A FORMATION MODEL FOR SUPPLY NETWORKS:

A FUNDAMENT FOR INVESTIGATIONS OF COMPLEX SUPPLY NETWORKS

Research paper

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Abstract

Companies today are sourcing products from complex networks. Managing and overseeing these networks is challenging and requires methods including network theoretical considerations. Developing these methods demands an underlying model that describes the supply network structure and structural data, ideally representative samples. However, large-scale data of real supply network structures is rare, which restricts research in this field. This paper presents a formation model that generates supply networks from a focal company's perspective. By conducting this formation process, exemplary networks are derived and compared to the structural patterns revealed by rare studies investigating real supply networks. The generated networks close the gap of non-available empirical data of large-scale supply networks. The formation is based upon a widely accepted concept of supplier selection. Necessary input parameters are a structured bill of materials. Further details, like the number of competitors, are modelled using a probability distribution. This approach makes it possible for further research to investigate more advanced methods for supporting the management of supply processes. Additionally, using this framework for generating large-scale supply networks makes it possible to acquire a more detailed insight into supply network structure.

Keywords: Supply network, network structure, supply side, formations process, modelling supply network structure

1 Introduction

Supply disruptions can be very costly and even threaten the existence of the affected companies. This has become particularly apparent through events such as those at Ericsson (Norrman and Jansson, 2004) or the Great East Japan Earthquake (Fujimoto and Park, 2014). In this context, the commonly used term "supply chain" suggests that supply processes can be depicted using a linear model. However, a linear model does not reflect modern reality (Hearnshaw and Wilson, 2013). Modern supply chains form complex networks (Blackhurst et al., 2004). Emphasizing this, many researchers and practitioners are increasingly replacing the term "supply chain" with the term "supply network" (Braziotis et al., 2013).

This "networkization" of supply structures is challenging and supply processes have frequently struggled with this increasing complexity (Choi et al., 2001). Nevertheless, avoiding and mitigating the effects of supply disruptions are key components of a successfully operating company. That is why new methods are being developed to include network aspects into the management of supply processes

(Galaskiewicz, 2011). In an extensive literature review, Ivanov et al. (2017) revealed that minimal attention has been given to quantitative methods in the field of structural aspects such as resilience, stability and robustness.

In this context, the development of methods is especially challenging because network theoretical applications that work well in other fields are not easily transferable to the field of the supply side of supply networks. Compared to networks such as power grids or telecommunication networks, supply networks transmit many different kinds of flows, which means that not only energy of information is transmitted, but also many different kind of products. For example, even the breakdown of the supply of one small component can lead to a breakdown of the whole supply network if this one small component is not substitutable. Mitigating the effects of a disruption in a power grid, on the other hand, is far easier because it can often be bridged.

When developing methods applicable for supply networks, the underlying structure of the supply network needs to be utilized. However, data about large-scale supply network structures is rare, and the structural data presented in studies are limited to particular industries and mostly depict cut-outs of larger systems. Kito et al. (2014), Kim et al. (2011) presented structural investigations of cut-outs of automotive supply network. Orenstein (2016) and Sloane and O'Reilly (2013) presented cut-outs of supply network in retailing.

Other studies of network concepts in the supply context have used approaches that model networks. These approaches are transferred from other fields such as the preferential attachment model, as for example by Nair and Vidal (2011). However, these approaches do not provide network structures that are particularly usable for the supply side of supply networks and their particular characteristics.

To further enhance the development of such methods, especially with regard to supply processes, the present study provides a formation model for supply networks for the supply side, which includes the special characteristics of this particular group of networks. The formation model is conducted from the perspective of a focal company. The formation model is derived based on an analytical description of supply networks and a well-established description of the functioning of a supplier selection process.

This formation model serves as a fundament for developing new methods and for further investigations aimed at network effects in the supply network supply side context. Additionally, this formation model - as a basis - can help explain the effects that shape contemporary supply network structures. Deeper knowledge of the fundamental mechanisms of action is a key for further concepts.

