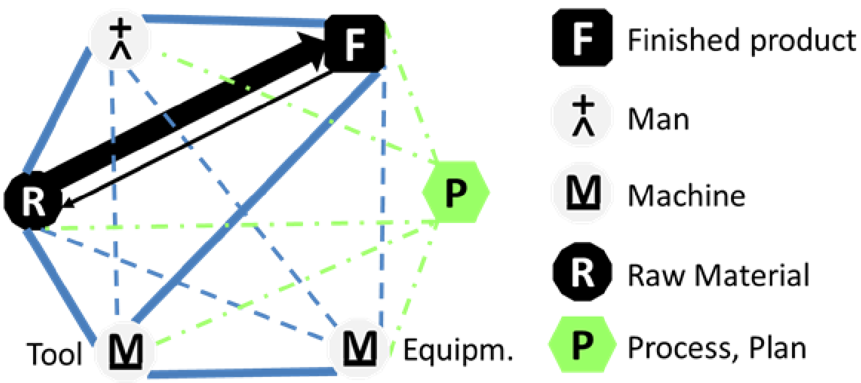


Figure 16. Multipartite structure of the organization

In such a case, as a rule, the tool has stronger, more direct interaction with the finished product than the generic equipment – like specific mold and the generic press equipment. Solid line links emphasize the strong dependence between the nodes – the **thicker** the link the

stronger the dependence is. **Dashed** line links are usually more **transient** or indirect, e.g. the interaction between man and tool runs only at the tool change. The **process**-subnetwork describes the interactions between the nodes of the above mentioned subnetworks.

Fig. 17 highlights the **group behavior of the intra-organizational links** and the **multipartite structure** of the conversion module in the organization (network-element of the DSN). The 3-M's must be available at the same time (in strong sync) for producing a finished product. The materials, built into the product, must be also available in synced way (acc. to Bill of Material). Regarding to men and machines the symbol is 'few alternative in-links' since in most of the cases those resources are in (degenerative) redundancy – e.g. multi-skilled operators. Please note that while the in-links of the finished products behave as described above (for all products), the out-links of the resources vary in wide range. On the left side of Fig. 17, I bring some examples on the cause of the group behavior of the links. This phenomenon underlines the importance of **analyzing the distribution** and the **behavior of the out-links** in the DSN.

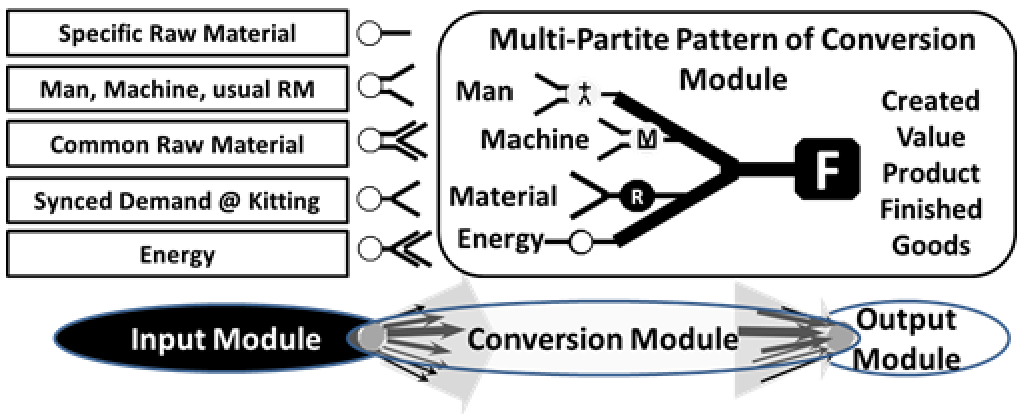


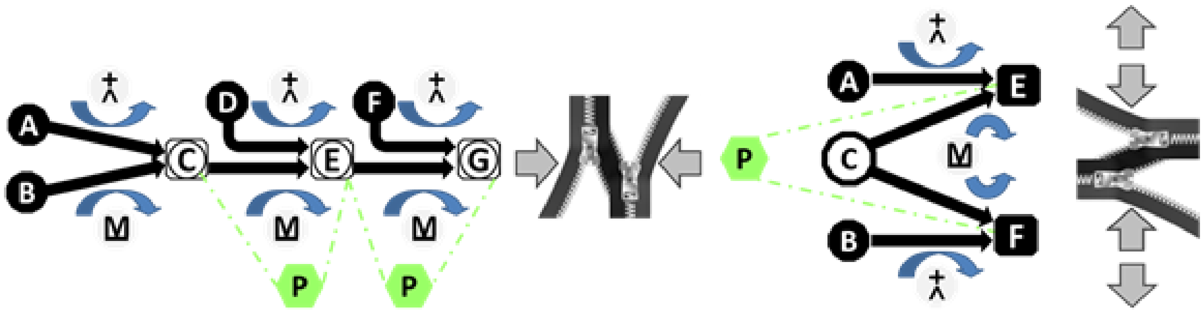
Figure 17. Group behavior of the intra-organizational links in the conversion module

4.6.4. Optimization driven recursive modularization in the organization

The modularization is driven by optimization in network space [Csermely 2009, p. 35]. In metabolic transport processes and in protein interaction networks the resistance and diffusion dependence drives to optimal scale-free distribution, and nested modularity with very similar dynamics to DSN [Ghim et al 2004; Gallos et al 2007; Serrano and Boguna 2008]. The modularization in an organization is manifested in simultaneous **integration and**

segregation, both in **longitudinal and transversal** dimensions. In Fig. 18 I show the modularization process in material conversion. The longitudinal integration creates flow. Materials A and B are converted into product C, what in turn is a material input in the next conversion step, and so on. The already mentioned **overlapping** nature of the input, conversion and output **modules** is obvious from the shared distribution of the internal nodes of the organization – Input Module (A B D F), Output Module (G) and Conversion Module (A B D F, C E, G). When zooming into the production line it turns to be a set of strongly coupled material conversion oscillators, what use the materials and intermediate semi-finished products subsequently (Fig. 18 left).

The **transversal** dimension of the modularization creates the product family. The more commonalities are in machines, materials and processes between two finished products the more reasonable is to produce them on the same line. That is a transversal integration and segmentation. However, in that case sequencing in time is required (Fig. 18 right).



Longitudinal dimension of modularization. Creating flow in value chain. Production line of strongly coupled oscillators. Overlapping modules of Input(A B D F), Conversion(A ... G), and Output(G)

Transversal dimension of modularization. Product family creation: transversal segmentation in space and sequencing in time.

Figure 18. Optimization driven modularization of the bottom network (organization)

The **above driving forces** for modularization **and** the **following counterbalancing forces lead to an optimum in the LSCN**:. 1. limitations in the line-side material storage, 2. increasing time sequencing due to proliferating portfolio, causes increasing changeover losses, 3. the challenges to keep the elements of the production line in strongly coupled oscillators mode during production (disregard to product, material or process alterations and the difference in processes and timing of the changeovers).

In Fig. 19 the **recursive modular structure of a large factory** is visualized, where the late customization/postponement of the product design [Salvador et al 2002, 2004; Snyder and Shen 2011] aligns the nested internal modular structure of the factory, and so being able to manage the large number of the built finished products responsively and efficiently. The surface mounting devices were integrated into SMD-lines. Those latter formed the Board Assembly Operation producing 22 different intermediate products (boards). In the Assembly-1, a few large production lines produced the 51 engines. The next decoupling is justified by the fact that the variety funnel blows up to 1600 products. Therefore, in Final Assembly and Packing a large number of small and flexible production cells produced those finished products. As expected, the number of the intra-modular links in the conversion module are several times higher than the inter-modular ones.

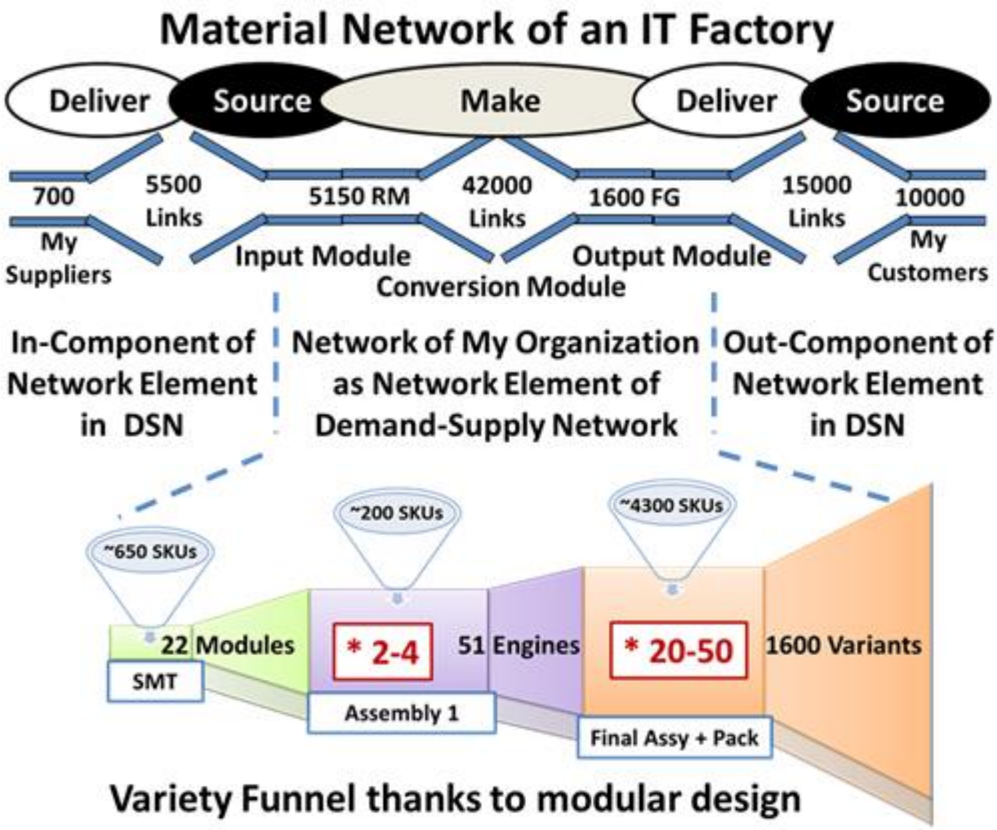


Figure 19. Optimization driven recursive modularization in a large factory

Similar optimization process leads to fractal-like recursive modular structures in other viable networks [Dodds et al 2003; Song et al 2005; Goh et al 2006; Csermely 2009].

Certainly, modularization takes place at the top-network level as well (in DSN). The supply chain segmentation [Geissbauer and Householder 2011; Becks 2012] is the stratification of the out-component of an organization, what is not in the focus of my dissertation.

4.7. Plasticity-rigidity cycles in DSN

The economic cycles are reflected also in the cyclically changing emphasis of one or another solution in supply chain management: e.g. the ‘show me the money’ and savings vs the flexibility focused articles in the Supply Chain Management Review periodical [Brown 2011; Geissbauer and Householder 2011; Melnyk et al 2014; Trent 2015].

As in **supply chain and operations management** the focus, the canalization, the standardization, the exploitation – in other words the **rigidity serving processes** – are **well developed** and widely exploited, **I focus** in my dissertation **on the plasticity** supporting properties.

Some obvious examples from LSCN are as follows: different suppliers at dual sourcing deliver functionally identical material; the multi-skilled operators in factory community represent degeneracy in skills and capabilities what could be utilized to explore the best possible assembly mode of a new product in few days at the large telecom factory in Hungary; at an automotive supplier the different subassembly machines (conduit cutters) were able to produce the sub-assemblies of the other machine with sub-optimal conditions but with the same outcome; process flexibility through chaining of the factories in the network detailed in Section 2.3 also creates degeneracy. Melnyk et al define the operating flexibility in their article similar to degeneracy, i.e. degenerative redundancy [Albert et al 2000; Melnyk et al 2014].

As we could see, the plasticity occurs when stable hubs with proliferated large number of links de-constrain the other processes so generating the **epigenetic variation to be selected** [Darwin 1859; Kirschner and Gerhart 2007]. I describe **similar** phenomenon in Section 4.8 **about Toyota**: Many **core processes are highly conserved mechanisms** and are either optimized after repeated selections (exploitation/focus) or are so-called ‘frozen accidents’ (natural selection works with the best available at the time and not the best possible). In this way the core processes generate variation of the processes.

We can detect several plastic-rigid dualities especially in the **Toyota Way**: creating flow (plasticity phase), then stabilization and standardization for reliable repeatability (rigidity phase); the PDCA cycle; starting with fuzzy specification what delivered dozens of potential solutions on Toyota Prius engine design then selecting and focusing on only one; or kaikaku vs kaizen [Liker, 2004; Liker and Meier 2006]. Similar plastic exploring phase is the **supply**

chain segmentation’s first step, when based on multi-dimensional characteristics we define a few-dozens clusters. In the focus phase we reduce down to manageable 3-5 classes [Becks 2012].

Weak-linkedness contributes to plasticity. The modular design and the mass customization [Salvador et al 2002, 2004], analogously to the compartmentisation in biological networks [Kirschner and Gerhart 2007], also smoothen the innovation landscape for the network-element of DSN and create weak-linkage through scale-free distribution both in out-degrees and in link strength, what further stabilizes the network.

When Geissbauer and Householder write about supply chain flexibility in fact they mean resilience [Geissbauer and Householder 2011; Melnyk et al 2014]. Melnyk et al means resilience quite similar to Csermely just for **DSN**. They distinguish two capacities (capabilities) of resistance and of recovery separately while in network science those are treated together. Resistance enables the organization to minimize the impact of the disruption and shorten the time till the recovery phase. The recovery is the ability to return to normal functionality as soon as possible. The rationale behind such split is that not all organizations can afford to invest in both resistance and recovery. More known predictable a disruption is (where the adaptive response can be developed beforehand), more the resistance is suggested, while in case of unprecedented disruptions the quick recovery is more beneficial. Their resistance definition is more the rigid mode of the plasticity-rigidity cycle, while the recovery capability corresponds to plastic mode. [Melnyk et al 2014].

4.8. Toyota, the complex network of high stability and evolvability

In this section two fundamental monographies from Liker could be referred frequently [Liker 2004; Liker and Meier 2006]. Those books need to be read carefully and thoroughly. I will not give the references in each paragraph, neither the pages where the referred aspect occurs. As Liker emphasizes, the Toyota Way is a complex and complete (holistic) system where **all the building blocks are important**. In fact, they are **interlinked** creating a fully connected graph where the links’ strength and the nodes’ weight are **dynamically changing in space-time** depending on the environmental/contextual situations. This is perceived by western people – as Liker explains – as if the Toyota Way would be full of paradoxes.

That level of complexity of the Toyota Way can be understood, felt through learning by doing for years, at best, with the support of a sensei. A sensei's knowledge is at the level of grandmaster in terms of Mérő. The cognitive schemes are of a magnitude higher than of a master (MSc) reaching hundred-some thousands cognitive schemes which are organized in complex "fuzzy hierarchy". Consequently, that is a **tacit knowledge** which can not be gathered though classical teaching of cognitive schemes structured only by the formal logic [Mérő 2008]. And here comes the first mistake often performed by the western people and companies. The fundamental core of Toyota philosophy is lost while the focus is wasted on the (lean) tools.

As described above at the evolvability of the organisms, the Toyota Way Principles are those highly stable conserved comparted rigid sequences in **Toyota's DNA** which did not change for tens of years. These **stable hubs** with large number of links (application in very diverse concrete situations) **proliferate the possible lower level principles**, game rules so generating the epigenetic variation, i.e. the concrete appropriate solutions – phenotypes. This is why Toyota puts enormous emphasis on preserving the core DNA and the **high fidelity transcription of that DNA** through its leaders from the top to the very bottom.

Apart from core DNA segment of eliminating the waste, the other fundamental DNA of Toyota is the **creating stability and predictability** in a strongly linked and synced module of the DSN, i.e. lean enterprise of Toyota (including its partners). The reserve of tens of billions of dollars assure that even a major disruption will not kill Toyota. Its widening and elevating continuous improvement cycles of "create flow → standardize → level → stabilize → create flow → etc." is a great example of Csermely's **plasticity-rigidity cycles**, where the flow creation in larger-and-larger segments of the network corresponds to plastic behavior with exploration and learning, while the standardization, level, and stabilize reflect to the rigid phase with focus, exploitation, canalization, and memory (see also Fig. 5). As Liker highlights the **rigid stability phases in Toyota are considerably longer** than the plastic flow phases – and Toyota is more rigid in quick responses to environmental changes as Melnyk et al underlined [Melnyk et al 2014]. Before creating the flow (bottom-up modularization) all processes must reach the basic level of consistent capability, i.e. the bottom networks' stability is a prerequisite of creating network on higher level. These continuous improvement cycles create first only the so-called disconnected stability, at next level the multi-process connected stability, then the value stream connected stability (entire organization), and finally the connected lean enterprise (including the key partners as well). That is also a great example how **a network of increasing complexity and rigidity** creates a more differentiated stability landscape and **stability in its neighboring environment**, see also csermely [Csermely 2015]. The smaller changes through series of kaizens during stability phase and the large scale radical kaikaku-type developments correspond to the punctuated evolution and to plasticity-rigidity cycles as well [Csermely 2009].

Toyota developed **extraordinary method** for handling **perturbations** of different scales. Opposite to the mainstream optimization approaches, Toyota insists on as small as possible batch sizes – creating flow of single piece at best – so reaching an 'all available' situation of extreme flexibility. The load levelling (heijunka) with flow **converts the unpredictable perturbations** (of scale-free distribution both in time and in magnitude) into **all-time tight perturbations of standard magnitude** (ABACABADA). The **power-of-two** is also utilized: e.g. produce every day, every second, every fourth day, sometimes every sixth day group may also exist, end the rest as others.

As we could see in Section 4.3.1, an **optimal noise** is vital in a network's survival. One of the core values of Toyota (in 4P's) is **respect** people and partners and grow them. Respect in Toyota terms does not mean creating stress-free environment but **creating the optimal stress for growth**. That is also well in line with Csikszenmihályi's flow concept [Csikszentmihalyi 1990]. In 2002-2004 Toyota increased the noise level (perturbations) in its supply base by setting aggressive cost reduction target to its supplier partners for challenging the calmly flowing continuous improvement processes.

Csermely brought several examples how the network **isolates the destabilized** network-element(s) protecting itself [Csermely 2009]. Similarly, Toyota emphasizes the need of reducing the variability of the system by isolating it, more precisely the more variable part of it. Utilizing the well-known Pareto law, without extensive 'analysis paralysis', Toyota slices the population into 3 groups only. Then the most stable lower group is enough stable to be integrated in the already strongly connected and strongly synced stable network module (flow phase of the continuous improvement cycle – plasticity half-cycle).

Toyota masters in balancing the **right ratio of strong-links and weak links** and the right level of **sync**. When the flow has been created, then the interlinked processes are in strong sync with strong interdependency. Therefore, it is vital to create a stabilized environment to them. If the process is less stable and/or predictable and/or reliable **Toyota does use buffers**, to be minimized or eliminated later during the stabilization phase. The hejunka also

decouples the customer demand from stable, flowing production, i.e. weak link between customer demand/deliveries and the production.

Toyota – learning from past failure – selects from 3-4 suppliers minimum 2, i.e. weak links through multi-sourcing with suppliers.

The Asian languages are more symbolic than the European ones. That **fuzziness already creates weak linkage** – in case of **design** for example, what can be further magnified by giving general black box specification to partner suppliers. The result is a **wide range of** possible **solutions**. In case of Prius, 80 viable hybrid engine variants were reduced to 10 first and then to 4.

The traditional engineered automation is often rigid – means strong links between network-elements, while Toyota thinks always in **human-machine system**, so creating **weak linkage thanks to degenerative redundancy of humans**.

Last but not least, Toyota formulates **fuzzier orientating weak linked expectations to its leaders** rather than rigid duties and responsibilities.

In summary, Toyota is a **complex nested over-connected over-optimized stabilized network** with **quick** (planned if possible) **change from rigid to plastic mode**.

4.8.1. Why not then the Toyota Way to go for?

The waste elimination, the extreme stability, reliability, and predictability are fundamental to Toyota Way. Doing, reaching those you **need to have time, money and power**. Therefore, only large powerful companies can decide to go for that path independently. Smaller companies can follow Toyota through **becoming a Toyota partner**, in my view. If Toyota selects us, we can learn from them, and become part of Toyota's lean enterprise. In all other cases we have to admit that **we have perturbations** of scale-free characteristics (external noise and large disruptive perturbations), and our **processes are not so reliable**, predictable as of Toyota. Consequently, we have to **build such supply chain and internal operations which encounters those perturbation**, and not mimicking the Toyota Way.

4.9. Supply chain and operations solutions in the context of network science

CSCMP's **definition of supply chain management** is as follows: "supply chain management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies" [CSCMP 2015].

The goal of the supply chain and operations management solutions in **evolutionary network science** terms is to deliver better performance and contribute to success and survival of the network.

While in the first half of the 20th century the focus was more inside-out, it has shifted to a more balanced view of the organization acknowledging that our organization is a link in a greater supply chain; a shift from push to more a pull mode. Apart from the influencing mainstream focuses in supply chain and operations management the own evolution of a given company also determines the appropriate solutions to that particular company. It can happen so that even the one-size-fits-all approach may be justifiable in 21st century.

4.9.1. More inside-out view – internal focus

The solutions on the left side of Fig. 20 reflect to the goals of creating stability in our operations, having standardized and optimized processes, and of focusing on the right things. Some of those solutions can still work effectively for small organizations in economic niches or in the blue-ocean segment [Chan Kim and Mauborgne 2004, 2005].

The optimization with economic order quantity (**EOQ**) is dated back to 1913 [Harris 1913], while the strongly synced execution through material requirements planning (**MRP**) was developed by Joseph Orlicky in mid-sixties. Both EOQ and MRP are included in the academic tuition, therefore I avoid their detailed introduction.

Stabilization through one-size-fits-all (**OSFA**) approach has only one rule or no-rule [Geissbauer and Householder 2011]. In inventory management that means either there is no inventory target level, just gut feeling and thumb-rule or there is one rule for all items. In such a case we may have an inventory target for the finished products (or finished goods – FG) and another for the upstream inventories of work in process (WIP) and of materials (RM). The SKU’s (stock keeping units) are usually managed by an ERP system based mainly on forecast data. In a demand driven environment, if we neglect the differences in SKU behaviors, the unbalanced inventory profile leads to poor customer service and – in the same time – poor cash-to-cash cycle management [Becks 2012].

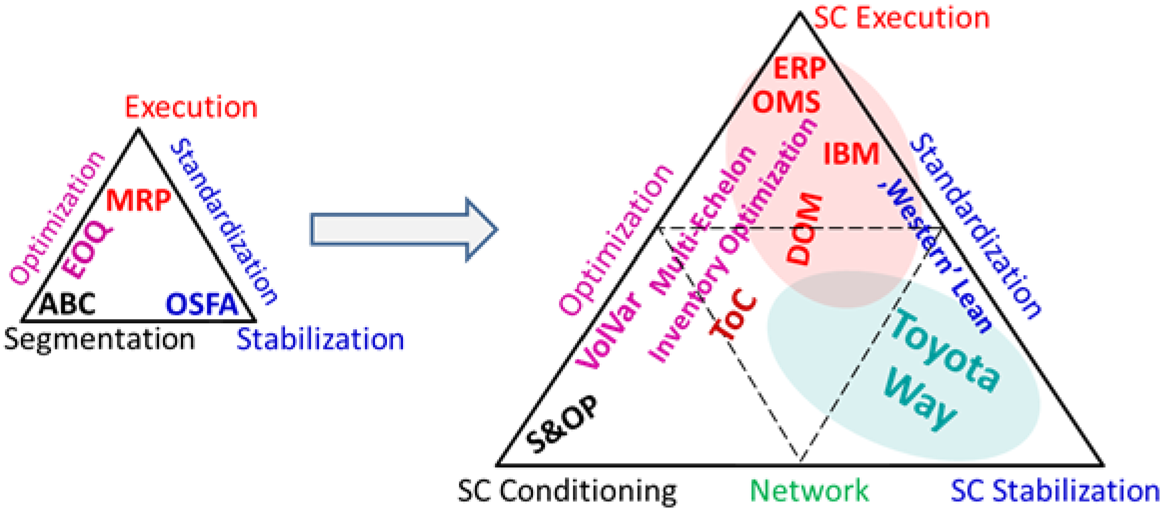


Figure 20. Comparison of the supply chain and operations management solutions

Not only small size companies use such simplistic one-size-fits-all approach. When **Nokia** earned 30%+ market share, and it was in dictating position, it could stabilize its supply chain utilizing the most simplistic one-size-fits-all inventory management approach.

A great number of the companies are still using the **ABC-analysis** for portfolio segmentation what based on cumulative ranking of the items – mainly FG or RM – according to their used/sold volume or value. In most of the industries we can detect the **Pareto-**distribution of the ranked items, just the steepness of the curve will vary [Pareto 1897]. Usually, the first 10-20% of the SKU’s are delivering the 75-80% of the value grouped as A-items, while the B-items (about a third of the SKU’s) are contributing to additional 15-20% of the value, and the rest of the C-items are accountable for only 5% of the value. The inventory policies and other parameters then are determined to the A, B, C categories separately but as same within the category. The long tail of C-items and ‘dead’ D-items are often challenged by the ‘cutting the tail' approach, though already thirty years ago Stafford Beer proved that cutting the tail may lead to system's destabilization and portfolio deterioration [Beer 1979]. The other trap in value-based ABC-analysis is that the highly-connected hub-type material nodes of low dollar-value may be ranked as C. As a consequence, the low level of attention to those low value hubs may lead to their destabilization and to firing cascading failure in the entire organization.

4.9.2. More balanced supply chain view

In the last third of 20th century the solutions more and more covered the extended supply chain management with closer partnership-type management [Mollenkopf 2012; Blackhurst et al 2015]. Burnson suggests first to differentiate our supply chain whether it is brand-, technology-, or asset oriented. That determines our main focus, like: demand cycle reduction with stronger sync, time-to-volume responsiveness, or asset utilization focus respectively [Burnson 2012]. On the right side of Fig. 20 I show the relationships among solutions in a multi-dimensional space. First, I compare the set of more IT and execution focused solutions with the fundamentally different Toyota way. Then I describe three other inventory optimization methods in separate section as the inventory optimization is pivotal to my dissertation. Finally, I introduce the sales and operations planning – the often missing link between annual planning and the operational execution.

The large and powerful enterprises can utilize expensive, proven methods of high IT procession requirement in combination with their economic and influential power. The way of Toyota is special – it is the closest to the function of the evolutionary complex systems, in my view. **Either ways** can **lead to success**, though picking building blocks and mixing may generate 'Frankenstein-results'. Both approaches are very powerful for powerful companies who can afford to invest substantial time and money in developing those capabilities in their enterprise, and can influence their neighborhood aligning it to their need.

The Toyota way is the most holistic approach covering philosophical depths and real physical solutions in a complete system (the greenish-blue region in Fig. 20). As I have described in the Section 4.9, Toyota also creates strongly connected and synced value streams by stratifying the network with parts-quantity-process-routing (PQPR) and value stream mapping based on similarities in product families, customer groups, and processes. Liker highlights, the standardization and the self-disciplined obedient behavior of the employees assure the predictability of the cause and effect, the process-product link, etc. The biggest challenges to apply the Toyota way are: 1/ lack of self-discipline at the level of Toyota communities; 2/ high systems complexity of the Toyota way. The Toyota way is holistic requiring tacit knowledge management and transfer. Therefore, in the western culture we often only mimic it with a fraction of the results compared to Toyota. Blunt deployment of the lean tools is an obvious example of such mistake [Liker 2004; Liker and Meier 2006].

The **IT solution focused optimization, planning and execution** with MRP/ERP approach (pink region in Fig. 20). The ERP (enterprise resource planning), MRP II, OMS (order management system), DOM (distributed order management), Logistics Flow Control, the inbound management (IBM) are more execution focused with graph theory and deterministic or stochastic foundations, aiming an optimized seamless order fulfilment [Supply Chain Digest 2010, 2011; Descartes Systems Group 2012; Petridis et al 2015]. In these solutions the enormous number of elementary data are processed for modeling a hierarchically organized nested demand-supply network with a graph of just one hierarchical level – i.e. sophisticated calculations in an overly simplified model of reality. Often these solutions refer to JIT/JIS (just-in-time, just-in-sequence) managed through electronic signal, which is based on a future expected demand. That is not pull. Therefore, frequent small disruptions cause queueing in the supplier processes and – due to negligence of nested hierarchical structure – sometimes cascading failures occur. The latter phenomenon I describe in details in Section 6.1.2

Theory of Constraints (ToC) fills in a special place – a linear programming-based optimization. ToC focuses on the bottleneck process (according to the market constraints – demands) to maximize the output of it and so maximizing the total throughput, and at best, maximizing the profitability through producing the maximum profit portfolio. The upstream process management shows similarities with Kanban driven pull methods – drum, buffer and rope [Goldratt and Cox 1992]. The downstream processes are fed by the constrained one. The philosophy of the ToC is anyhow very important and useful. The risk of shortsighted opportunity picking of ToC, on the other hand, can be well balanced by the S&OP process, which is more holistic in finding the optimum for the entire enterprise and its stakeholders and bridging the short-term and long-term perspectives.

The **smaller enterprises** are often forced to align themselves to one of the large players – becoming a strongly linked Tier-n supplier (network-element) in the star net of a large OEM described later – and benefit from that subordinated learner position [Brányi et al 2015].

4.9.3. The 'evolution' of the inventory optimization

Barns underlines, before inventory optimization, the customer order frequency and the delivery frequency need to be increased, if possible, to better synchronize the supply with demand, and with or without MEIO optimizing the material flow path [Barns 2015]. Inventory optimization is not an isolated activity from other **supply chain design and management solutions**. Cox gives a good list of the possible ways to lower the inventory levels where the right combination is to be defined for a given organization [Cox, 2011]. In all cases the inventory profile segmentation, the integration or combination of inventory optimization with S&OP, and the distributed order management (DOM) are 'mandatory elements' of the solution [CSCO 2011; Willems 2011, 2013, 2015]. We have already discussed the simplistic one-size-fits-all and the ABC-analysis approaches. More sophisticated approaches are the volume-variability analysis (Vol-Var), the multi-echelon inventory optimization (MEIO), and the combined quantity-irregularity graphs (CQIG). The relationship among those methods is seen in Fig. 21.

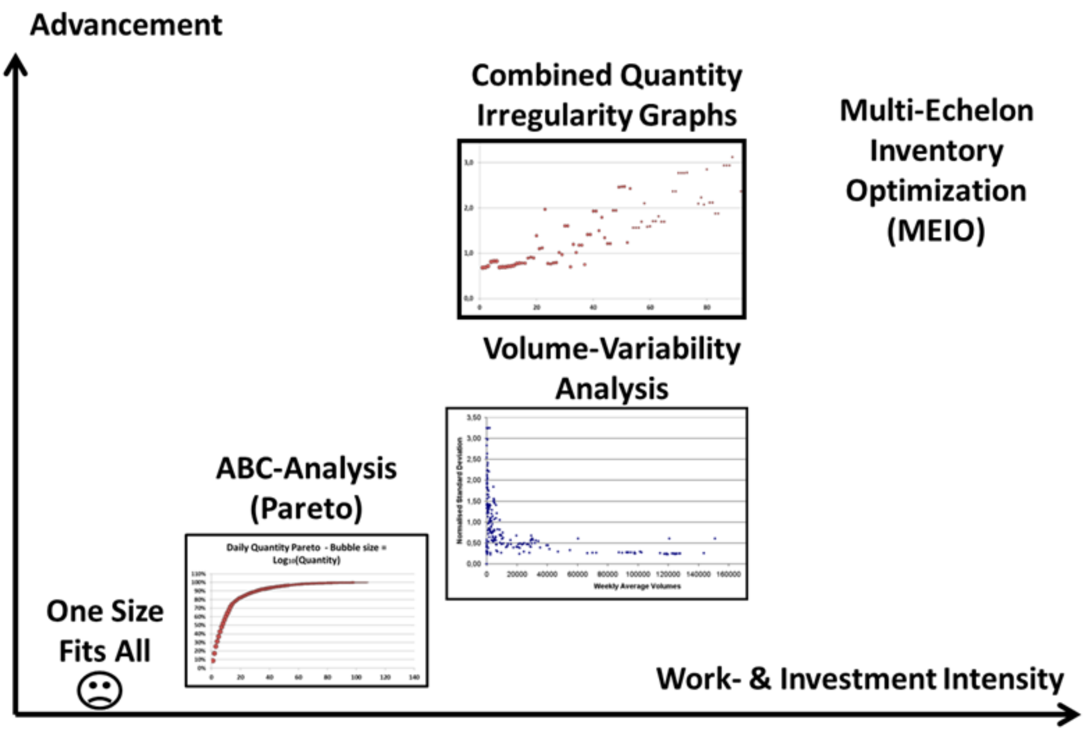


Figure 21. 'Evolution' of the inventory optimization

The **volume-variability analysis** (Vol-Var) is dated back 40 years. When using this method, we take into account the variation of the demand as well. Volume dimension is the average of the periodical demand data of a given SKU. Variability is the normalized standard deviation (NSD) of the periodical demand data of that SKU. Using these two dimensions in the volume-variability graph we can distinguish items of different behaviors. Vitasek et al explains, according to those behaviors we are able to determine safety stock levels as well as the most appropriate planning and execution process to given SKU, like assembly cells or assembly line, make-to-order or make-to-stock, rate based scheduling, Kanban driven execution, etc. [Vitasek et al, 2003].

The **inventory optimization** is a process to scientifically identify the right inventory levels across the supply chain. It is also called **multi-echelon inventory optimization** (MEIO) emphasizing that the optimization takes place in subsequent adjacent blocks (echelons) of the supply chain network [Logility 2010; Snyder and Shen 2011]. Since the focus is on the network component of a given node at the same hierarchical level, the also used 'multi-level' wording is misleading and inappropriate. MEIO deals with uncertainty – with the statistically predictable stochastic perturbations – based on what the safety stocks and other stock elements/targets are calculated. MEIO is a further advancement to volume variability analysis in wider (non-hierarchical) network context covering even 7-10 echelons, like RM's, blank WIP's, Colored WIP's, Sub-assemblies, FG's, Distribution Centers, etc. [Willems 2011, 2015]. Several companies offer professional IT solution for MEIO. However, the triggering point is digital without any flexibility or freedom, i.e.: above the point the production/replenishment is prohibited, below the point it is mandatory. A combination of supply chain and inventory optimization approach is the multi-objective supply chain network optimization which creates so-called Pareto front from a set of possible optima [Dzupire et al 2014].

There is a separate field of **modeling sporadic demands** covering patterns of slow, lumpy (intermittent) and erratic classes [Boylan et al 2008; Babiloni et al 2010; Dobos and Gelei 2015]. As Snyder and Shen also highlight the detected demand pattern is heavily dependent on the time resolution [Snyder and Shen 2011]. In fact, the scale-free distribution of demands manifested in the Pareto distribution combined with cyclical synergetic processes of an organization – e.g. optimized, scheduled deliveries on say every Tuesday (mainly) – creates those patterns of slow, lumpy, erratic, and fast classes. The alternative solution of the sophisticated modeling is the increased flexibility and reduced response time to sporadic demands. Therefore, I will not introduce that methodology in my dissertation.

The, developed by me, **combined quantity-irregularity graphs (CQIG)** offer a strong alternative for small and mid-sized enterprises (SME's) to make a step-change from one-size-fit-all or ABC-based inventory target setting. CQIG is an advancement to volume-variability analysis in terms of visualization and of adapting network science methodology. Due to that latter it opens new pathways also for large enterprises. That approach I introduce it in Section 5.

4.9.4. Sales and operations planning (S&OP)

The high level annual budgeting aligns the company's resources to the expected customer demands and to the shareholders' expectations. The short-term supply chain execution focuses on responsively fulfilling the actual customer demands. The sales and operations planning bridges the two levels mentioned before (see Fig. 22.).

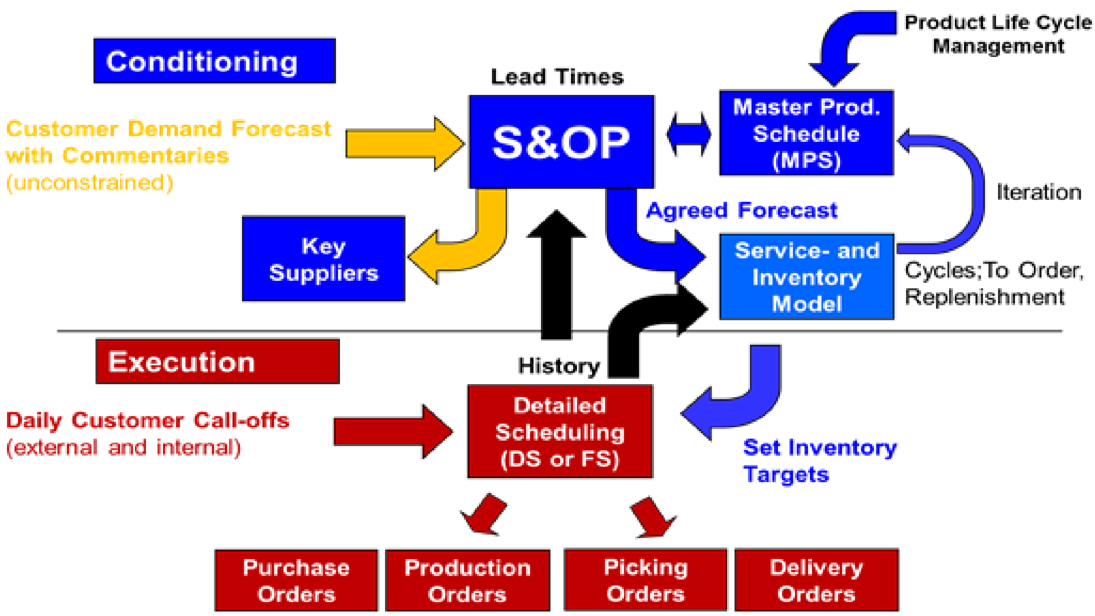


Figure 22. The S&OP (conditioning) and Order Fulfillment (execution)

It is the mid-term supply chain conditioning, that sets the supply chain parameters enabling the company to meet the customer demands at agreed service level and agreed costs according to the annual budget. It is a formal high level business process of an organization assuring that all the key functions see – and are committed to – the same plan [Karrenbauer 2015]. In Fig. 22. I show the main elements of S&OP, their relationship, and also the linkage to the execution processes. S&OP is a very powerful solution complementing to order fulfillment and to those execution-focused solutions situated in pink area of Fig. 20. Therefore, it is advisable to implement S&OP in organizations of any size. S&OP process implementation is widely supported by large consultancy companies and relevant IT solutions as well [Aberdeen Group 2012].

5. The developed analytical tools and methods

For finding our way we need to understand the networked structure of our organization first. In the previous sections I have highlighted several analogous structural phenomena with other viable networks which lead to similar behaviors. In Section 4.2 I have already detailed my visualization method. In this section I introduce two analytical methods to map the main characteristics of the networked structure of an organization. The combined quantity-irregularity graph (CQIG) was developed in the last few years. As it will be seen, it has its limitations, where the matrix analytical approach can deliver better solution. That latter approach is also unique in its fully adjusted structure to the characteristic structure of the LSCN.

5.1. Combined Quantity-Irregularity Graphs (CQIG) method

The CQIG method was fine-tuned based on empirical investigations and factual data analyses of about a dozen of factories from different industries, i.e. electronics, telecom, automotive, FMCG. Antal et al suggest to take into account the propagation of perturbation both inside the network-element and at its meta-level, i.e. between the network-elements of interactomes [Antal et al 2009] – we do similarly with **CQIG** approach, when investigating the behavior of each node and of the meta-level structures and behavior. In the interactomes, apart from high importance high degree hubs, other high importance but low degree bridges were determined.

Those high importance nodes with strong links form the **network skeleton** – the conduits for signal propagations and for cascading failures. Csermely underlines the two phenotypic behaviors of ‘large’ and ‘small’ players, network-elements [Csermely 2009]. In Fig. 23 I show the discriminating dimensions of ‘largeness’ in LSCN. The X and Y axes of the graphs correspond to cumulative Pareto-ranking.

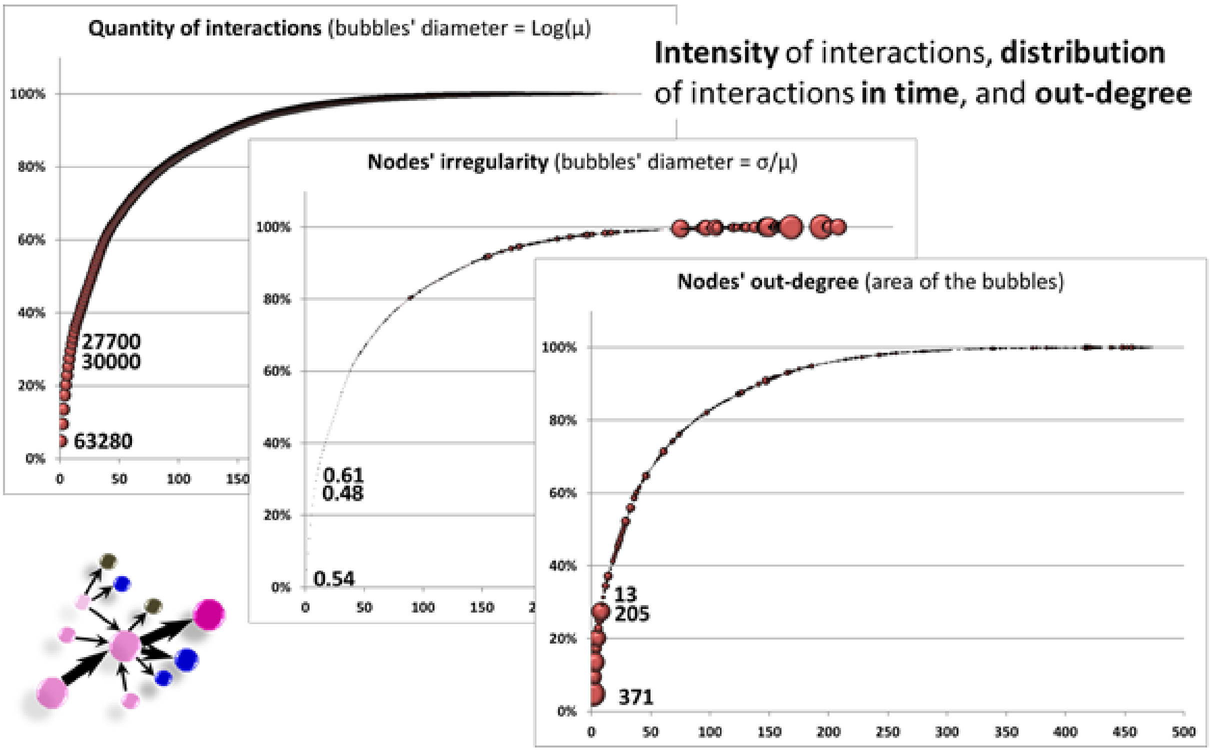


Figure 23. The three characteristics of the nodes to be visualized together

In the left graph the bubble’s diameter is proportional to the intensity of the interactions the network-element/node is involved. The other important behavioral dimension is the distribution of those interactions in time. I call it irregularity what can be characterized by the coefficient of variation (CoV, CV), i.e. normalized standard deviation [Vitasek et al 2003; Barabási et al 2004; Snyder and Shen 2011]. The diameter of the bubbles in the middle graph is proportional to irregularity (middle graph in Fig. 23). The irregularity itself and its variation item-by-item are small at the beginning of the Pareto curve, while both become large at the end of the Pareto. As we could already see, the out-degree distribution of the nodes is an important characteristics of the directed networks. As a rule, the hub type nodes with many out-links are at the beginning of the Pareto, though nodes with low out-degree may also behave as the hubs (right graph in Fig. 23). **My aim was to visualize those three dimension in one graph**. That **led to creating the CQIG** representation [Fekete and Hartványi 2012].