The remainder of the paper is organized as follows. The second section introduces the theoretical background, before section 3 presents an analytical description of a supply network. In section 4, the approach principle is presented for modelling supply networks from a focal company's perspective. Section 5 compares an exemplary network, which is generated by the introduced algorithm with the few existing studies that have investigated larger real supply network structures. Section 6 summarizes and presents an outlook of the application of this algorithm.

2 Theoretical background

In order to produce and distribute a final good production, the service, transportation and storage processes are combined. Hence, a supply chain (or network) is broadly defined as a set of several partners that are connected, through their involvement in producing a final good, connected via flows of products, services or information (Mentzer et al., 2001).

On the supply side, the companies providing the components of the final product are called suppliers. It is common in supply chain management for a company's suppliers to be grouped into tiers. First-tier suppliers supply a company directly, second-tier suppliers supply first-tier suppliers, and so on. In the present study, non-first-tier suppliers are often pooled under the term "sub-supplier". Supply networks are often seen as systems that provides goods from raw material to a final product to a costumer. In this comprehensive perspective, the focal company divides the supply network into supply and demand sides.

Paper	Representation of vertices	Representation of edges	Consideration of different kind of material	Supply & Demand side	Origin of the structural data
Basole and Bellamy (2014)	Suppliers (companies)	Material delivery relations (unweighted and undirected)	No	Supply side	Modelled networks via standardized models such as preferential attachment
Craighead et al. (2007)	Suppliers (companies)	Business relations (unweighted and undirected)	No	Holistic: S&D	General topological concept
Dong (2006)	Suppliers (not specified if company or facility)	Material delivery relations (unweighted and undirected)	No	Supply side	Exemplary derived simple supply network
Hearnshaw and Wilson (2013)	Suppliers (companies)	Material flows, information flows, cash flows (unweighted)	No	Supply side	General topological concept
Kim et al. (2011)	Suppliers (companies)	Material delivery relations (unweighted and undirected)	No	Supply side	Real supply network data
Kim et al. (2015)	A physical location in a supply network (such as manufacturing facility, warehouse, retail store)	Edges represent material flows	No	Holistic: S&D	Exemplary derived simple supply network
Kito et al. (2014)	Suppliers (companies)	Material delivery relations (unweighted)	No	Supply side	Real supply network data
Lambert et al. (1998)	Suppliers (companies)	Business relations (unweighted and undirected)	No	Holistic: S&D	General topological concept
Mizgier (2017), Mizgier et al. (2013)	Supplier's facilities	Flow of material (weighted and directed)	Yes	Supply side	Exemplary derived multi-tier model of a supply network
Nair and Vidal (2011)	Warehouses/distribution centres	Material flows (unweighted)	No	Demand side	Modelled networks via standardized models such as preferential attachment
Nuss et al. (2016)	Suppliers (companies) and products	Material delivery relations and relations between companies and products	No	Supply side	Real supply network data
Orenstein (2016)	Suppliers (companies)	Material delivery relations (unweighted)	No	Supply side	Real supply network data
Simchi-Levi et al. (2015)	Supplier's facilities	Flow of material (kind of weighted and directed)	Yes	Supply side	Real supply network data, lacking in deeper tiers
Sloane and O'Reilly (2013)	Suppliers (companies)	Material delivery relations (unweighted and undirected)	No	Supply side	Real supply network data
Yan et al. (2015)	Suppliers (not specified if company or facility)	Flows of information and material, (unweighted and undirected)	No	Supply side	General topological concept

Table 1. Aggregation of studies aiming at supply network models.