5.1.1. The four dimensions of CQIG and the required data

CQIG is made in Excel, containing all the required data and the visual representation. The combination of the above characteristic data in CQIG delivers four visual dimensions: two of them – quantity and irregularity – are absolute dimensions while the other two – ranking and synchronicity – are relative ones. See Fig. 24.

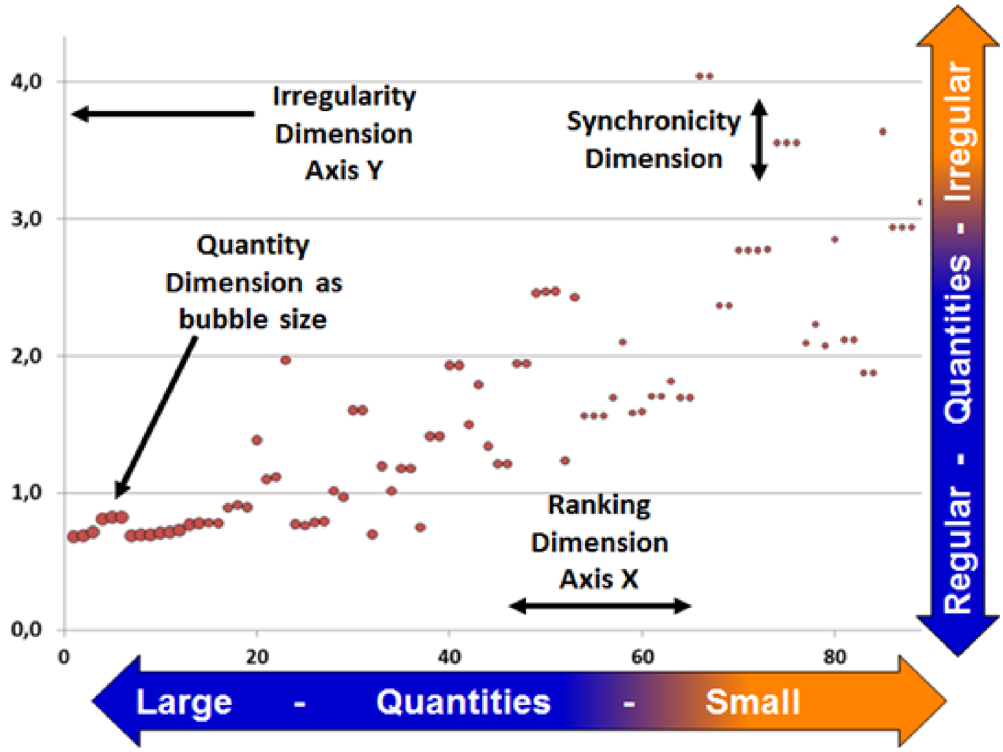


Figure 24. The four dimensions visualized in CQIG
(raw material echelon of one product family in a small OEM organization)

The **ranking** dimension is the **Pareto**-ranking according to the intensity of the interactions of a given node. That may be the average usage of that item or the weight of the interactions, i.e. the average usage normalized by the total usage in that echelon.

The **quantity** is visualized as the **size of the bubble** proportional to the parameter value. That parameter can be the used physical volume, the sold value, the profit contribution, or the node's degree. In network analysis, the bubble's territory will be proportional to the **out-**

degree of given node. When visualizing volume or value data with the bubble size, it is advisable to use logarithm of the volume with rounding up, otherwise the large bubbles overlap each other while the bubbles of the Pareto-tail will not be seen.

The **irregularity** is a characteristic value on the interactions' behavior in time and on the node's noise generating impact in the network. The irregularity **may** be the **same as the variability** or coefficient of variation (CoV), and calculated as the standard deviation of the periodical volume data divided by the average of the periodical volume data. The **meta-level irregularity** of a node characterizes its contribution to the network's perturbations. In CQIG the 'classical supply chain normalization' is used (CoV or NSD) while in matrix modelling the meta-level one.

When nodes have identical downstream out-component (e.g. materials built into the same finished products with same BoM quantities), then the similar irregularity of the nodes and the sensitivity of Pareto-ranking arrange those nodes side-by-side horizontally and at the same heights in the CQIG. That is the fourth emergent dimension of the CQIG what I call **synchronicity**, as those nodes show strongly correlated behavior. The tiny difference, in case of material nodes, may come from slightest differences in scrap rate or other type of inventory leakage or discrepancy.

5.1.2. Building the two CQIG's of the organization

When studying the biological networks at least two adjacent hierarchical levels are to be investigated [Antal et al 2009]. In LSCN we build CQIG's for both the finished products and the resources/materials at the same time. That enables us to investigate the conversion module and the output module of an organization both at node-level and at the meta-level of the echelons. See Fig. 25.

The network structure of the input module is usually simple with single sourcing, or probable dual-sourcing. The characteristic **network pattern** of the conversion module is **driven by the out-links** of its input nodes – $\boldsymbol{R_i}$ in the left CQIG in Fig. 25. The in-links' pattern of the output (finished product) nodes is quite homogenous: in-links in strong sync – $\boldsymbol{F_j}$ in the right CQIG in Fig. 25. The out-degree distribution of the finished products is represented by the right CQIG – $\boldsymbol{F_i}$ in the right CQIG in Fig. 25. The nodes' distribution in the CQIG and their relative position vs each other or to a population refers to the networked structure of the entire organization, while the concrete wiring of a node is informative about the node level structures, or motifs.

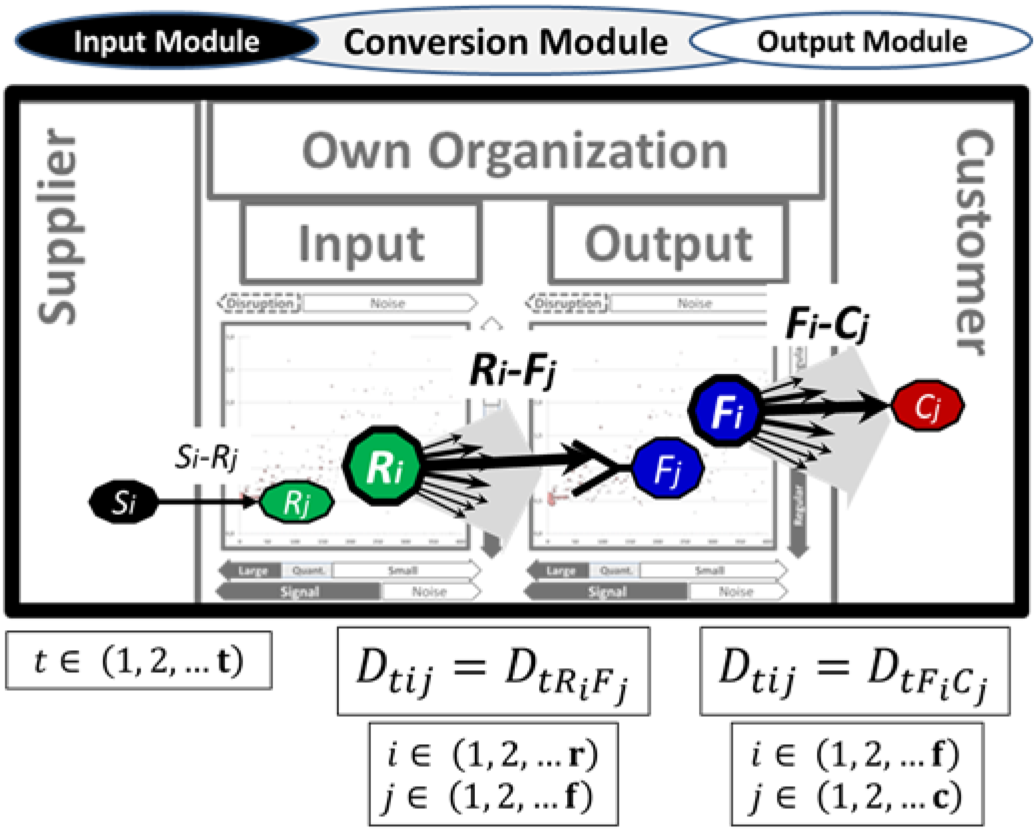


Figure 25. The two CQIG characterize the organization and its modules

In all businesses we can get the **time dependent demand data** according to **Source-, Make-, Deliver-**processes of the SCOR model [Supply Chain Council 2011]. For building the CQIG of the finished product (output) nodes we use the **historical customer deliveries**, as those represent the factual demands triggering, destabilizing the finished product nodes ($D_{tF_iC_j}$). For building the CQIG of the material resource (input) nodes ($D_{tR_iF_j}$) we can either use the **material backflush** data of the ERP system or calculate from **historical production and bill-of-material** (BoM) data as:

$$D_{tR_iF_j} = D_{tF_j} \times B_{R_iF_j} \qquad \text{Equation 5.1-1}$$

where $\times$ stands for Descartes-multiplier, D_{tF_j} are the time dependent production data of F_j , $B_{R_iF_j}$ is the BoM value of R_i and F_j node-pair, and $t \in (1, 2, \dots \mathbf{t})$, $i \in (1, 2, \dots \mathbf{r})$, $j \in (1, 2, \dots \mathbf{f})$ are respectively. See Fig. 25.

Depending on the business, either weekly or daily time buckets are to be used and data of minimum 13 periods are required [Snyder and Shen 2011]. **From the time series** D_{tij} we can **calculate the derivative data** required for CQIG analysis, as per the equations 5.1-2 till 5.1-9 in Fig. 26.

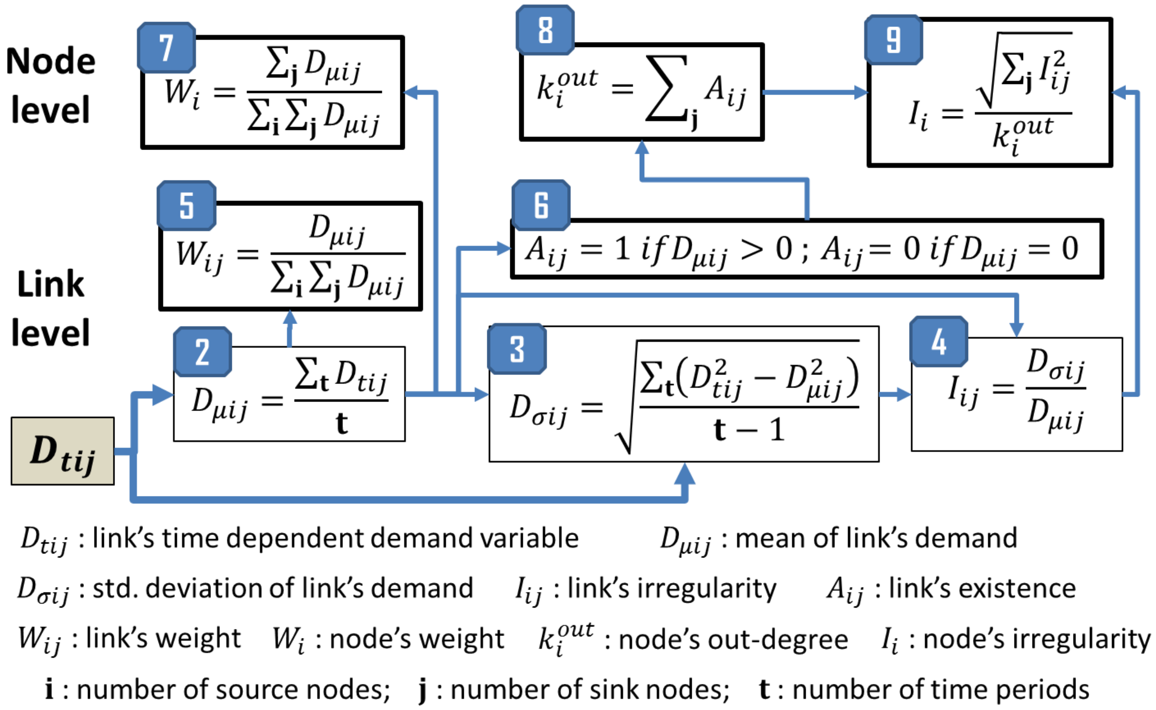


Figure 26. Equations from 5.1-2 till 5.1-9 of derivatives for CQIG analysis

First we calculate $D_{\mu ij}$ the mean of the time dependent demand series link-by-link from D_{tij} (Eq.5.1-2). From $D_{\mu ij}$ and D_{tij} follows $D_{\sigma ij}$ the standard deviation of the time dependent demand series link-by-link (Eq.5.1-3). $D_{\mu ij}$ and $D_{\sigma ij}$ result the link level irregularity of I_{ij} (Eq.5.1-4). Normalizing $D_{\mu ij}$ by the echelon-level mean we get W_{ij} the **weight of a link** (Eq.5.1-5), the characteristic values for defining the **conduits** of cascading failures. We consider only those links A_{ij} in LSCN analysis what have larger than zero interaction intensity, see Eq.5.1-6. Eq.5.1-7 delivers W_i the **node's weight** in the echelon, what is used for **Pareto-ranking** in CQIG. Apart from the weight of a node (the total intensity of the interactions of a node), other important characteristics in CQIG is the **node's out-degree** k_i^{out} (the bubble size), what is available through Eq.5.1-8. Finally, we calculate the third characteristic value of the CQIG, the **irregularity of the node** (I_i) through Eq.5.1-9. Please note that **we calculate the meta level irregularity** in accordance **with non-correlating demands** as per **risk pooling** (see Section 2.2).

5.1.3. Distribution in the CQIG – a node's behavior and its out-component

Fig. 27 visualizes the main characteristics in CQIG in general (left graph) and brings a concrete example (graph at the right). The distribution of the network nodes in CQIG in all business cases will show an upward-right oriented fan-tail [Fekete and Hartványi 2012].

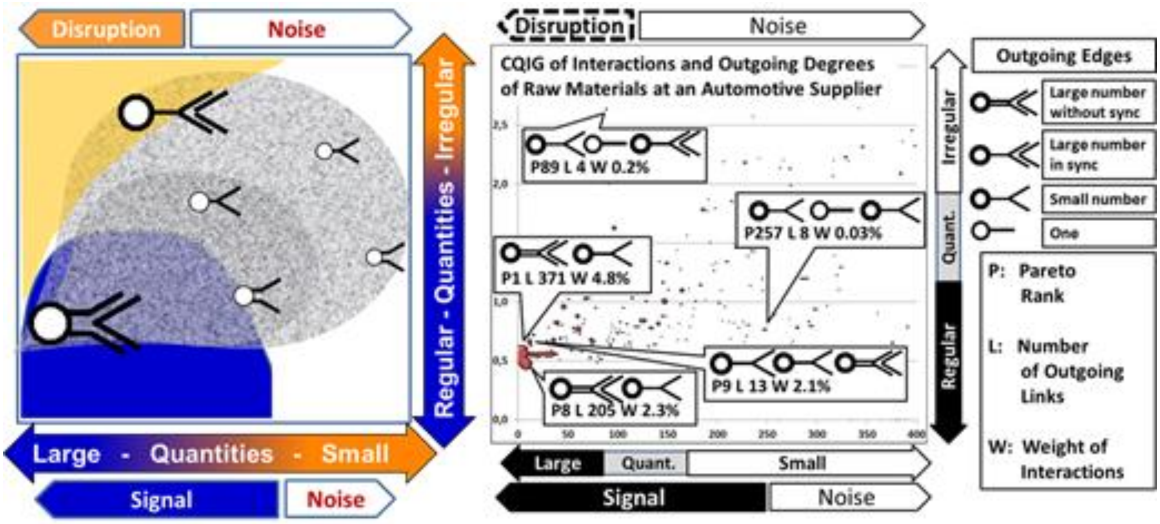


Figure 27. The topology of the nodes' out-component and the resulted in behavior represented in the CQIG (materials of a mid-sized Tier-1 automotive supplier organization)

In the **bottom left squeezed area** are situated the large volume items which have large downstream out-component combined with demand pooling making their quantities regular. The large number of links and the weak sync may be a result of large number of neighbor nodes with non-correlating behavior: P1 and P8 in Fig. 27 are typical high out-degree **date-hubs** with large number of alternative, transient out-links, possessing 10.2% and 5.6% of the out-links as well as 4.8% and 2.3% of the interactions respectively (the total number of links in the conversion module between raw material and finished product nodes were 3630). However, such behavior can also emerge from **demand pooling** in farther echelon downstream, like P9 node with only 13 out-links, but possessing 2.1% of the interactions and similarly low irregularity. In the left graph of Fig. 27 I visualized the out-component's networked structure in generalized form with only one divergence symbol. In the real life that is an emergent structure of combined structural and behavioral characteristics of nodes trough several echelons. The **bottom-left area is of signals**, where the triggered interactions are very frequent and regular, and where our network needs to develop "well defined adaptive responses" [Csermely 2009], i.e. the area for optimization and focus.

Large out-component combined with strong transversal synchronicity (e.g. due to promotions or focused marketing activities) generate large and irregular quantities – causing **disruptions** in the network. Those are the nodes in the **top-left area** having still large number of interactions while the interactions are more irregular. Raw material P89 in Fig. 27 was built in four finished products, which were delivered to only one large factory and built into a large number of different final consumer products. But, since all the final consumer products were driven by strong seasonality, the relevant demands were in strong transversal sync (strongly correlated demands). The top-left area is the reign of disruptions where the focus is to build resistance and/or recovery capability of Melnyk et al but also in the bottom network of DSN, at the organization level [Melnyk et al 2014].

The rest area in the CQIG is the reign of '**noise'** as the vast majority of the nodes are distributed here with small number of either regular or irregular interactions. The out-component of those nodes is small, short and/or narrow with either stronger or weaker transversal sync in it. Here the task will be the intrinsic noise reduction enabling the organization to focus on the previous two regions. On the other hand, the priority nodes are also situated in that area, what must be protected from the negative effects of the disruptive nodes. Those will be discussed later.

5.1.4. Behavioral node archetypes of the network skeleton in the organization

Guimera and Amaral distinguished general node archetypes according to their structural position through modularity measures [Guimera and Amaral 2005]. I distinguish **seven**

behavioral archetypes of the nodes in the bottom-network of LSCN, which create the important motifs and the network skeleton of the organization, and substantially contribute to the emergent behaviors of the organization.

Cool Node-Out (**CNO**) are the finished product items at the bottom left of the right CQIG in Fig. 28. CNO is involved in large number of regular interactions. Either the adjacent out-links are in large number and in weak sync (date-hub) or that phenomenon emerges from the structure of the node's out-component. The former is better as that pattern falls within our span of control. The latter case can also be exploited, though a transversal synchronization effect in the out-component (e.g. a 'big-bang', worldwide promotion) may push that node from CNO to DNO mode.

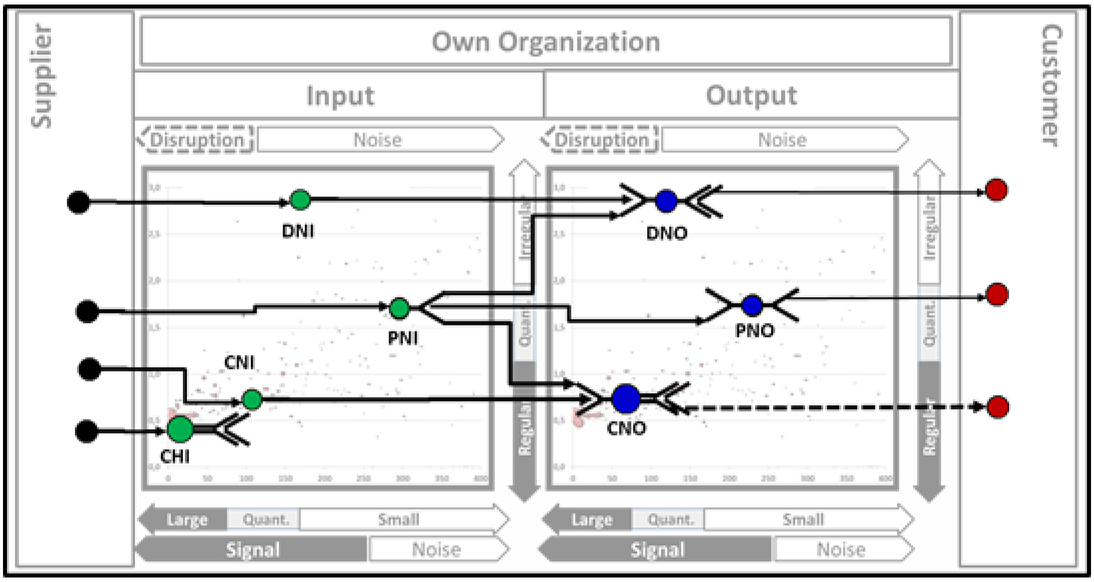


Figure 28. Behavioral archetypes of nodes and their linkedness in the organization

Disruptive Node-Out (**DNO**) type of finished products are distributed at the top left of the right CQIG in Fig. 28. DNO is involved also in large number of interactions but the distribution pattern in time is irregular. Such products are in ramp-up phase or involved in large nation-wide or world-wide promotions (or of seasonal/XMAS effect). The less mature and/or more homogenous downstream out-component results in minor pooling effect. That causes the high irregularity in demands. Such products may cause large disruptions for the entire bottom-network (organization) through the commonly used resources.

The small finished product items create the noise and occupy the largest part of the upward opening fan in the right CQIG of Fig. 28. The more homogenous and narrower is the out-component of such node, the more irregular will be its behavior, e.g. customer specific finished product variant serving a small market segment. As the small items create ‘noise’ in the system (what defocuses our efforts and resources), our inventory and operations management solutions must enable simple handling of those items with minimized noise effect. However, due to any strategical or customer specific reasons we may consider some (but not all) of them as of high priority nodes. That archetype is the Priority Node-Out (**PNO**). Those PNO’s are to be protected from cascading failures generated by disruptions.

Cool Node-In (**CNI**) is a large regular specific raw material, which inherits its ‘cool’ behavior from its cool finished product parent (CNO). CNI’s occupy the bottom left segment of the left CQIG in Fig. 28. The irregularity will be similar to its parent while its ranking position will depend on other aspects as well, e.g. the BoM values. Such cool raw material can create stability in upstream network and for the suppliers, if for example we put a CNI in Kanban replenishment, Vendor Managed Inventory or other continuous replenishment mode rather than managing it in to-order mode.

Disruptive Node-In (**DNI**) is the large irregular specific raw material which inherits its ‘hot’ behavior from its hot finished product parent (DNO). Such ‘hot’ raw material can create demand spikes in the upstream network processes when the parent finished product is produced to order and the material itself is also in (pick-)to-order mode. When creating dissipative motif of creative element, the relevant buffer of the DNI must be carefully calculated and maintained, otherwise the freed up common resources through the creative element motif will be wasted due to lack of specific material of DNI.

Raw materials what are built into large number of finished products have large number of regular interactions, and concentrated at bottom leftmost segment of the graph. See the left CQIG in Fig. 28. That archetype is the Cool Hub-In (**CHI**). Those items have large heterogeneous downstream out-component, which results in large and regular volumes with minimum demand uncertainties. These nodes are the hubs of the most connected network part of the bottom-network. With its hundreds or thousands of links a CHI may have diminishing impact on the network performance if such hub is destabilized or taken out [Barabási 2003; Newman 2010]. Therefore, it is crucial to protect such hubs against network perturbations especially from upstream, i.e. cover the supply uncertainties with safety stocks and sourcing alternatives if possible. ‘No optimization’ but building preferably resistance and secondarily recovery capability of Melnyk et al [Melnyk et al 2014].

A significant portion of the resource nodes have more than one parent finished product items, but far less than of a CHI. Their behavior will be an intermediate one compared to the finished products they are linked to. For our investigations **only that group of nodes** are important which are **linked to all the three finished product archetypes** of our focus in creating resilience to our organization, i.e. linked to CNO, DNO and PNO simultaneously. The disruption from DNO will be propagated through such common Priority Node-In (**PNI**) towards PNO’s destabilizing those as well.

The nodes of CNO, DNO, PNO, PNI, CNI, and DNI archetypes in Fig. 28 with their common links and links from supplier nodes, as well as to customer nodes are forming the high importance **network skeleton of our organization**. Within that the DNO-PNI-PNO and DNO-PNI-CNO paths are forming the **skeleton of the creative element motif**, which solution will be detailed in Section 6.

5.1.5. CQIG vs Volume-Variability and MEIO and limitations of CQIG

As other optimization solutions – like Volume-Variability or MEIO – the CQIG helps in adequately grouping the finished products and the material items (the SKU’s in the echelons) according to their behavior similarities and difference, and in setting the appropriate operations and inventory management modes to those groups. Across industries it has been proven that the irregularity (or CoV) falls usually in the range of 0.5 and 4-5. Higher than 4-5 usually represents such irregular intermittent demand pattern that such item has to be treated more in project mode, e.g. new product in ramp up phase. The published literature and my own experience suggest that above 2 it is better to think about make-to-order approaches, below 2 the Kanban-driven replenishment can be appropriate, while around 0.5 the rate-based-scheduling can also be employed [Vitasek et al 2003; Babiloni et al 2010; Logility 2010; Snyder and Shen 2011; Willems 2011, 2013, 2015; Fekete and Hartványi 2013; Dobos and Gelei 2015].

The CQIG well supports the product design phase for utilizing the existing commonalities in the portfolio and through that to further stabilize the supply chain network rather than unconsciously generating SKU proliferation. The finished product **portfolio clearance** can be done so that we avoid the mechanistic cutting-the-tail, but exiting those items which create direct negative impact on the business performance and their removal will not destabilize the network. And finally, the CQIG considers and visualizes other dimensions as well, what helps to **utilize the emerging network dynamics of the organization** and utilizing innovative solutions apart from the classical ones [Fekete and Hartványi 2013] – discussed in details in Section 6.

Evidently, the CQIG method has its **limitations**. In case of large organization of nested structure and of thousands of nodes in echelons, the visualization is cumbersome (Fig. 29) and the analysis is complicated and slow. For example, when determining the network skeleton through filtering the links of high importance nodes – CNO, DNO, and PNO and their neighboring resource and customer nodes, then subsequent cycles of filtering, Pivot-table creation and analyses are required. The more complex and nested is our organization, and the more influential and informed we are regarding to our suppliers and customers, the more appropriate is the matrix method I have developed with the support of Dr. Gábor Kallós.

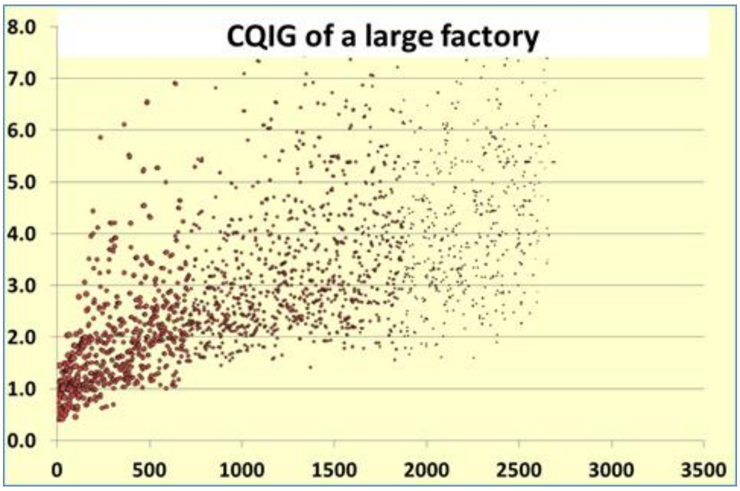


Figure 29. CQIG of a large telecom-OEM organization with nested modular structure

5.2. Matrix method

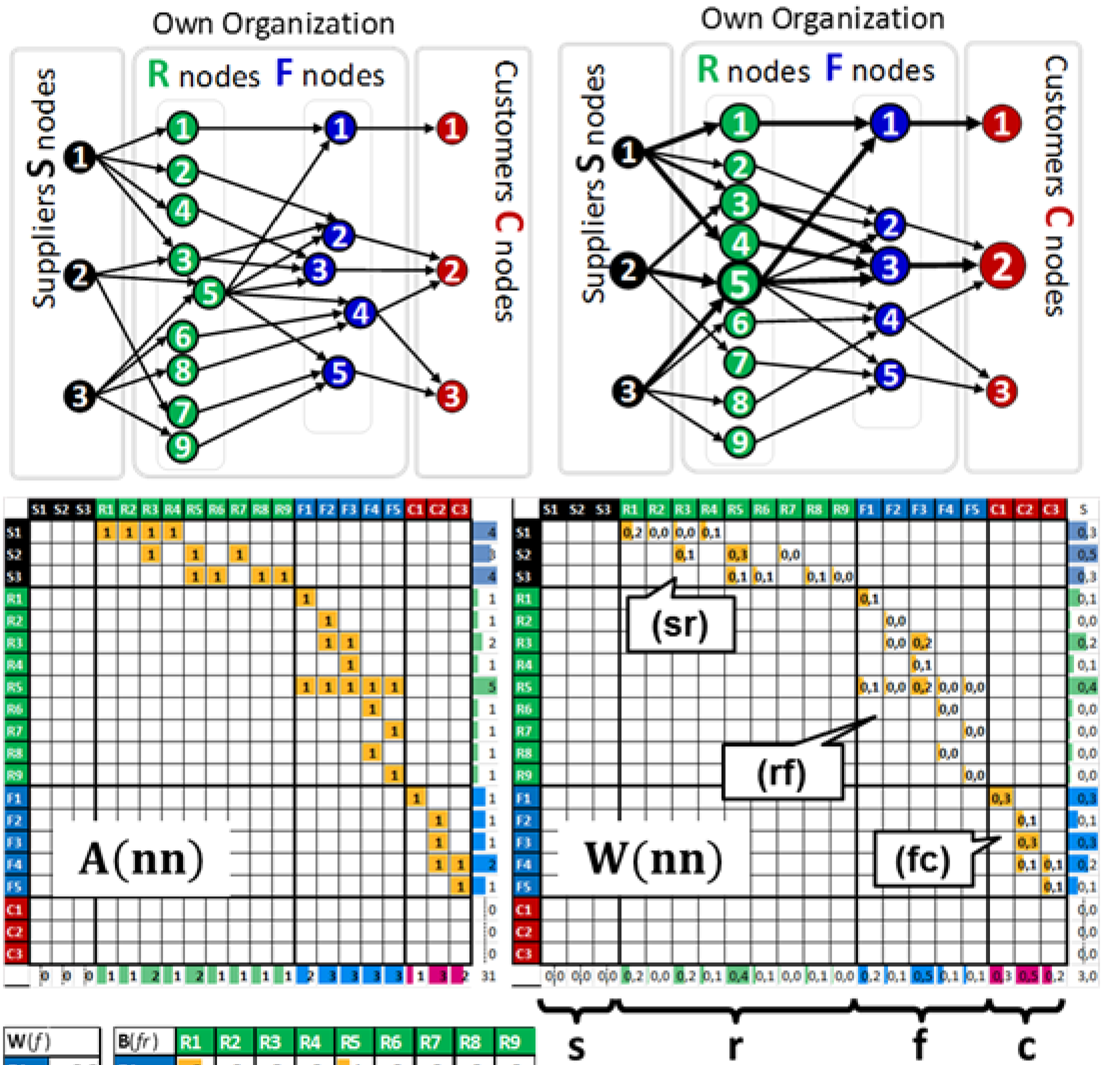
The matrix method enables us to analyze the **entire network** of an organization **simultaneously**, including the supplier and customer nodes as well, and modeling organizations with **complex modular structure** shown in Fig. 19. It opens the way for

modeling the failure propagation as well [Fekete et al 2016c]. As we already discussed, usually we have information and data about an organization's internal structure at very detailed level (fine-grained representation). Regarding to organization's external structure, the links with the organization's suppliers and customers are well known, while the finer-grained structure of the suppliers or customers are usually poorly known to us. Therefore, when analyzing our organization's external structure, I suggest to consider the customers and suppliers as nodes (network-elements of DSN/LSCN) grouped in echelons. The nodes from our organization are linked to those network-elements, rather than to the resource nodes or finished product nodes of unknown to us structure in supplier or customer organizations respectively (please compare Fig. 15 and the top diagrams of Fig. 30).

Because of the large number of different matrices and symbols defined in this section I use the **following** simplified **notation** for matrix **A** of size s×r : $\mathbf{A}(\mathbf{sr}) = (a_{ij})\epsilon\mathbb{R}^{\mathrm{s}\times\mathrm{r}}$. The entry of that matrix **A** will be noted as $A[s,r]$ instead of commonly used form of a_{ij}. In both cases the capital letter (sometimes with lower case letters of additional information) defines the entry type – like **A** for adjacency matrix, $\mathbf{C_{bc}}$ for betweenness centrality matrix. The difference to Newman's notation is that (a_{ij}) represents a directed link from node *i* to node *j* according to the Hungarian notation in transport and logistics literature [Newman 2010; Bakó and Kádas 1981].

According to our network model of an organization, **4 echelons of nodes** are to be investigated: echelon of suppliers (S_1-S_s), echelon of resources (R_1-R_r), echelon of finished products (F_1-F_f) and echelon of customers (C_1-C_c). As I already highlighted, in case of suppliers and customers we neglect their internal structure. In Fig. 30 a simple networked structure of an organization and its matrix representation are shown on the left, where the materials flow only in one direction, from suppliers to customers, through material conversion and transport process, i.e. **directed acyclic graph** or DAG in the literature [Newman 2010].

The **adjacency matrix** $\mathbf{A}(\mathbf{nn})$ of such organization model is a **quadratic upper-triangle strictly nil-potent matrix** (no self-edges, no reverse flow), **containing three rectangular adjacency matrices** of $\mathbf{A}(\mathbf{sr})$, $\mathbf{A}(\mathbf{rf})$, and $\mathbf{A}(\mathbf{fc})$ for the adjacent echelon pairs – where $\mathrm{n} = \mathrm{s} + \mathrm{r} + \mathrm{f} + \mathrm{c}$ is the order of the represented network. The values in the quadratic matrix are either 0 (no link) or 1 (linked). Such basic upper-triangle quadratic matrix representation is suitable **for** analyzing the **path length characteristics in our network**, for **stratification** through creating the bibliographic coupling and co-citation matrices [Newman 2010; Fekete et al 2016c] and calculating the **betweenness centralities** as well. Evidently, if the organization model is having **additional echelon**, then that additional echelon will form **further rectangular block** in our matrix with its relevant adjacent echelon pair.



W(f)	
F1	0,3
F2	0,1
F3	0,3
F4	0,2
F5	0,1

B(fr)	R1	R2	R3	R4	R5	R6	R7	R8	R9
F1	2	0	0	0	1	0	0	0	0
F2	0	1	1	0	1	0	0	0	0
F3	0	0	3	1	3	0	0	0	0
F4	0	0	0	0	1	1	0	1	0
F5	0	0	0	0	1	0	1	0	1

B(sr)	R1	R2	R3	R4	R5	R6	R7	R8	R9
S1	1,0	1,0	0,2	1,0	0,0	0,0	0,0	0,0	0,0
S2	0,0	0,0	0,8	0,0	0,7	0,0	1,0	0,0	0,0
S3	0,0	0,0	0,0	0,0	0,3	1,0	0,0	1,0	1,0

Figure 30. Network model of an organization. Top-left graph and its matrix representation below it are without weight, while on the right are with weight. Small tables at the bottom show the weights of the finished products, the bill-of-material and the share of suppliers in dual sourcing (just for traceability).

The **nodes and links may have weights** [Csermely 2009; Newman 2010] in the network representations. That has pivotal role in **differentiating** the so-called **weak links** from the **strong links**. While the latter links determine the network skeleton, the former links contribute to network's stability in several ways (see the previous sections). The top right network and the matrix $\mathbf{W}(\mathbf{nn})$ below it in Fig. 30 models a weighted network of the same structure. The weights were calculated according to the tables at the bottom of Fig. 30.

5.2.1. Data sets of an organization and the created derivatives for network analyses

We use the **same initial time dependent variables** for creating the needed derivatives as in case of CQIG in Section 5.1.2. For each echelon pair of **sr**, **rf** and **fc** we collect the time dependent variables generating the entries of $D[t,i,j]$, where *i* stands for the node from which the link goes to the node *j* and *t* differentiates the time slots (see Fig. 31).

The historical **material arrivals from our suppliers** determine the **links** between the supplier and resource nodes – $D[t,s,r]$. The historical **finished product deliveries to our customers** determine the **links** between the finished product and customer nodes – $D[t,f,c]$. The historical **material consumption in finished products** determines the links between the resource nodes and the finished product nodes – $D[t,r,f]$. That can be either downloaded as backflush data from MRP/ERP system or calculated through multiplying the produced volumes of the finished product node with its Bill-of-Material (BoM) – see the Eq.5.1-1 in Section 5.1.2.

We generate the **link related derivatives** for each echelon pair of $\{\mathbf{sr}\}$, $\{\mathbf{rf}\}$ and $\{\mathbf{fc}\}$ separately according to Eq.5.2-1 till Eq.5.2-4 in Fig. 31. From time dependent variables $D[t,i,j]$ we calculate the mean $D_\mu[i,j]$ for each link in the echelon pair (Eq.5.2-1). $D_\mu[i,j]$ serves for calculating the adjacency $A[i,j]$ through Eq.5.2-2 and the weight of the link $W[i,j]$ as per the Eq.5.2-3. The time dependent variables $D[t,i,j]$ and the mean $D_\mu[i,j]$ deliver the standard deviation $D_\sigma[i,j]$ of the links between the nodes of the echelon pair through Eq.5.2-4.

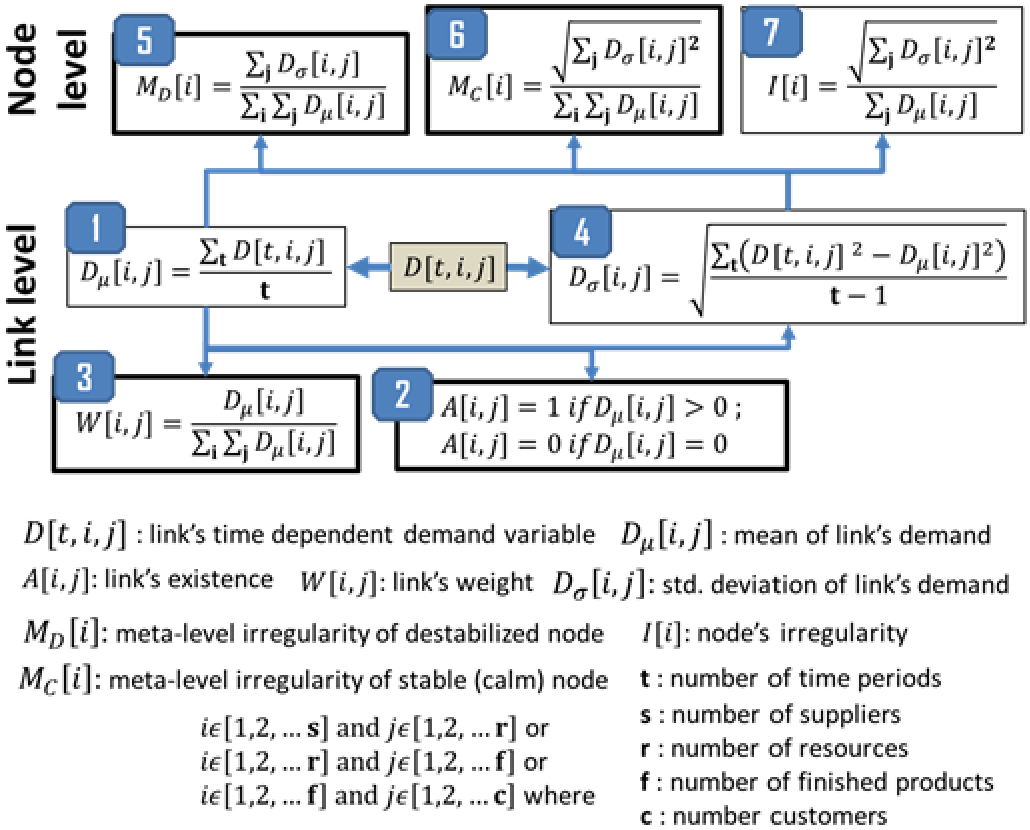


Figure 31. Equations from 5.2-1 till 5.2-7 of derivatives to create the data sets of matrices for network analyses of an organization

The Eq.5.2-5 till Eq.5.2-7 in Fig. 31 determine the **different types of irregularities** of the nodes. **In matrix-analytical method I use echelon level normalization** to calculate a node's irregularity **both in destabilized and normal** (calm) modes. Such irregularity I call **meta-level irregularity** and are denoted as $M_D[i]$ and $M_C[i]$ respectively (see Eq.5.2-5 and Eq.5.2-6). The Eq.5.2-7 $I[i]$ delivers similar to CQIG irregularity of the node according to its out-links' behavior. However, the meta-level irregularity is more reasonable to use, since the meta-level irregularity of a node underlines its contribution to the network's perturbation. Similar meta-level normalization of the standard deviation is done at the analyses of food webs, which are also directed networks, just the in-links of the predators (users of the resource preys) are not in strong sync, but behave as alternative in-links.

There is a high potential in **simulating the failure propagation** through modelling the switch of a node's state from normal (calm) to destabilized and contributing to the load increase in the node's neighborhood through switching from $M_C[i]$ to $M_D[i]$.

Please note: 1. When including the man-nodes and machine-nodes in the resource echelon as well, due- to **multi-partite structure** of LSCN/DSN, the **normalization of the different resource types (3M) must be carried out separately** within the cluster of that type – e.g. man-node by the echelon-level mean of man-nodes, etc. **2.** My aim with weighting is to define the network skeleton of the organization what has specific structure of in-links of finished product nodes (mandatory sync). Therefore, **the wide-spread centrality measures and load approaches** [Latora and Marchiori 2003; Newman 2010] **would mislead** as those work well in undirected networks or in directed networks with alternative in-links.