The differentiation of the demand and supply sides is a fundamental one, because the network behaviour and characteristics between both sides differ dramatically. The main difference is the kind of product flows. For a classical production company, the demand side must distribute a final product. These flows of products between partners contain the same kind of product. In contrast, the flows of material on the supply side are different between the partners, because each partner transforms the flows in a unique way. This means that, in general, flows of material on the supply side represent completely different products. The disruption of one part, even if the volume is extremely small, can lead to disruption of the entire production. A model that describes this behaviour must distinguish between the different products.

Most of the literature builds on the fundamental models, in that components represent business units or companies and edges material flows (e.g. Hearnshaw and Wilson (2013), Sloane and O'Reilly (2013)). Moreover, other models interpret the components as production facilities (e.g. Mizgier et al. (2012)) or, in rare cases, as products (e.g. Nuss et al. (2016)). Nuss et al. (2016) analysed the solar industry and its suppliers by creating a product tree for solar module and, for every component, adding all companies that can offer the particular product.

Furthermore, there are also several separation of flows: material flows, information flows and financial flows (e.g. Lambert et al. (1998), Craighead et al. (2007), Hearnshaw and Wilson (2013)). Some models consider differences between the flows of material, meaning that different kinds of products are transmitted. Moreover, some models highlight the differentiation between the demand and supply sides. For a quantitative analysis of the supply side, the presently used models rarely model a supply side with the necessary complexity. However, especially in the area of disruptions and risk management, this is highly desirable.

For now, the academic literature does not contain studies that reveal large-scale topology of supply chain networks with detailed insights and structural information of these real supply network structures. As a consequence, studies of advanced methods such as cascading failure are limited to extremely simplified supply networks (Tang et al., 2016). Table 1 shows an aggregation of studies in this field.

3 Analytical modelling of supply networks

Summarizing the various models in the literature, supply networks consist of different kind of edges and vertices. A key point when realistically modelling supply networks is that the various kinds of interactions between the various kinds of entities needs to be depicted.

The supply chain structures depend heavily on the produced product and there are extreme structural differences of supply chain networks in different industries (Harland et al., 2001). Also, Graves and Willems (2005) highlighted the influence and importance of the produced products. For this reason, an analytical model of supply networks has to be extremely variable and must include the product structure. The following section lists and analytically describes, the different kind of components that supply networks consist of.

In general, networks can be analytical described as a pair $N = (V, E)$. V represents the set of vertices $V = \{V_i\}, i \in \mathbb{N}$ and E represents the set of edges $E \subseteq \{(u, v) | u, v \in V, u \neq v\} = \{E_m\}, m \in \mathbb{N}$, which connect the vertices.

The adjacency matrix A of a network summarizes all edges in a network. The entry a_{ij} of matrix A represents the connection between vertices i and j (Fournier, 2009). The entries are not limited to being binary. The weight of an edge represents its potential throughput or its importance. Because edges connect two vertices, the index of the edges can be transformed directly to a set of two indices representing the index of the vertices the edge is connecting. Edges can be directed or undirected, representing whether or not a flow has a direction.

Modelling supply networks, vertices represent different kind of partners, such as companies, products or production facilities. Consequently the set of vertices consists of the following subsets:

- $\boldsymbol{C} = \{C_j\}, j \in \mathbb{N}$, representing the companies and j_{max} the total number of companies in the network,
- $\boldsymbol{P} = \{P_k\}, k \in \mathbb{N}$, representing the products and k_{max} the total number of products,
- $\boldsymbol{F} = \{F_l\}, l \in \mathbb{N}$, representing the production facilities; that is, the locations where the products are transformed, and l_{max} the total number of facilities in the network, respectively.

This is summarized as: $\boldsymbol{V} = (C, P, F)$

It is necessary to differentiate between several kinds of vertices. As outlined explicitly later, the product combination processes, from raw material to the final good, are the backbone of a supply network. Without generating restriction, it is possible to differentiate between companies and their production facilities by introducing different kind of vertices.

The set of edges $\boldsymbol{E}$ also contains several subsets:

- $\boldsymbol{MF} = \{MF_{ll'}\} \subseteq \{(f, g) | f, g \in F, f \neq g\}$ represents the flows of materials between production facilities, which are typically directed.
- $\boldsymbol{MP} = \{MP_{kk'}\} \subseteq \{(p, q) | p, q \in P, p \neq q\}$ represents the flows of materials between products, which are typically directed.
- $\boldsymbol{MC} = \{MC_{jj'}\} \subseteq \{(c, d) | c, d \in C, c \neq d\}$ represents the flows of materials between companies, which are typically directed and represents the complement of CF.
- $\boldsymbol{CF} = \{CF_{jj'}\} \subseteq \{(c^*, d^*) | c^*, d^* \in C, c^* \neq d^*\}$ represents the flows of cash between the companies, which are typically directed.
- $\boldsymbol{IF} = \{IF_{ll'}\} \subseteq \{(i, j) | i, j \in F, i \neq j\}$ represents the flows of information between facilities, which are typically undirected.
- $\boldsymbol{BR} = \left\{BR_{jj'}\right\} \subseteq \{(c^r, d^r) | c^r, d^r \in C, c^r \neq d^r\}$ represents business relations, which can be broadly depicted as edges, too.

Furthermore, there are connections between the different subsets of companies:

- $\boldsymbol{CPc} = \{CP_{jk}\} \subseteq \{(c, p) | c \in C,\ p \in P, \}$ represents the relations between companies and products; that is, which company produces which product.
- $\boldsymbol{CFc} = \{CF_{jl}\} \subseteq \{(c, f) | c \in C,\ f \in F, \}$ represents the relations between companies and facilities; that is, which facility is run by which company.
- $\boldsymbol{PFc} = \{PF_{kl}\} \subseteq \{(p, f) | p \in P,\ f \in F, \}$ represents the relations between products and facilities; that is, which facility produces which product.

Additionally, each subset of vertices has a particular set of characteristics. Examples are the geographical location of a production facility or the financial situation of a company.

With no loss of generality, the characteristics of a vertex (independent from the subset) can be described as a vector:

- $\overrightarrow{char} = \sum_{m=1}^{max} char_m \cdot \overrightarrow{e_m}$

This analytical description provides a holistic and general way to describe a supply network. Models so far have focused only on a subset of edges and vertices; for example, edges represent business relations (transportation processes) and vertices represent facilities (e.g. Kim et al. (2015)).

Because these flows cannot be treated independently, there are different kinds of product flows between the companies (or facilities). This model depicts the interrelations between products, facilities and facilities and products; that is, the combination of the flows of material between the companies (or facilities) and products. Therefore, the effect of every company (or facility) towards the whole supply chain can be calculated (compare the analysis of Simchi-Levi et al. (2015)). It is worth mentioning that newer research in the field of supply network structure has highlighted their multi-level (Zuo and Kajikawa,

2017) or multi-layer nature (Gong et al., 2014). Distinguishing different kind of edges and vertices anticipates this.

4 Proposed model of a formation process

4.1 General formation process description

With the aim of developing a formation framework that provides detailed supply networks, we look at the process as it occurs in reality. Graves and Willems (2005) stated that material management organizations start to source a product's supply chain when it is finally developed.[1] Furthermore, they use a model in which for each stage (and source) there are several sourcing alternatives. The role of Materials Management Operations, according to Graves and Willems (2005), is to identify options that can satisfy the supply needs.

Consequently, the entire formation process can be summarized in the following sequence of decisions.

At the beginning there is the development of a product and willingness to produce it. The focal company runs a final production line in which components are combined together into a final product. These components are produced in a separate location (maybe near by the factory) by suppliers, whom again need components and so on. The origination process is sequential. The focal company, with its bill of materials, decides on each required material for which the supplier should deliver the good. This process continues until the raw material supplier is reached and the supply path ends.