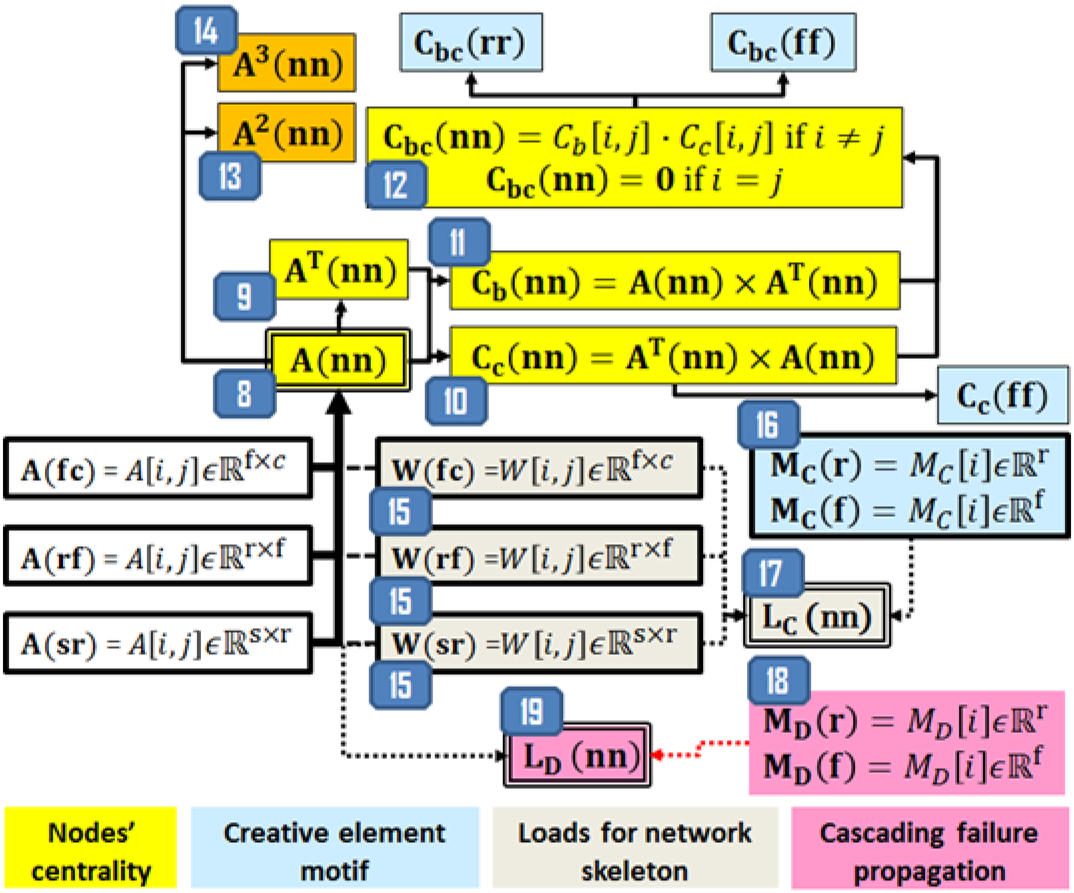


Figure 32. Matrices for analyzing an organization and their relationships – Equations from 5.2-8 to 5.2-19

Fig. 32 shows the matrices we create from the above determined data for analyzing the network structure and networked behavior of an organization. Building the matrices of 5.2-8 till 5.2-14 is possible either by non-weighted adjacency matrices $\mathbf{A(fc)}, \mathbf{A(rf)}, \mathbf{A(sr)}$ or by their weighted pairs $\mathbf{W(fc)}, \mathbf{W(rf)}, \mathbf{W(sr)}$ denoted as 5.2-15 in Fig. 32. Eq.5.2-8 shows how we build the quadratic matrix $\mathbf{A(nn)}$ from rectangular block matrices.

5.2.2. Stratification and the network skeleton of the organization

The connectedness within the organization is not evenly dense. The echelons are already well modelled by our quadratic matrix with rectangular blocks of echelon-pairs, while the **stratification** of the LSCN is manifested in value streams of an organization. The stratification may remain latent. However, those transversal interdependences can be well understood **through the combined bi-fan and bi-parallel motifs**. For mapping and quantifying the indirect and latent transversal dependences, first we build the **co-citation matrix** – $\mathbf{C_c(nn)}$ – and **the bibliographic coupling matrix** – $\mathbf{C_b(nn)}$ **–** i.e. the matrix product of the transposed of $\mathbf{A(nn)}$ and of $\mathbf{A(nn)}$ and vice versa as per Eq. 5.2-10, 5.2-11. The results are seen in Fig. 33 for both the unweighted and weighted graphs.

The **in-degree of the nodes** in the **matrix-diagonal** of the **co-citation matrix** highlight the **in-hubs** of high in-degree in our organization (Fig. 33 top-left). Those **in-hub finished products are magnifying the failure upstream when they become destabilized**, since their in-links are not alternative ones (unlike they are in food webs), but are in strong sync. That is a typical phenomenon in a stretched and MRP-triggered supply chain, where the destabilized finished product in-hub pushes back all the non-missing resources (in relative excess vs the missing one) creating a multi-dimensional wave upstream. If such pushed-back materials are supplied by the same supplier, then the synchronized push-back waves create a "super-wave" to that supplier.

In the **band-matrix part**, represented by sub-matrices $\mathbf{C_c(rr)}$ $\mathbf{C_c(ff)}$ $\mathbf{C_c(cc)}$, we detect the **number of common upstream-nodes of a node-pair** in the same echelon, i.e. common finished products of two customers, common resources of two finished products and common suppliers of two resources. In other words, those are the **bi-fans** in LSCN (see Fig. 4). The **larger** is the number of **common upstream-nodes** in sub-matrix $\mathbf{C_c(ff)}$ for given node-pair, the **greater** is the **transversal interdependence between that node-pair** in the one hand. On the other hand, the **greater** is the **benefit** of my solution of **creative element motif** discussed later. Therefore, **sub-matrix** $\mathbf{C_c(ff)}$ is separately highlighted in Fig. 32 as one tool **for detecting the creative element motifs in our organization**. In our simplistic network F2 and F3 have more common resources than the other pairs as it is also seen in top-left matrix of Fig. 33.

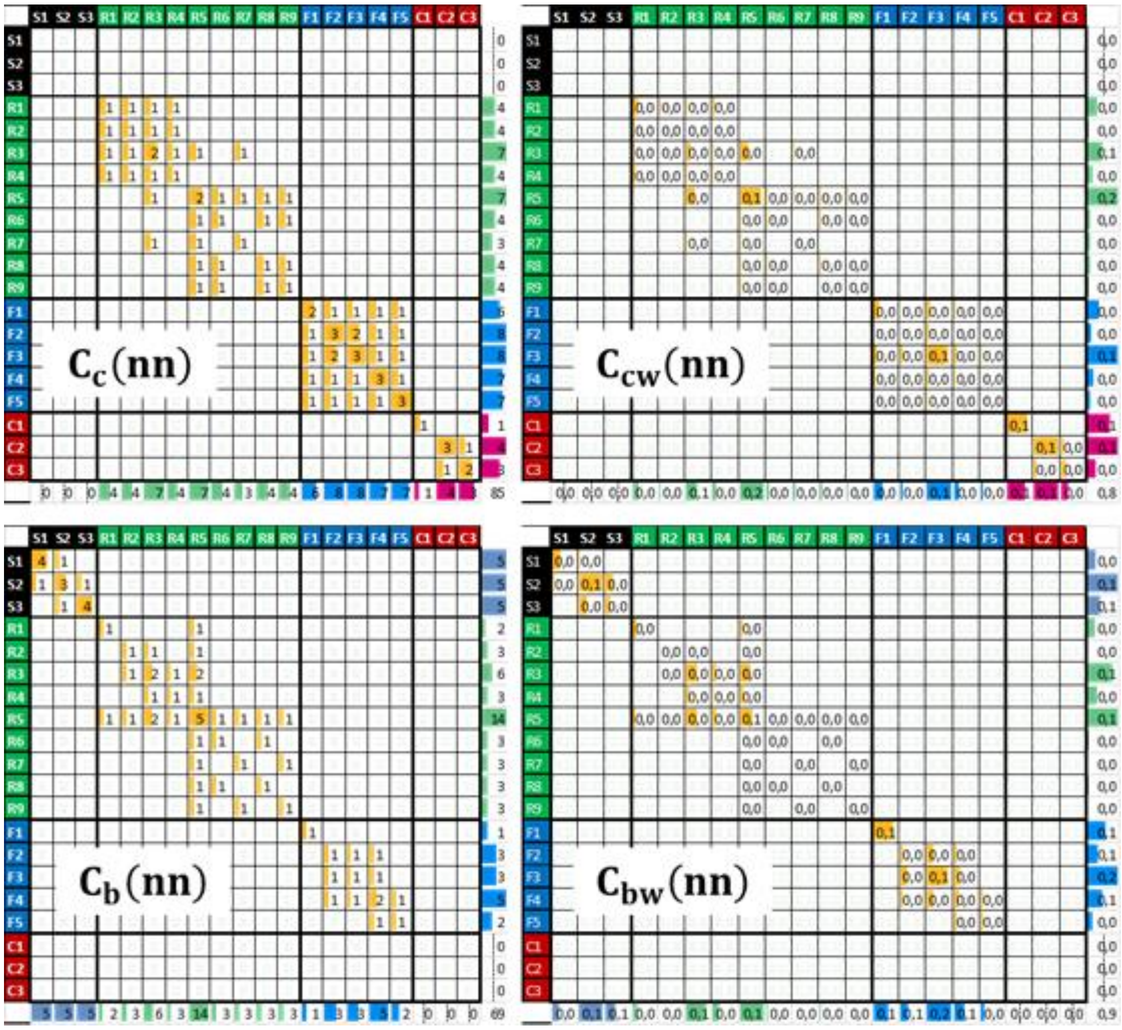


Figure 33. Co-citation matrix $\mathbf{C_c}(\mathbf{nn})$ *without link weight (top-left) and* $\mathbf{C_{cw}}(\mathbf{nn})$ *with link weight (top-right). Bibliographic coupling matrix* $\mathbf{C_b}(\mathbf{nn})$ *without (bottom-left) and* $\mathbf{C_{bw}}(\mathbf{nn})$ *with (bottom-right) link weight. In the diagonals of unweighted matrices (left) are seen the nodes' in-degree* $\mathbf{C_c}(\mathbf{nn})$ *and out-degree* $\mathbf{C_b}(\mathbf{nn})$.

The **bibliographic coupling matrix** (Fig. 33 bottom-left) is created as matrix product of the adjacency matrix and its transpose (see Eq. 5.2-11 in Fig 32.). The **out-degrees of the nodes** in the matrix-diagonal highlight the **out-hubs**. When an **out-hub have low** sales or consumption dollar-**value**, then we **may ignore its network destabilization power**, e.g. Zink ingots in Bowden-cable production at an automotive supplier. When such a node becomes unstable, it destabilizes its entire downstream out-component, which can be 60-80% of the organization. So, it is pivotal to **protect the out-hubs against upstream disruptions**.

In the **band-matrix part** we can detect the number of **common downstream nodes of two nodes** in the same echelon, i.e. common customers of two finished products, common finished products of two resources and common resources of two suppliers. The **relationship** between the **nodes in pair** may be **competitive** but also **complementing** (e.g. Rama Cube and Rama Brick margarines).

The matrices of **weighted** network (Fig. 33, right) highlight that the interdependence between R3 and R5 became far stronger versus the non-weighted graph, due to the intensive use of them in high-runner F3 (common sink) and due to their common source/supplier S2 in the same time.

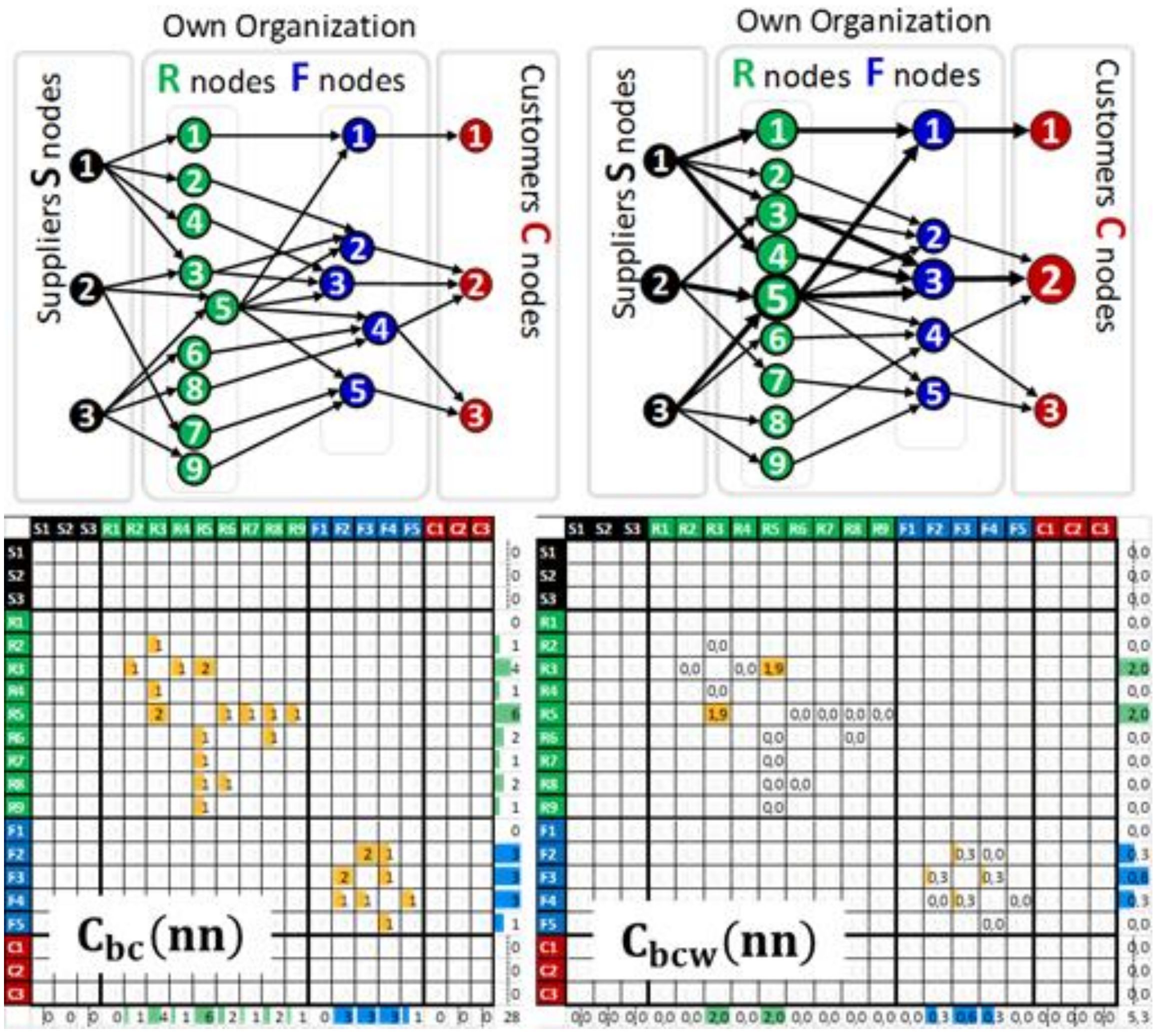


Figure 34. Betweenness centrality matrix $\mathbf{C_{bc}(nn)}$ *based on bi-parallels for unweighted graph (left graph and matrix) and for weighted one (right graph and matrix)*

The **coexistence** of common supplier/s and common finished product/s of a resource pair or the coexistence of common resource/s and common customer/s of a finished product pair results in **strong emergent interdependence between the members of that node pair**. Such relationship rooted in the neighboring echelons and creates the **bi-parallel motifs** in LSCN (see Fig. 4 for bi-parallel). In case of large number of common upstream and downstream nodes, the **node pair will have several bi-parallels building strong emergent interdependence**, what plays crucial role during cascading failures.

We can **visualize the number of bi-parallels** through multiplying the similar entries of the co-citation and bibliographic coupling matrices. See Fig. 32 – Eq. 5.2-12 and Fig 34. That serves as a good **betweenness centrality measure of the nodes in an organization**. The material resource pairs with high value in $\mathbf{C_{bc}(rr)}$ and the finished product pairs with high value in $\mathbf{C_{bc}(ff)}$ are to be investigated for three purposes:

1- Those nodes **can form value streams** in our organization thanks to their high commonalities and connectedness
2- Those nodes with their high betweenness possess **central role in failure** propagation
3- A **node-pair of a DNO and a CNO** with high value in $\mathbf{C_{bc}(ff)}$ matrix are excellent **candidates for utilizing the creative element motif**, especially **protecting** those **PNO's** which have also high value in $\mathbf{C_{bc}(ff)}$ matrix with both DNO and CNO of that node-pair.

5.2.3. Further potentials of the matrix approach

Evidently, in the real life we **also** detect (limited) **reverse flow** of materials, e.g. finished products rejected by customers (C to F), in-progress returns in margarine production or in iron casting (F to R), rejected materials by our organization to our suppliers (R to S). In such cases the relevant directed links appear in the lower triangle part of our quadratic matrix in the relevant rectangular area of echelon pair also with positive number.

For **modelling the propagation of the cascading failures** the real-life examples show that symmetrical matrices need to be used as the failure can spread both upstream and downstream (Fig. 35). **The emergent interdependence of the nodes through multiple bi-fans and bi-parallels** can be considered **as links** in matrix model through adding the betweenness centrality values to the adjacency matrices – $\mathbf{C_{bc}(rr)}$ and $\mathbf{C_{bc}(ff)}$ respectively.

I see high potential in adapting the traffic forecasting and traffic assignment approach [Bakó and Kádas 1981] where the basic load trough nodes and links could be represented by the echelon-level normalized weights of matrices $\mathbf{W(sr)}, \mathbf{W(rf)}\ \mathbf{W(fc)}$, and by the vector matrices $\mathbf{M_C(r)}, \mathbf{M_C(f)}$ – supplied by Eq.5.2-6 in Fig. 31 and by equations 5.2-15, 5.2-16, 5.2-17 in Fig. 32.

In case of modeling the propagation of cascading failure in the organization, the meta-level irregularity of destabilized node is to be used $\mathbf{M_D(r)}, \mathbf{M_D(f)}$, since the links of the destabilized node turn to behave in strong transversal sync – Eq.5.2-5 in Fig. 31 and equations 5.2-15, 5.2-18, 5.2-19 in Fig. 32. Bardoscia et al have set the example for us by modelling the cascading failures and network instability on the explored structure and with the factual data of the financial networks [Bardoscia et al 2016].

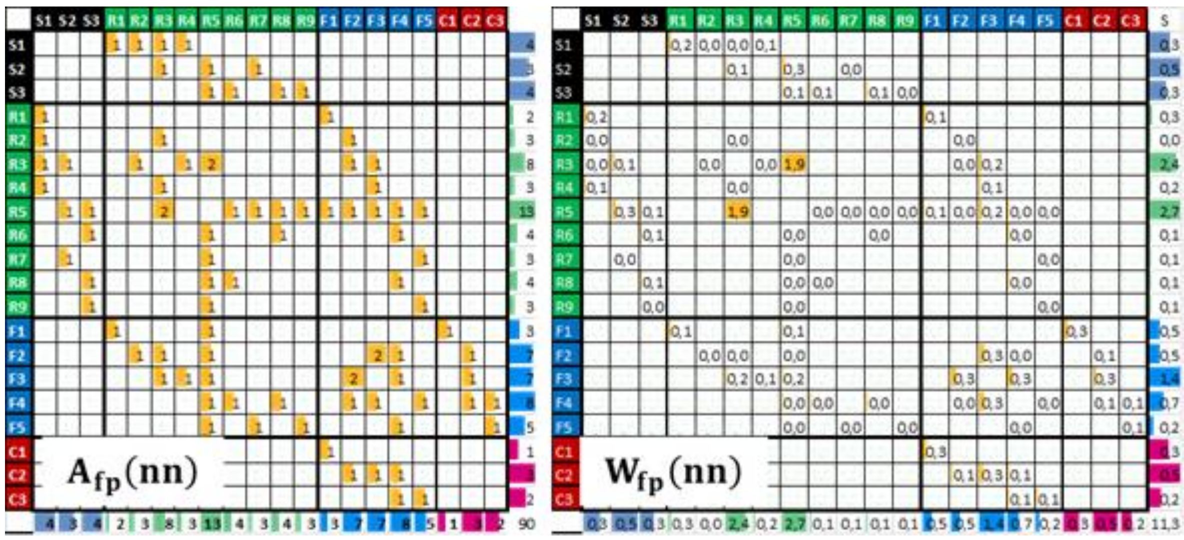


Figure 35. Symmetrical adjacency matrices representing undirected network completed with $\mathbf{C_{bc}(rr)}$ and $\mathbf{C_{bc}(ff)}$ *betweenness centrality figures for considering the emergent transversal interdependence as links. Unweighted on the left, weighted on the right.*

6. Innovative solutions to smoothen stability landscape, build degeneracy and nested plasticity

Engineering approach expects perfect interplay between elementary parts according to plans. However, it is possible to blend, **merge** the engineering and evolutionary ('tinkerer') approaches [Jacob 1977; Alon 2003]. Csermely gives a list of distinctions between the two approaches in his fundamental monography [Csermely 2009, pp. 97-100]. Antal and Csermely showed that evolvability lies between the two extremes of ‘error catastrophe’ and ‘perfection catastrophe’ [Orgel 1963; Antal et al 2009; Csermely 2015].

My suggested approach is about **building defined error tolerance in determined parts of the network at different hierarchical levels**. Since the disruptions and self-organized criticalities show fractal-like scale-free pattern [Sornette 2002, 2003; Joahansen and Sornette 2008] our solutions against those disruptions must correspond to such scaleability, i.e. **embedded plasticity** both in time dimension and network space extent. My approach **conditions an organization** to those environmental changes through **adaptive execution within the set frames of freedom at different hierarchical levels**.

In supply chain management, we require the right product, with right quality, in the right place, at the right time, in the right quantity. **I add** to these ‘rights’ **the ‘rights’ of the freedom**, i.e. the right freedom form, with appropriate fit, in the right place (hierarchical level, segment of the network), at the right time, in the right quantity (magnitude). So, the **adaptability emerges at the organization’s level** thanks to the built-in nested balanced ratio of plasticity and rigidity.