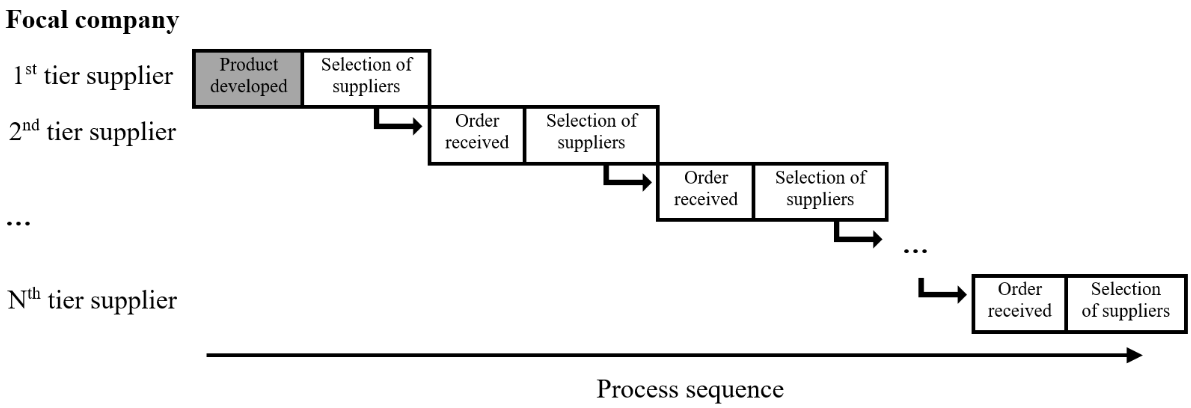

Figure 1. Supplier selection's process sequence.

This process states that a supply chain network is not planned centrally but is instead a result of sequential decisions of independent decision makers, although in some cases there might be several variations of this concept. The variation depends on the industrial background of a focal company. Because of this dependence, a supply network tends to be the result either of a central planning process or the result of sequentially executed decisions.

If the focal company is producing a product that requires only simple intermediate products, the network can be planned centrally. Examples can be found in the textile industry or in the direct further processing of raw materials (for example, a bakery). Such a supply network can easily be overseen and lacks the characteristics of complex networks. Consequently, this kind of network is not considered further in the present study.

[1] The product's functionality has already been determined at this point.

The more complex a product is, the higher the number of required products and the higher the complexity of the required products. For example, the number of suppliers a car manufacturer has is in the thousands (Choi and Hong, 2002). Such networks are not planned centrally. Depending on the market constellation, the final buyer can influence the structure a few tiers up.

4.2 Detailed description of the used algorithm

In this section, we present an algorithm that allows the creation of a supply network. Firstly, an environment is created and then, in a second step, particular networks are set up.

The basis of the supply network is a bill of materials, because the sourcing process starts when the product is finally developed and, thus, the components are defined. The bill of material forms a network that consists of $\boldsymbol{P}$, which represents the products, and $\boldsymbol{MP}$, which represents the flows of materials between these products. For each product P_k , a vector of characteristics $\overrightarrow{char}_{P_k}$ exists.

The final product is the sink vertex and the required raw materials are the source vertices. The intermediate products are the other vertices in between. This network, also known as a gozintograph, defines each product's predecessor in the production process. Each product is produced by a supplier. To depict this for each product vertex, a set of supplying companies must be defined, which is depicted by s_k. Therefore, function $ps\colon P_k \to s_k \; with \; s_k \in \mathbb{N}$ is defined. Input parameters that influence the number of potential suppliers are influenced by $\overrightarrow{char}_{P_k}$. This could be characteristics such as the product category (for example, in some industrial sectors more competitors produce the same products than in others).

Additionally, $\overrightarrow{char}_{S_k}$ can be defined. Characteristics can include the financial stability of companies. Depending on the purpose distribution, functions can be used for defining particular characteristics. This mapping is bijective, although a company can produce more than one good. To take this into account at the end, vertices of supplying companies are brought together.