We could see in genetic regulatory and other biological networks that the **game rules create adaptive response to unprecedented environmental changes. In my approach, we create more game rules rather than instructions**. Similar to swarm intelligence [Bonabeau and Meyer 2001, 2002], a complex adaptive group behavior was generated by the few simple rules of the Service Kanban designed by me in a large IT factory. That dynamically allocated the supply of different services to the changing demand in a self-organized way. It orchestrated the work of 1500-2000 men in different functions (employees) and hundreds of machines (cells, fork-lifts trucks, trolleys, pallet jacks), as well as the interactions among them in the scale of several thousands. Due to size limitations, I can not detail my Service Kanban approach in my dissertation.

There are great engineering solutions for creating flexibility in supply chain management – like chaining described in Section 3.3 and others referred. However, those solutions build on **ordinary redundancy** rather than degenerative redundancy. Whitacre and Bender have proven that the **degenerative redundancy,** or degeneracy, is able to **create high level of adaptability and evolvability** [Whitacre and Bender 2009; Whitacre 2010]. In the below detailed inventory management approach same product with different inventory levels may be healthy in the context of its meta-level. The large players like Kanban-items and creative elements (CRE) are having more choices, alternative ways to get the same result. So, different functions can deliver the same result while the network, as a whole, is resilient to environmental fluctuations. Similar degenerative redundancy is detected in the capacity management choices at the large IT factory – see Section 6.2.

6.1. Smoothening the stability landscape and balancing the plasticity and rigidity

Diversity in response thresholds emerges when the different sensitivity of the network-elements to perturbations leads to complementing specialization and degenerate response to environmental changes in the network. That creates large number of weak links and diverse combinations in solutions. [Csermely 2009, p. 188]. That is what we aim to achieve in inventory management. The **inventory** projection **versus the product node's own target levels** generates only digital decision on replenishment (as the other optimizations do), while the **evaluation in the meta-level** network **context** (healthiness) will **lead to diverse combinations on solutions**. The method will be described below, but first I highlight the structural and functional unity of the network skeleton of the organization and the cascading failure propagation.

6.1.1. The network skeleton of an organization and the cascading failure propagation

Both the CQIG method and the matrix method are suitable for defining the **network skeleton** of our organization. The seven archetypes of nodes in our organization and their internal and external links build up the network skeleton of our organization. The large failure-causing perturbations (disruptions) will enter into our organization on these highways (conduits) and the cascading failure is propagating mainly within that **highly connected part of our organization's network**. Those are the extrinsic disruption sources (See Fig. 36).

When the demands for the same finished product coming from different customers are strongly synced (correlated demands), then that transversal sync causes a total demand amplification as the variabilities are adding up (see Section 2.2 and Section 4.1). In case of large demands, the resulted behavior of that finished product node will be DNO. I would like to draw the attention again on such CNO, where the uncorrelated demands are a result of weak transversal sync further downstream, i.e. not thanks to the high out-degree of the CNO to different customers. Such connectedness may push the CNO to DNO behavior if the customer demands of that CNO change to correlated further downstream, i.e. out of our sphere of influence.

Evidently, we can protect our network from disruptions coming through DNO with buffers built from that finished product and will risk obsolescence. The supply-side solution requires the buffering in all affected resources (in man, machine and material). But **we can resolve that issue in a more innovative way**: **the higher the connectedness** of a DNO to common resources used by CNO and PNO types of nodes is, **the better** alternative **is the creative element solution** developed and successfully deployed by me in different industries.

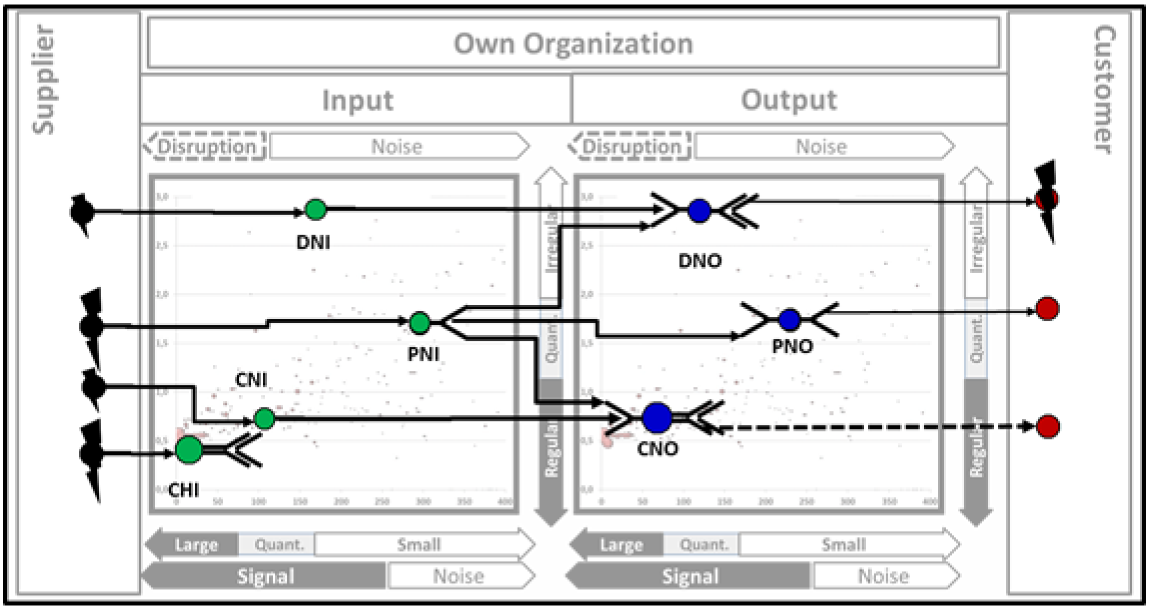


Figure 36. The network skeleton of the bottom network of the LSCN – the network skeleton of the organization – and the extrinsic disruption sources

Disruptions coming from the suppliers may cause **cascading failures** when those destabilize either an **input node of high out-degree (CHI)** or an **input node of high betweenness centrality (PNI)**. That latter may have not so high out-degree, while due to the connectedness to high importance nodes of high degree and/or priority (DNO, CNO, PNO) its destabilization fires cascading failure.

CHI behaves as **date-hub, when it is stable**. Then its out-links are not correlated, i.e. are in weak transversal sync in its out-component. The **destabilization of a CHI leads to more synchronized failure propagation** towards its finished product nodes further **downstream**. Since CHI in the organizations may link to the large portion of the finished product portfolio, CHI must not ever let go down; 'no optimization' but '**over-insuring**'.

Minor impact of failure propagation may occur when the supplier disruption destabilizes a specific material of DNO or CNO (input nodes DNI or CNI respectively). Those DNI and CNI need to be protected through classical solutions of safety stocks and/or multi-sourcing aligned with created extra plasticity through the creative element solution described later.

6.1.2. Real-life cascading failure in an IT-telecom factory

According to Watts, **cascading failure is a function of globally-connected vulnerable cluster**. In case of constrained relaxation, the tension in the network is building up and self-organized criticality creates over-connected rigid skeleton. The increased number of damaged, destabilized nodes of that rigid skeleton leads to further tensions and propagated failures in larger and larger part of the network, usually to 3-4 steps distance [Barabási 2003; Dobson et al 2007; Antal et al 2009; Newman 2010; Szalay and Csermely 2013].

Here I bring **a real business example from an IT-telecom factory**, where the cascading failure developed as building up self-organized criticality, what was **induced and catalyzed by a chain of wrong human decisions** and turned to catastrophe ('netquake') shaking down the entire organization. In Fig. 37 all the major aspects of that catastrophe are shown.

As the customer demands had increased the 'old good solutions' in MRP environment were applied by the **material source** planning people and the management: increase the safety lead-time. As a result, the average MRP safety lead-time was more than doubled (to create a fake safety) and some suppliers also significantly increased their supply lead-time (falsely reacting on the increasing supplier backlogs). As a combined effect, the purchase orders having formerly „normal" status became „overdue" further increasing the total supplier backlog, and amplified the demand towards the suppliers. See the top left and top middle graphs of Fig. 37.

The **production** reacted to the material shortages by changing the plan to what they had material for. As a consequence, the other raw materials ordered based on the original forecast have accumulated causing heavy excess alongside the existing shortage or the excess has pushed-back the material demand by MRP as a synchronized wave upstream. On the other hand, producing products with no demand led to excess finished product stock while the customer order backlog grew in parallel.

Those **vicious circles** caused catastrophe with extremely low delivery accuracy hovering around 40% and an ever-increasing backlog burden, wasting enormous amount of money in excess raw material stock and in at least 20 percent-point production uptime efficiency loss.

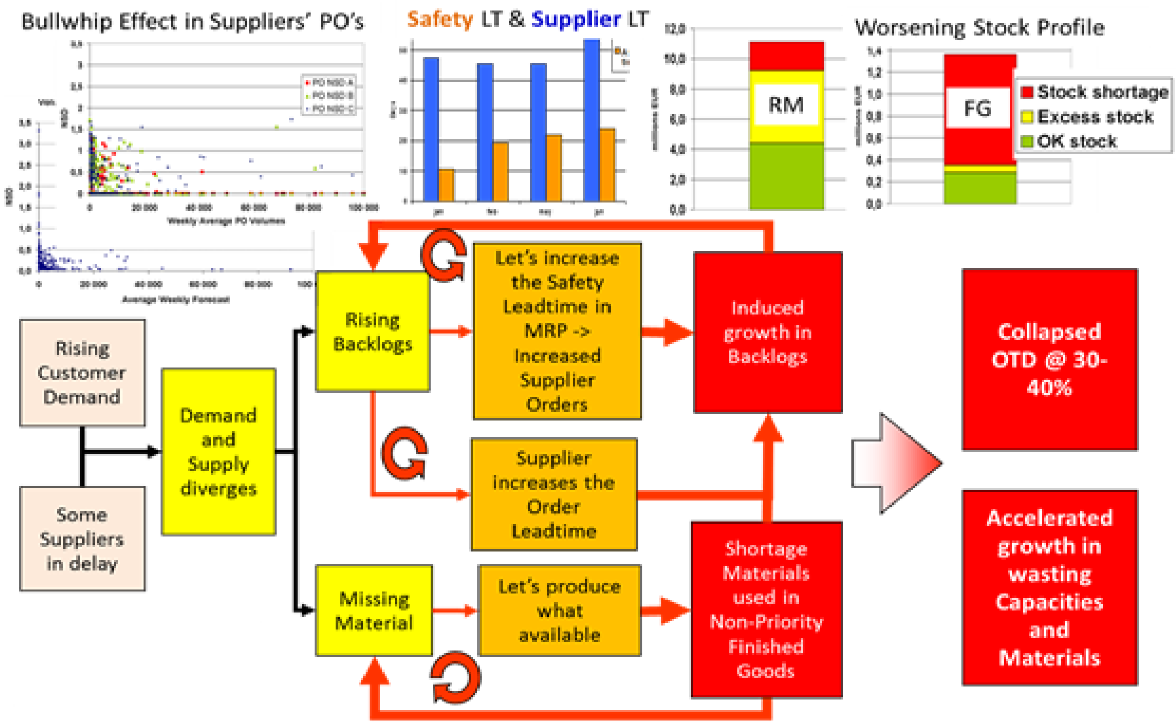


Figure 37. Cascading failure from real life at a Tier-1 IT-telecom supplier

Let us now **discuss that phenomenon in network science terms**. Increasing the safety lead-time in a strongly linked rigid and overstretched, MRP-driven DSN will not generate any safety but just increases the order backlog. Whatever safety lead time or safety stock we implement in a **rigid MRP-driven network the network remains rigid**. In **overly lean stretched network (´anorexia´ network)** those 'safety solutions' are **counterproductive** and **the path is paved for cascading failure**.

Fig. 38 shows the **butterfly effect in cascading failure**. Our detailed analysis showed that wasted production in only 3 products (1. in Fig. 38) circumvented the production of 11 finished products (4. in Fig. 38) through 5 common materials (2. in Fig. 38). Missing one common material means that **all the affected finished products are hindered in production in strong sync**. Those 11 finished product nodes became destabilized due to missing 1 or 2 material/s versus the customer demand. But the planned production of those 11 priority products had **already triggered all the materials in strong sync** (through the bill-of-materials and MRP). Therefore, the arrived materials turned to be in excess and the material demands became obsolete (5. in Fig. 38).

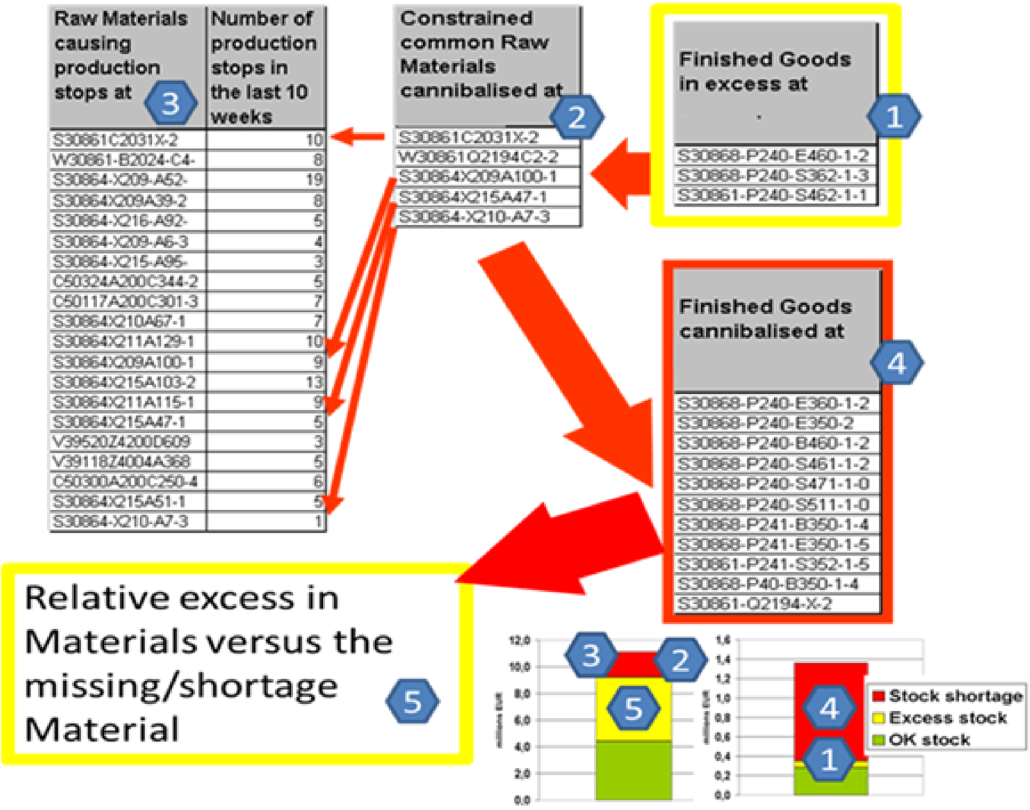


Figure 38. Butterfly effect during cascading failure advancement

Those relative excesses of all the other resources were **pushed back** by the MRP in mandatory sync as a **synchronized wave destroying** the production plans of the affected suppliers and causing (cascading) failures there as well. And so on. Such **self-organizing criticality** turns the **directed material-subnetwork to symmetrical undirected one as the failures are pin-ponging** in both directions (downstream and upstream).

6.1.3. The built-in nested plasticity in inventory management

In my solution, **the determined freedom will be different for differently behaving nodes** and **the plasticity will occur in two levels**, at the node's level and at its meta-level. That latter level may be a product cluster and/or the entire organization. The **inventory-elements of a node** are defined fully **in line with** its **connectedness**, and **network behavior**.

The aim is to **reduce the intrinsic noise** of our network **and** in the same time, we **distribute the free energy** so, that the organization is able **to dissipate the cascading failures with low risk of excess inventories.**

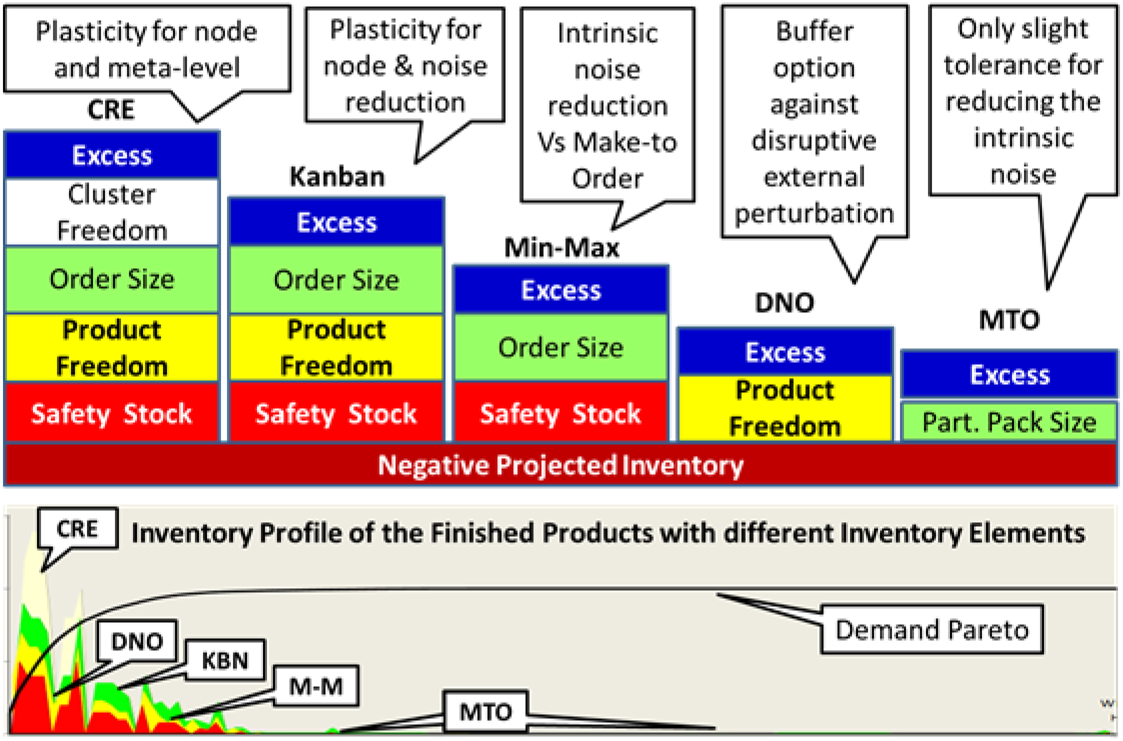


Figure 39. Built-in nested plasticity in the inventory-elements at a Tier-2 supplier

The **different inventory-elements build up the inventory management modes**. Fig. 39 highlights those **inventory management modes** for **creating meta-level plasticity** (CRE) **and node level plasticity** (CRE and Kanban) and for reducing the intrinsic noise in the network. The disruptive nodes (DNO) may have buffer to partially cushion the disruptive perturbation coming from the customer.

Red inventory-element – safety stock – is calculated only for reasonably predictable modes, i.e. Kanban, min-max and the creative element (CRE) modes.

Amber inventory-element is used as **node-level** flexibility/**plasticity**, that is the **freedom of the supplier process** either to start the replenishment or not **at his discretion**. It occurs in CRE, Kanban and may occur for DNO nodes. Concerning the latter, that is a classical buffer in finished product form.

White inventory-element is the other plasticity provider, delivering the **meta-level freedom**. That is determined only in case of creative element what I will explain separately later.

Green inventory-element corresponds to order-size. The large number of make-to-order items (MTO, low-runners) may have a tolerance on partial pack size, when the production process is not so reliable, predictable to end up with the exact quantity, and the rework or scrapping would be too costly (e.g. foundry).

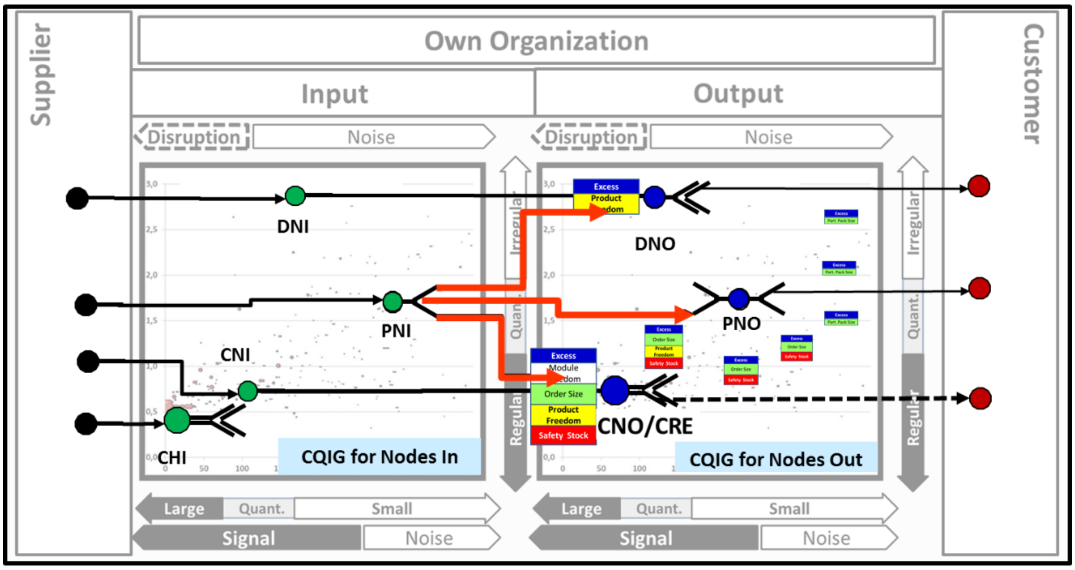


Figure 40. The distribution of the different inventory management modes in the CQIG

Those **colors** will play important role in **visualizing the emergent healthiness of the organization in space-time**. The bottom graph in Fig. 39 shows **the inventory profile** of each finished product items arranged in Pareto-ranking according to their weight in the organization's **demand profile**. As it is expected, the distribution of the different inventory management modes depends not only on Pareto-ranking. Further supporting the understanding, in Fig. 40 I visualized the distribution of the inventory management modes in CQIG as well.

6.1.4. The creative element motif and its parametrization in LSCN

As Csermely underlines, the creative elements are active centers in the network with free energy, which help in the survival of complex systems against unprecedented challenges [Csermely 2008, 2009; Fekete and Hartványi 2014; Fekete and Hartványi 2016b]. **The large cool finished product node (CNO) is the key node in the creative element motive of the organization.** With the creative element motif, **we do not focus on all common resources** of PNI type **node-by-node**, rather we **build plasticity in the strongly connected network skeleton**, what create alternative intensity in the PNI-DNO and PNI-CRE pathways, and keeping 'untouched' the PNI-PNO pathways. See the **motif** highlighted **with red arrows** in Fig. 40.

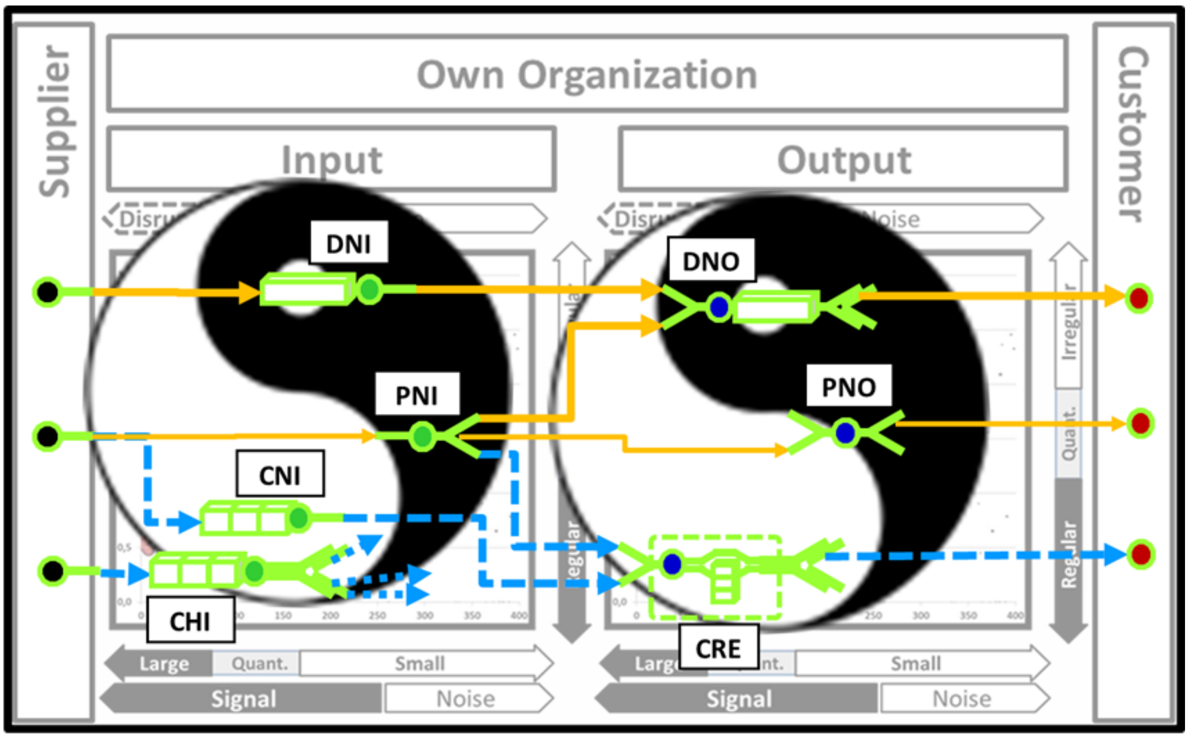


Figure 41. Creative element motif and other classical solutions create the optimal balance in links' strength and in synchronicity

The **demand signal of the disruptive finished products** (DNO) can easily **rearrange** and **intensify the relevant resource paths** to the relevant DNO, as the creative elements (CRE) can scarify their needs on commonly used resources (PNI), to the designed extent. See Fig. 41.

As the yin-yang-type symbols highlight in Fig. 41, we **keep the rigid behavior** and **execution** (orange arrows) in the **top-top-right segment of the CQIG's** (the reigns of disruption and noise), but **allowing node-level, partial plasticity** in the **top-left quarter** (reign of disruption, of DNO and DNI).

On the other hand, we **create plasticity and symmetrical weak-linkedness** (blue dashed arrows) in the reign of signals, i.e. in the **bottom-bottom-left segment of CQIG's**. We do it at least at node-level (RAG-Kanbans) and also at meta-level through CRE [Fekete and Hartványi 2015].

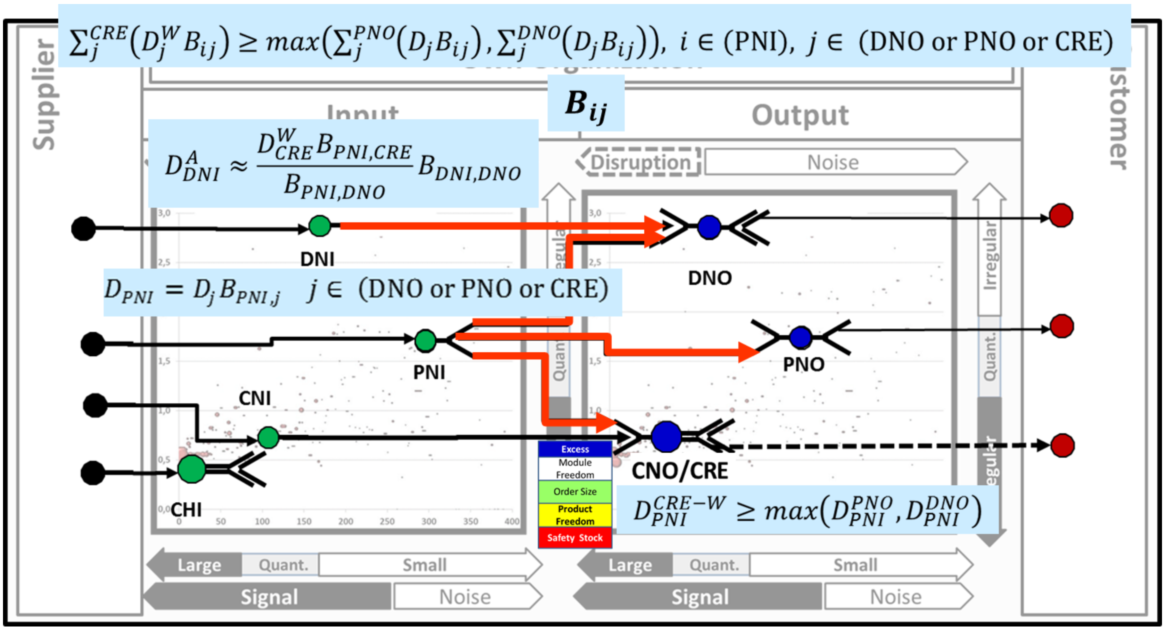


Figure 42. Calculating the specific inventory-elements of inventory management modes to node archetypes in the creative element motive. Equations from 6.1-1 till 6.1-4.

Fig. 42 visualizes the functions, how we can **calculate and align the different inter-dependent inventory-elements of the nodes forming the creative element motif**. Defining the meta-level **white inventory** of the CRE is specific. The affected resource quantity D_{PNI} of PNI can be calculated through relevant bill of material $B_{PNI,j}$ and the relevant finished product quantity D_j:

$$D_{PNI} = D_j B_{PNI,j} \quad j \in \text{ (DNO or PNO or CNO/CRE)} \qquad \textit{(Eq.6.1-1)}$$

We expect that **in PNI-equivalent** the white inventory of CRE (D_{PNI}^{CRE-W}) accumulates more or equal quantity than the targeted to-be-protected finished product quantity of PNO (D_{PNI}^{PNO}) or the planned to-be-dissipated perturbation quantity of DNO (D_{PNI}^{DNO}):

$$D_{PNI}^{CRE-W} \geq max(D_{PNI}^{PNO}, D_{PNI}^{DNO}) \qquad \textit{(Eq.6.1-2)}$$

In a cluster, we (may) have **more** DNO, PNO and CRE **nodes** – as it is seen also in the real-life case at the bottom of Fig. 39. Therefore, the equation is more complex:

$$\sum_j^{CRE}\left(D_j^W B_{ij}\right) \geq max\left(\sum_j^{PNO}\left(D_j B_{ij}\right), \sum_j^{DNO}\left(D_j B_{ij}\right)\right),\ i \in \text{(PNI)} \qquad \textit{(Eq.6.1-3)}$$

I.e. from the entire finished product population **j**, we take into account all the CRE, PNO and DNO type of nodes with all the relevant PNI type nodes. The right side of the above equation can be calculated easily, while on the left side we may **distribute** the **required white inventory** quantity among the CRE-nodes evenly, or pro-rata, or according to other consideration. Evidently, a sophisticated optimization could be also carried out. However, I follow more the Toyota approach of roughly right, since the healthy balance at the organization-level allows the projected inventory levels in a wide range – within the set frames. Consequently, it does not matter if we have some sub-optimality in the distribution of the white inventory quantities (see Section 3.1 about sub-optimality effect). It is seen in Fig. 39 that in **real-life** situation, the **white inventory** varies about 0.5-1.3 times of the R+A+G-inventories, which generates about **15-20% degenerative redundancy/plasticity** (not just flexibility) to the given cluster and/or **to the organization**.

I have already underlined that **DNI** must have also **node-level plasticity** (amber inventory-element) aligned to the magnitude of plasticity supplied by the white inventory of the CRE, otherwise the latter's plasticity will be killed by missing plasticity from the former, i.e.:

$$D_{DNI}^{A} \approx \frac{D_{CRE}^{W} B_{PNI,CRE}}{B_{PNI,DNO}} B_{DNI,DNO} \qquad \textit{(Eq.6.1-4)}$$

With the above solutions, we can protect the DNI- and PNI-type nodes against disruptions coming from the customers. We protect the input nodes (left CQIG of Fig. 41) against upstream perturbations with the classical methods [Vitasek et al 2003; Babiloni et al 2010; Logility 2010; Snyder and Shen 2011; Willems 2011, 2013, 2015; Dobos and Gelei 2015].

6.1.5. The stability landscape and the balance between plasticity and rigidity

Fig. 43 shows a **real-life example of the stability landscape** – a fragment of the planning board. The horizontal axis corresponds to **time** periods. The vertical corresponds to **network-space** and visualizes **two hierarchical levels**: of the clusters and of the items (the planned items were grouped in 3 clusters first, and within each cluster those items were Pareto-ranked). The third dimension is **the status of a finished product node**, i.e. is the relative status of its projected inventory vs its target specific levels (see also Fig. 39). The fourth emergent dimension is the **healthiness of the network** what is **derived from the overall spatiotemporal picture**.

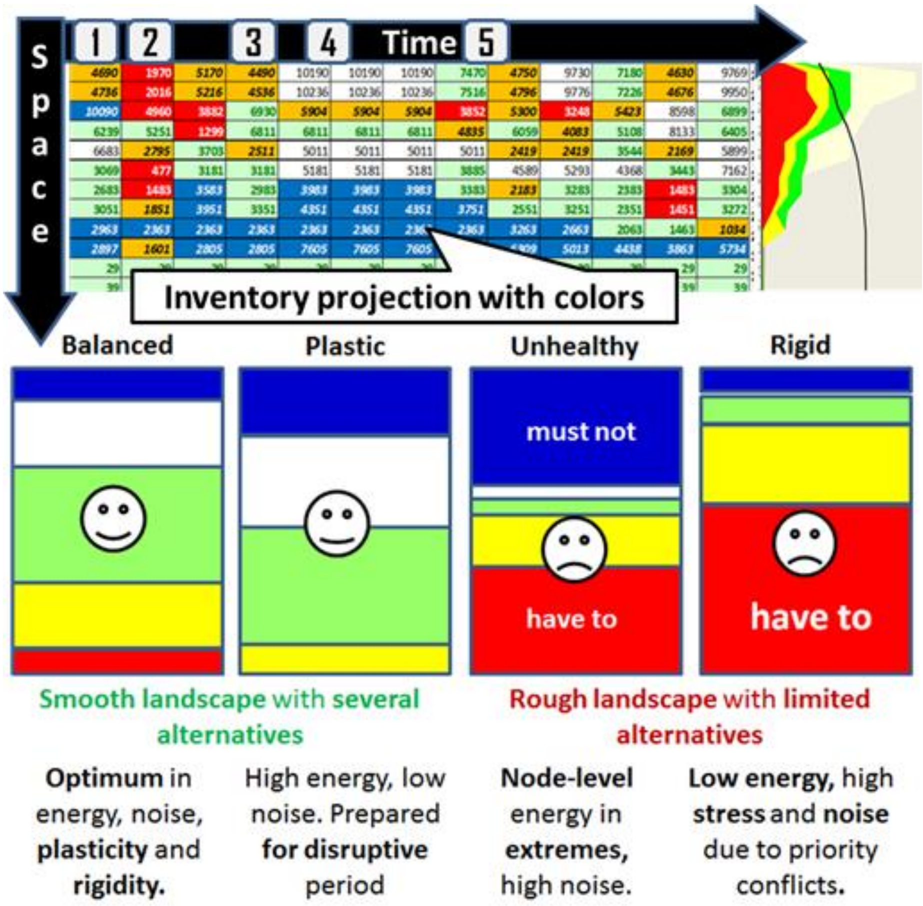


Figure 43. Three dimensions of the stability landscape and the emergent healthiness

In time point-1 of Fig. 43 the organization (bottom-network of DSN/LSCN) was in **balanced** state, but the longer than planned maintenance hindered the production, pushing the overall state to **rigid** (point-2). After recovering back to **balanced** state (point-3), the decision was made to develop the network to **plastic** state (point-4), since disruptive period (5) was expected due to factory stoppages at the customers and in own organization.

There are **simple rules in planning and execution**: **At scarcity** of resource(s) first all R, then A, then G if possible. While **in plethora** of resource(s) after R, A, and G we can consider execution of W. Especially, if scarcity of resources is expected or turbulent inventory projection is detected. Too blue is to be avoided. Try to **reach and maintain smooth landscape** (balanced or plastic).

Let us now investigate the **stability landscape of the organization** (network-element of LSCN) in wider context of Csermely, comparing Fig, 43 and Fig. 44.

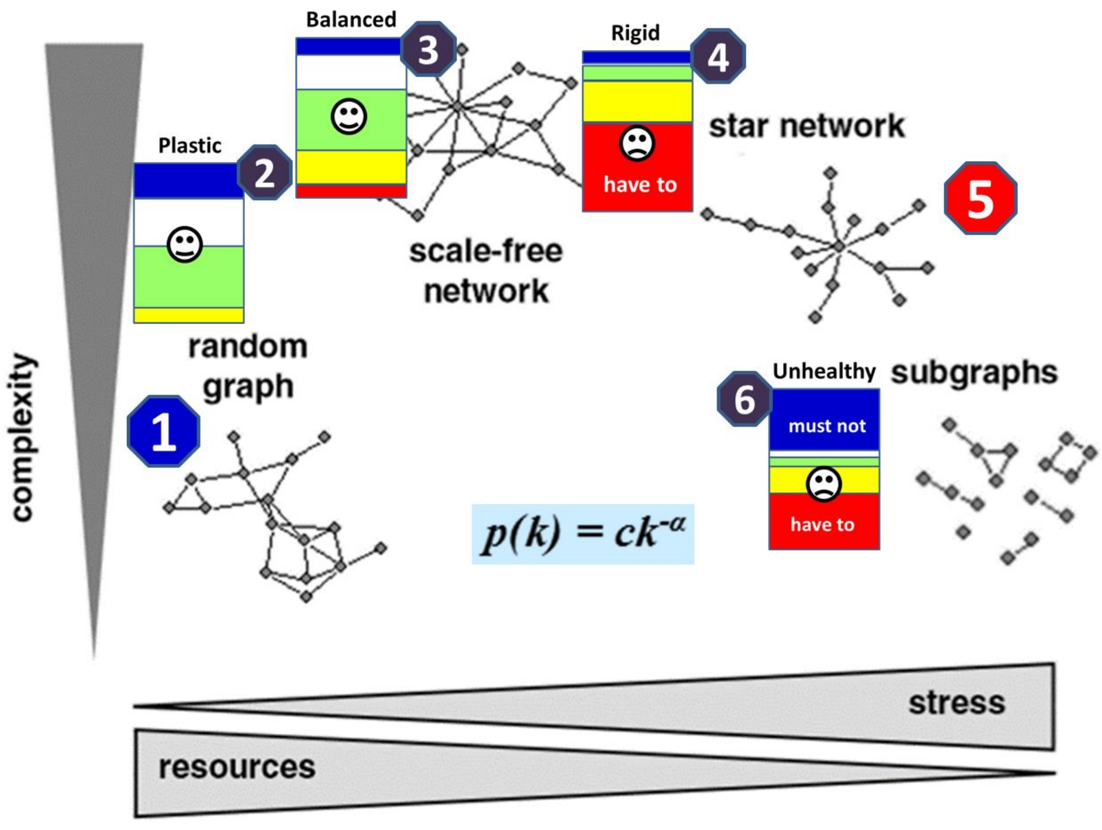


Figure 44. Stability landscape and topological phase transition in the LSCN at changing resource and stress levels (adjusted with kind permission of Csermely Péter) [Csermely 2009, p. 81]

If the overall picture is **blue** – general **overstocking**, then the **landscape** is **too smooth** and **unstable**. Nothing should be and anything could be produced, i.e. all links turn to equally weak (statistically). That is the **random graph topology** as the decisions have no priorities – ‘any random decision can be made’ (Fig. 44, case 1).

Our **plastic state** corresponds to intermediate network topology **between random graph and scale-free network** (Fig. 44, case 2). The well-balanced inventories on node-level and on meta-level – the **balanced state** corresponds to **scale-free** topology (Fig. 44, case 3). **Rigid state** corresponds to intermediate network topology of **scale-free network and star-net** (Fig. 44, case 4) – please see also the cumulative distribution of Fout nodes in Fig. 8 bottom graph.

When the overall picture tends to be **red**, then the accumulated energy is extremely low or depleted – **overstretched rigid state** (Fig. 44, case 5). Due to emerging frequent priority conflicts, the network is very noisy. The organization may/is forced to decide to produce only some of the products (e.g. the high runners) and temporarily neglecting others (e.g. the low runners) and/or deliver to a limited circle of customers. The topology moves to **star net** direction, as a large number of weak links towards finished products and customers will disappear for the time being.

The lack of prioritization at overstretched rigid state, or other wrong planning and execution decisions can lead to network **fragmentation**, where the items ‘live their own life’. That is the **unhealthy** state (Fig. 44, case 6). At extreme, the organization may fall apart – **the network dies**. See the near-death symptom described in Section 6.1.2.

Consequently, the stability landscape may be **smooth or rough**. Smooth landscapes offer several planning and execution alternatives, like the buffed energy landscapes of proteins smoothen the landscape with alternatives [Plotkin and Wolyne 2003]. The **more turbulent** the **overall demand pattern** is, the **rougher** the **landscape** will become (colors at the extremes). Therefore, we adjust/increase the inventory levels **to plastic state** before the rougher overall demand pattern arrives. On the other hand, when we face a **smoother overall demand pattern**, then we can lower the projected inventories keeping the alternative choices in balance and turning the network into **balanced state** at lower inventory/energy level.

6.2. Nested plasticity-rigidity cycles and degeneracy create adaptability and robustness

In a large organization of several thousands of employees we had to integrate 1-2 thousand newcomers within weeks. In the same time, the short product life cycles required 1-2 week-long ramp-ups and quick reallocation of the capacity in a magnitude of several hundreds of employees. We utilized the classical approach of keeping in the organization and reallocating the employees of higher value creation capability (e.g. fork-lift driver, SMT-operator), while for the simpler functions we hired from the street.

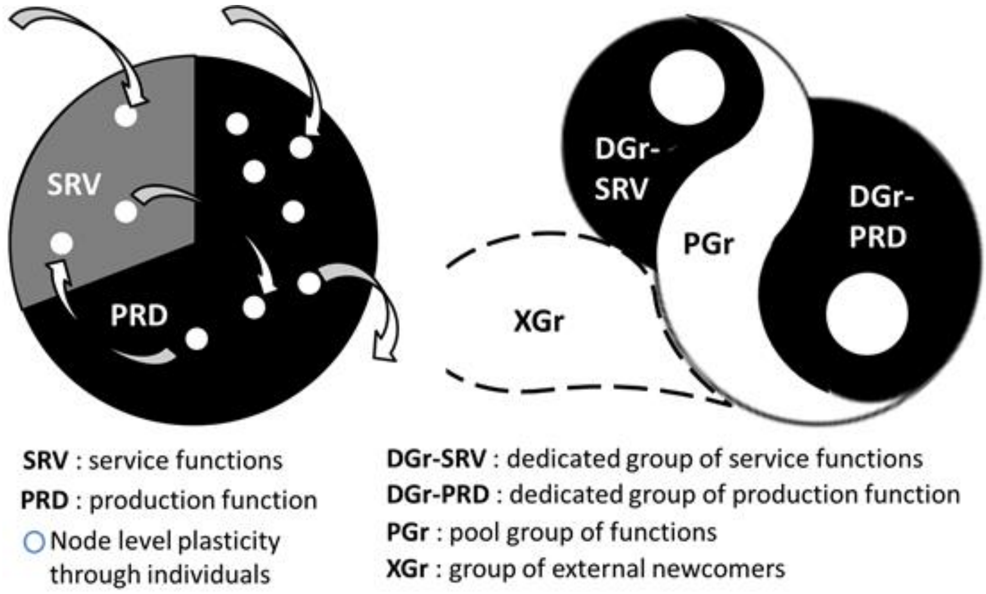


Figure 45. Plasticity through individuals (left) and through nested modules (right)

The newcomers joined **individually** a team, and were forced to catch-up quickly. That caused frictions between the newcomers and the 'old' workers. The frequent product portfolio changes, on the other hand, 'bombarded off' the old teams. As a consequence, we faced alienation, fragile quality and efficiency (Fig. 45, left).