This procedure defines the following subsets:

- $\boldsymbol{CPc}$, the relations between companies and products.
- $\boldsymbol{C}$, the set of companies.

In addition, production facilities, where the particular product is produced, are added for each company. This can be based on real data or can be modelled randomly.

The result is

- $\boldsymbol{F}$, which represents the production facilities.

This procedure leads to a bijective relationship , meaning each facility F_l is assigned to a company and a particular product. To avoid losing generality, we conduct a unification step at a later time that merges the vertices of facilities. The following are determined:

- $\boldsymbol{CFc}$, the relations between companies and facilities.
- $\boldsymbol{PFc}$, the relations between products and facilities.

In order to subsequently define the supply relations between companies within the product structure, a preferred partner must be defined. Function $sr\colon (C_k; P_i) \to \{(C_{k'}, P_{i'}), (C_{k''}, P_{i'}), \ldots\} \; with \; s_k \in \mathbb{N}$ defines a preferred order of potential supply relations. Thus, company C_k, which produces P_i, ranks its preferred partner for receiving product $P_{i'}$ among the set of companies that are producing product $P_{i'}$. For single sourcing, the first company is selected; for dual sourcing, the first and the second companies are selected, and so on. Function sr , which creates the ranking for each company, can be created by a randomization or an algorithm. The arguments of such a potential algorithm are the branch of the product or the geographical location of a company headquarter or production facilities.

Hereafter, the process of bringing vertices together is conducted. At this point, each facility and each supplier are limited to one product. To eradicate this, supplier vertices and facilities vertices are brought together.

This completes the environment in which supply networks are currently set up. To create supply networks, sourcing strategies must be added. Sourcing strategies, such as single-, dual- or multi-sourcing, can be set on a global base, meaning every company follows the same strategy. For example, one focal company dictates a specific strategy for its suppliers and all sub-suppliers. Furthermore, the distribution of production quantities between the production facilities of a company must be determined. Another aspect of the sourcing strategy is how multi-sourcing is organized if a company runs more than one facility. It can be that all incoming supplies are consolidated in a warehouse and then transported to the facilities, or there could be a direct delivery process from a supplier to a facility. For example in a dual-sourcing case with two facilities: one supplier delivers to one facility where as the other supplier delivers its goods to the other factory. This means a sourcing strategy contains information about how many suppliers are chosen for each product and how these supplies are distributed among the facilities of a company.

Given a sourcing strategy for each supplier, a supply network is created. The starting point is the focal company in its production facility. For each facility, the production quantity of the product is determined. Hereafter, depending on the sourcing strategy (which can vary from product to product) for each of the needed products (predecessors in the gozintograph), a set of suppliers is selected (one supplier or several suppliers). Depending on the sourcing strategy, the delivery scenario is determined. This continues until the end of the product tree is reached; that is, the source vertex, which represents a raw material that has no predecessors. All this results in:

- $\boldsymbol{MP}$, the flows of materials between products.
- $\boldsymbol{MC}$, the flows of materials between companies,
- $\boldsymbol{MF}$, the flows of materials between production facilities,

Furthermore, if prices of the products are added, the flows of cash $\boldsymbol{CF}$ follow the opposite direction of the flows of materials (between the companies):

The flows of information $\boldsymbol{IF}$ can be assumed to be parallel to the flows of products (between the companies and the facilities). Of course, for more efficient information transmission, additional edges can be added.

Conducting this formation process, networks are generated in which the different kind of flows of products can be investigated separately. This is enabled by the edges connect products with companies and facilities. Another important point is that the other kind of flows are integrated, such as the flows of information. All these points are necessary for developing comprehensive business processes that include more than one perspective of a network.