6.2.1. Nested plasticity-rigidity cycles create robustness in the organization

In an expanding world and at increasing complexity our only escape is to redefine and **segregate a small-world for us**, otherwise we are lost and alienated [Csermely 2009, p. 13]. Dunbar highlighted the reasons, why we have very close tights/links only in small number of about 5 (family nucleus), and we can handle more-and-more relationships with weaker-and-weaker links – like approx. 15, 35, 80, and 150 respectively. The latest number corresponds to the ancient village size. **Stable teams** require **frequent interactions**, cyclical synergetic processes, like gossiping (vocal grooming), rituals, etc. – and these activities require also stable teams [Dunbar 1993].

Due to the complexity increase described above, and the targeted network stabilizing small-worldness, we had to **implement intermediate systems-hierarchical levels** in appropriate way. Therefore, the large population of the organization (network) was grouped into **four groups** (large network-module) **serving** either the **rigidity** (dedicated group of production and service functions) or the **plasticity** (newcomers and pool) **of the organization** (see Fig. 45, right). Please note that the two **rigid groups have also embedded plasticity** (white dot), what will be explained later.

When we zoom in the groups (large network-module) we can realize that their smaller network-modules (teams) and the building network-elements (employees) **contribute differently to plasticity or rigidity** – Fig. 46.

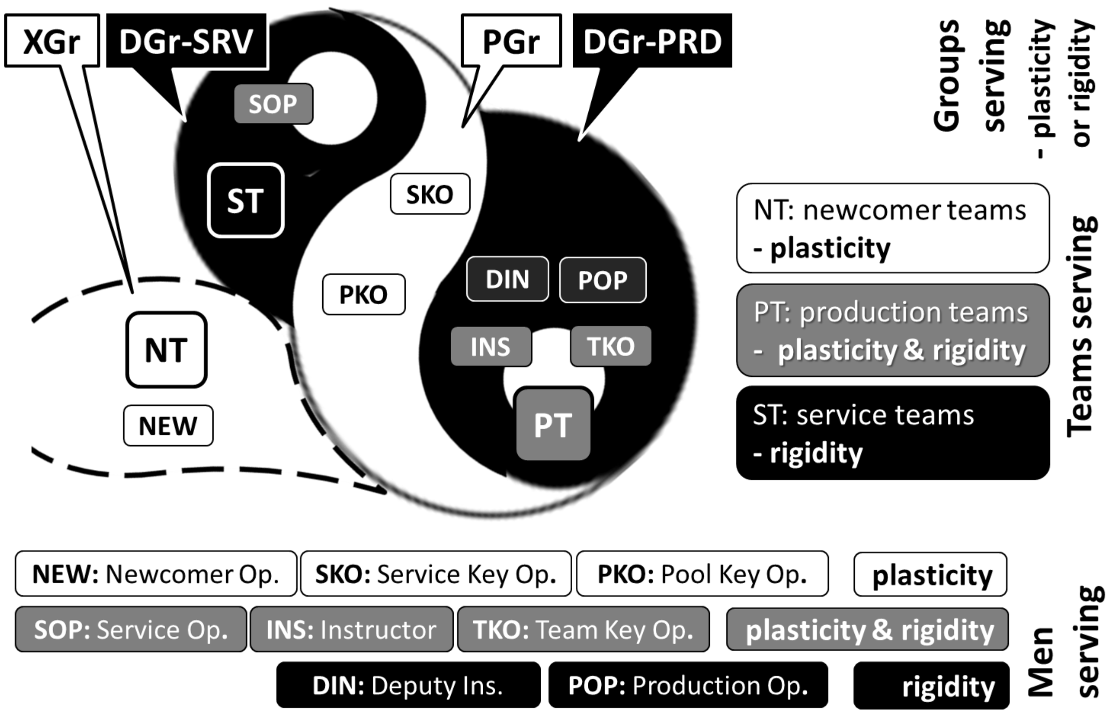


Figure 46. Plasticity-rigidity cycles at different hierarchical levels create the robustness of the large organization

Pool group (**PGr**) does not have teams. Its lower level is the **network-element** – i.e. the pool key operators (**PKO**) and the service key operators (**SKO**), who contribute to **plasticity** of the organization. The group of externals is other plasticity serving group (**XGr**) of the newcomers

(**NEW**) are **integrated into the organizations as team of newcomers** (**NT**), not as individuals – i.e. people of Dunbar-team-size start and work for several months together. So, both the **network-element-level and the network-module-levels** contribute to **plasticity**.

The **rigidity** supplying group of services (**DGr-SRV**) consist of network-modules (teams). Service teams (**ST**), like quality, logistics, test technician, maintenance, etc. are rigid and dedicated for 'years' (technology driven structures). The **embedded plasticity in the service group** (SGr) is delivered not by network-modules (ST) but **by the network-elements** (service operators: **SOP**), when they have to work as production operator (POP) during low season.

The **rigidity** supplying group of production (**DGr-PRD**) consist of network-modules (teams). The production operators (**POP**) in a team of about 20 people work together for several quarters under the leadership of an instructor (INS), but time-to-time as a team they have to learn new products and move to another product family. Therefore, the position of the **network-element** (team member) in the module (team - PT) is **quite rigid/dedicated**, but the **team itself contribute to plasticity and rigidity** of the organization. The instructor (**INS**) and the team key operator (**TKO**) **individually** contribute to the **organization's plasticity as well** through supporting a newcomer teams (NT) or an other production team (PT) when that team has to learn the product family of the helping TKO and INS.

Although in such **nested plastic-rigid half-cycles** the **actors of plastic** network segments and/or time segments (network-elements or modules) **sacrifice their stability-need and predictable-environment-need**, that sacrifice significantly differs from those self-destructive cooperation, what occur from bacteria up to human's heroism [Csermely et al 2008]. That limited fragment of the population who change its position frequently even prefers such dynamically changing working environment and – on top of that – such contribution was additionally rewarded.

6.2.2. Degeneracy (not just redundancy) stabilizes the organization

Both the specialist of **deep-narrow knowledgebase** and the generalist of **shallow-wide knowledgebase** correspond to simple **Lyapunov-stability landscapes** at individual level – rigid or plastic respectively. The knowledgebase of the cooperating individuals, on the other hand, form a **complex knowledge stability landscape** offering several alternative optima and more sophisticated, but quick adaptive response **at the organization level**, i.e. **system level**

emergent plasticity-rigidity. In Fig. 47 I show the **emerging degenerative redundancy** (network-elements of different knowledge structure are fulfilling the same function) following from the above described nested structure (modularity) and function (plasticity-rigidity).

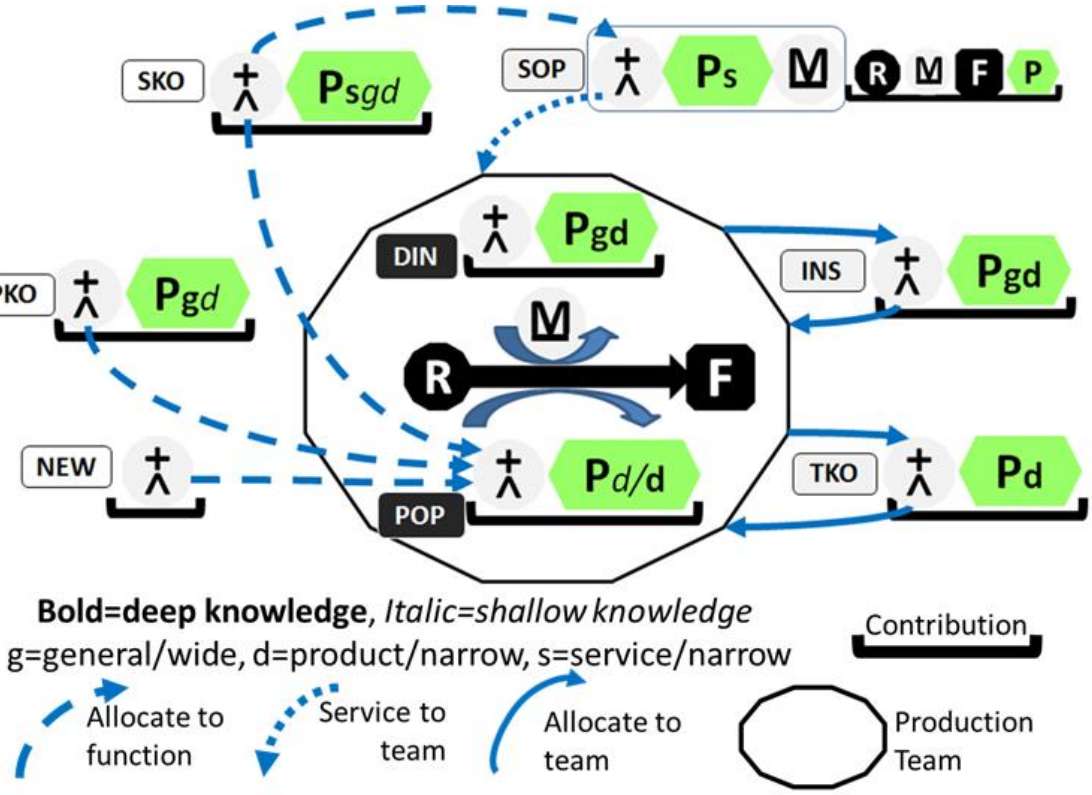


Figure 47. Degeneracy in the organization

The **plasticity serving network-elements** (SKO, PKO, NEW in Fig. 47) **are structurally different from POP network-element**, the function what they can also fulfill, e.g. the NEW has often no adequate knowledge at all, PKO has deep general process knowledge (**g**) and shallow product one (*d*). SKO has deep service knowledge (**s**), and only shallow general process and product knowledge (*gd*). That knowledge structure of SKO differs from both network-elements (SOP, POP) s/he can substitute. Those alternative contributions are visualized with dashed line arrows in Fig. 47. That **is the degeneracy by definition** – structurally different network-elements are functionally identical.

The '**structural holes**' in the required knowledge of a newcomer team (NT) or of a team learning a new product (PT) are filled in by supporting TKO and managed by INS, who have already that knowledge and are allocated temporarily to such learning team (full line arrows).

Some **remarks** about the solutions developed by me based on network science: Due to the limited size of the dissertation I have not covered the solutions to the other subnetworks of the organization (machine and material), nor important solution elements what created self-organized adaptiveness anticipating various perturbations of different spatiotemporal extent and magnitude – e.g. Service Kanban, Alarm Chain. For the sake of simplicity, I have not mentioned the team leader-led teams of about 100-130 colleagues, what covered a half a dozen of instructor-led teams, and produced a product cluster of few product families. Since the ‘atomic’ unit of the knowledge (capacity and capability) management was the instructor-led team, that simplification does not change the described dynamics fundamentally.

Please note that in classical approach we pay a colleague when s/he delivers the extra flexibility, and the **goal** is **full utilization** with probable alternative FTE-filling. In the **plasticity enabler approach** we pay for the plasticity capability all time. The built up nested structure, the simple clear game rules assure the quick autonomous adaptation. And since the system is so conditioned the **end-result is full utilization**. In other words, that is an investment with very strong return.

7. Conclusions and my theses

Here I have formulated my theses and the possible future investigation directions.

7.1. The model

In Sections 4 I have shown the link between well-known and widely utilized supply chain heuristics, laws and the network science interpretations to them. I proved the applicability of the network science approach in analyzing DSN/LSCN, by introducing important structural and functional characteristics based on large and diverse network science literature. By the end of Section 4, I could prove that the network science approach can deliver similar groundbreaking insights, and breakthroughs also in supply chain management as it did in other disciplines. In the same time, I have proved that the DSN/LSCN are also weighted, mainly directed, complex networks with nested structure, showing lots of similarities to other viable networks. The structure of LSCN is a kind of combination of the metabolic network, protein networks and a bit of the food-web (especially the trophic levels vs echelons). Therefore, I have defined the network-space dimensions in LSCN (longitudinal, transversal, hierarchical) what played crucial role in network analytical adaptations I have developed and presented in Section 5.

Thesis 1.
Using the **network science approach** and adapting the analytics, I have **built** the **mid-grained** and **fine-grained model** of the logistics supply chain network: the material conversion and transport process forms a weighted predominantly directed nested hierarchical network with overlapping modules of different subnetworks (of man, machine, and material). I have defined **four spatiotemporal dimensions in the logistics supply chain network**: 1. longitudinal (parallel to flow); 2. transversal (perpendicular to it – corresponding to echelons); 3. hierarchical ('vertical'); 4. time dimensions.

7.2. The analogies

I have brought several examples and evidences especially from biochemical, biological networks and other networks, and I have highlighted the analogies from supply chain management reign. Hopefully, the large number of graphs and figures could help the understanding. Special focus was dedicated to scale-freeness, small-worldness, weak-linkedness, nested modularity, optimization driven recursive modularization, perturbation and relaxation (Section 3 and Section 4). In separate sections I detailed the network-transport process and the analogies with material conversion and transport process of the LSCN, as well as the (demand)-signaling in general and of DSN (Section 3.5 and Section 4.5).

Thesis 2.
I have determined that the logistic supply chain networks have a **great number of structural and functional analogies** with metabolic and protein networks and partially with neural network and food webs. Those **structural analogies** are the scale-freeness, the small-worldness, the nestedness, and the analogous motifs. I have **proved functional analogies** in the following: the material conversion and transport process; the self-developing criticality at confined relaxation culminating into cascading failure; the optimum driven recursive modularization resulting in scale-free out-degree distribution, and is accountable for forming

value streams (longitudinal dimension) and echelons (transversal dimension) in the logistics supply chain network.

7.3. The differences

The man-made, man-induced networks are often full of strong links, with low tolerance, and high rigidity. Therefore, a particular attention was dedicated in my dissertation to plasticity-rigidity cycles and to degeneracy (especially in Section 3.6 and Section 4.7), i.e. to those mechanisms what significantly contribute to networks' robustness, resilience, adaptability and survival, and what are practically missing in the DSN/LSCN.

Thesis 3.
The degenerative redundancy (network **degeneracy**) and the **nested plasticity-rigidity cycles** in the viable networks substantially contributes to weak-linkedness and to the **exceptional resilience, adaptability and evolvability** of the viable networks. I have realized that those above structural and functional properties either are not detected or those are perceived as unfavorable (harmful) in the logistics supply chain network. I have determined that – knowing the network structure of the organization – **those differentiating properties can be adapted to the logistics supply chain network**.

7.4. The new methods

Both for CQIG method and for matrix analytical approach I have defined the ways of getting and transforming the demand data appropriate for generating further derivatives. For better traceability, I have visualized the complex relationship among those equations as well (Section 5.1.2 and Section 5.2.1).

The CQIG method (Section 5.1) can simultaneously visualize the functional and structural characteristics of the interacting nodes and delivers insights about perturbation patterns in the network of the organization. With the help of CQIG's of two adjacent echelons (of resources and of finished products) we can determine the few players of high importance – nodes of the seven archetypes and the relevant links. Those together build the organization's network skeleton, what in turn plays important role in cascading failure propagation and enables us to define the possible creative element motif structure.

Thesis 4.

I have developed the **combined quantity irregularity graph** (CQIG) method for exploring the networked structure of simpler organizations of non-hierarchical modular structure. The CQIG simultaneously **explores** the important **structural and functional/behavioral patterns** of the interacting network-elements and the relationship between them.

I have developed the matrix analytical approach as well (Section 5.2). Fundamental step was to define the adequate matrix representation of the organization's network, i.e. quadratic matrix of rectangular adjacency submatrices of the adjacent echelon-pairs. That matrix representation turned to be very effective in determining the characteristic values of the bottom network of DSN/LSCN. The matrix method is more powerful approach than of the CQIG with further development potentials. However, the CQIG method can already deliver simple, cheap solutions for small organizations.

Thesis 5.

For large hierarchical organizations of complex nested structure I have developed the **matrix analytical method** (LSCN-MM). The matrix model of an organization is a **quadratic upper-triangle strictly nil-potent matrix containing the rectangular adjacency matrices of the adjacent echelon-pairs**. My matrix model opens the pathway for modelling the cascading failure propagation in the discovered network structure of the organization with relevant derivatives of the time dependent demand data.

7.5. The innovative solutions

Finally, in Section 6 I have brought two examples how we can develop innovative solutions through understanding our organization's networked structure and adapting the lessons learnt: 1. developing smoothened stability landscape of the material-subnetwork, and the optimum between plasticity- and rigidity modes; 2. building nested plasticity-rigidity and degeneracy in the man-subnetwork. Those breakthrough solutions have proven the applicability of the network science approach and the link between the theory and practice in different industries, and served as empirical proofs as well.

Thesis 6.

I have **worked out and empirically proved** how we can create **weak-linkedness** in the material-subnetwork of the logistics supply chain network, and how can be **smoothen the stability landscape** of it. In the man-subnetwork of the logistics supply chain network I could build **nested plasticity-rigidity cycles** and **network degeneracy**. With those innovative solutions, I have increased the adaptability of the organizations and their resilience against the cascading failures.

7.6. Further possible directions of investigations

In Section 4.9 I have highlighted some pivotal supply chain and operations solutions putting them into a multi-dimensional space (Fig. 20). In the modern solutions, the deployment of graph theory is very common. I.e. an implicit network approach can be detected, though the network topology, the hierarchical nestedness, the degree distribution, or the links' strength are neglected (see Fig 48, right). I brought several examples, evidences on why Toyota is a complex network of high stability and evolvability. However, Toyota utilizes the network (science) approach coming from its Asian/Japanese culture, and that network knowledge is more of tacit origin/form (Section 4.8). There is an obvious structural hole in the solution landscape on explicit utilization of the network science approach, what has already delivered groundbreaking results and breakthroughs in several other disciplines

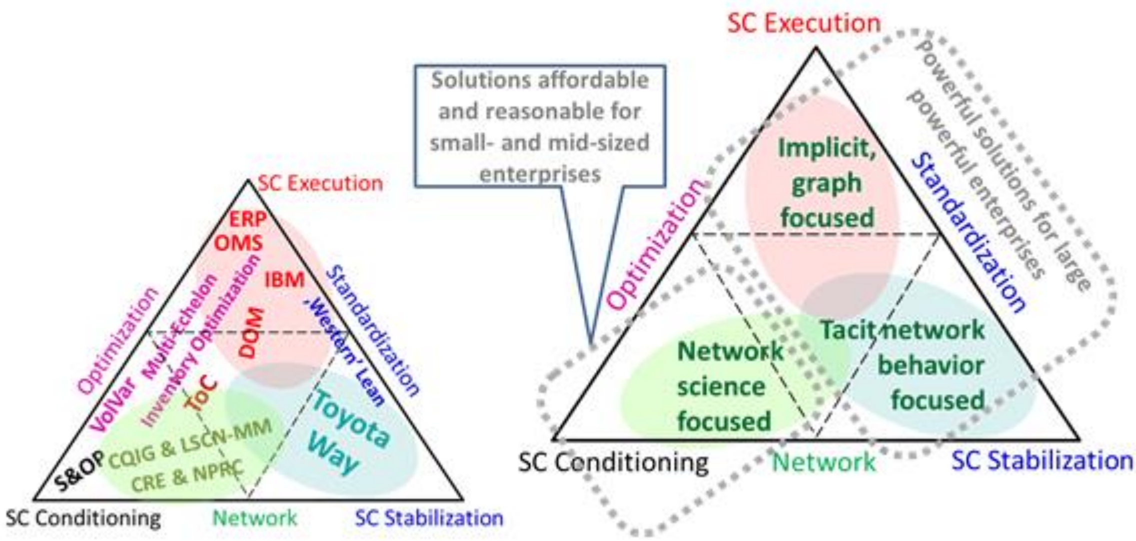


Figure 48. My network science approach and my innovative solutions (green ellipse) fill in a structural hole in the solution landscape, especially for small- and mid-sized enterprises

That hiatus is more striking in the mid- and fine-grained network representations, i.e. at the level of the organization, including its internal and external networked structure. I think, I have made the first steps to fill in that structural hole in the solution landscape.

Further possible directions of investigations:

1. Modelling the system's behavior based on real network structure with the factual time dependent data sets. That can explore the latent weaknesses in the factual networked structure. Great example is available from banking sector [Bardoscia et al 2016].
2. My matrix analyses of an organization of thousands of nodes in Excel or MatLab is cumbersome and very slow. Therefore, I see a big potential in developing more robust platform, enabling fast and standardized data analysis done by non-expert supply chain specialists.
3. Adapting the traffic forecasting and traffic assignment approach, where the basic load through nodes and links could be represented by the echelon-level normalized weights of matrices $\mathbf{W}(\mathbf{sr}), \mathbf{W}(\mathbf{rf})\ \mathbf{W}(\mathbf{fc})$, and by the vector matrices $\mathbf{M_C}(\mathbf{r}), \mathbf{M_C}(\mathbf{f})$ – supplied by Eq. 5.2-6 in Fig. 5 and by equations 5.2-15, 5.2-16, 5.2-17 in Fig. 8. When modeling the propagation of cascading failure in the organization, the meta-level irregularity of destabilized node is to be used $\mathbf{M_D}(\mathbf{r}), \mathbf{M_D}(\mathbf{f})$, since the links of the destabilized node turn to behave in strong transversal sync – Eq. 5.2-5 in Fig. 5 and equations 5.2-15, 5.2-18, 5.2-19 in Fig. 8.

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9. List of Figures

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