The exceptional benefit of this formation process is that realistic supply networks can be derived for a given product structure (gozintograph). As previously mentioned, the information of detailed large-scale supply relations are not available, but the information of product structures is available. Additional the industrial background information is available, too. In this formation model the particular information of particular industries is represented by the functions sr and pr or the vector of characteristics. Consequently for varying products from varying industrial backgrounds this formation process provides realistic supply network structures.

5 Instance generation, analysis and discussion

5.1 Instance generation

To test the provided formation process, example networks are derived and compared to existing studies in this field. We conduct the formation process without any merging process and focus on the company level, meaning that each company produces in only one facility. Because existing studies only reveal companies, the facility level is dropped in this comparison. As a basis, a product structure is defined; therefore, edges of a hierarchical tree structure are randomly added and deleted (approximately 25 per cent of the total number of edges). The basic hierarchical tree structure is inspired by the results of Choi and Hong (2002); the randomly added and deleted edges ensure that the structure has more complex interrelations than a pure hierarchical one. The resulting gozintograph is used as the basis for generating supply networks. Different sourcing strategies are tested: a pure sourcing strategy, a dual sourcing strategy and a mixed strategy.

Because the literature in this field provides either insights in supply networks with sizes in the order of hundred or thousand vertices, two kinds of networks are derived in the following part, one for each size. For both cases, the maximal number of supplier for one product is four. For the small variant, the pictures below show the product structure (figure 2) and the final network for the dual and mixed sourcing strategies (figure 3). In the mixed strategy, each supplier randomly chooses a sourcing strategy with a 20 per cent probability of a single sourcing strategy, 50 per cent chance of a dual, and 30 per cent probability of a triple sourcing strategy.

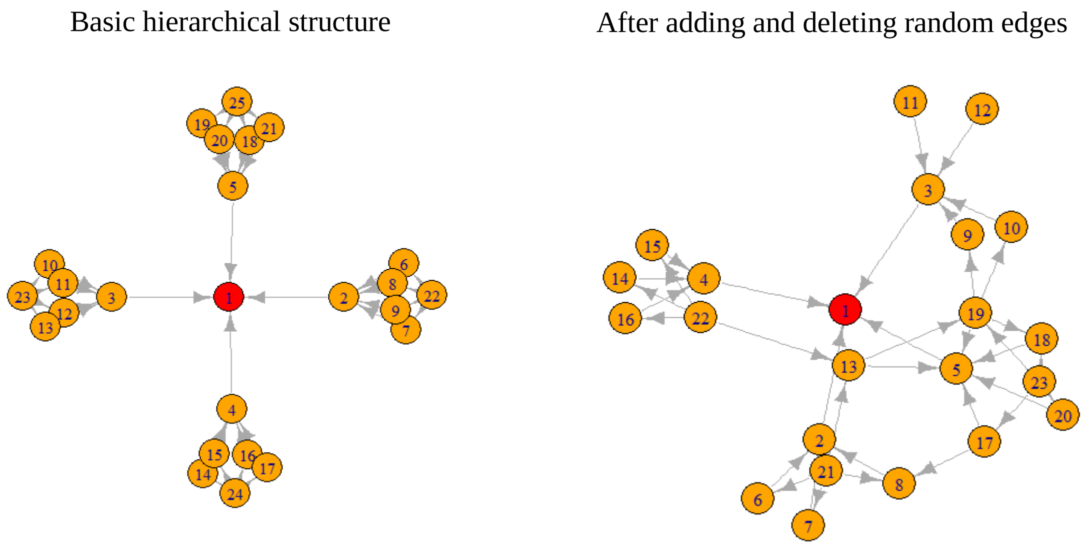

Figure 2. Product structure (gozintograph).

For the large variant, we use a hierarchical tree structure with 700 vertices as a basis. Twenty-two per cent of edges are randomly added. A mixed sourcing strategy has a 60 per cent probability of a single sourcing strategy, 30 per cent of a dual strategy and a 10 per cent chance of a triple sourcing strategy. Because of the large size of this network, a graphical depiction is clearly displayable and therefore left out.

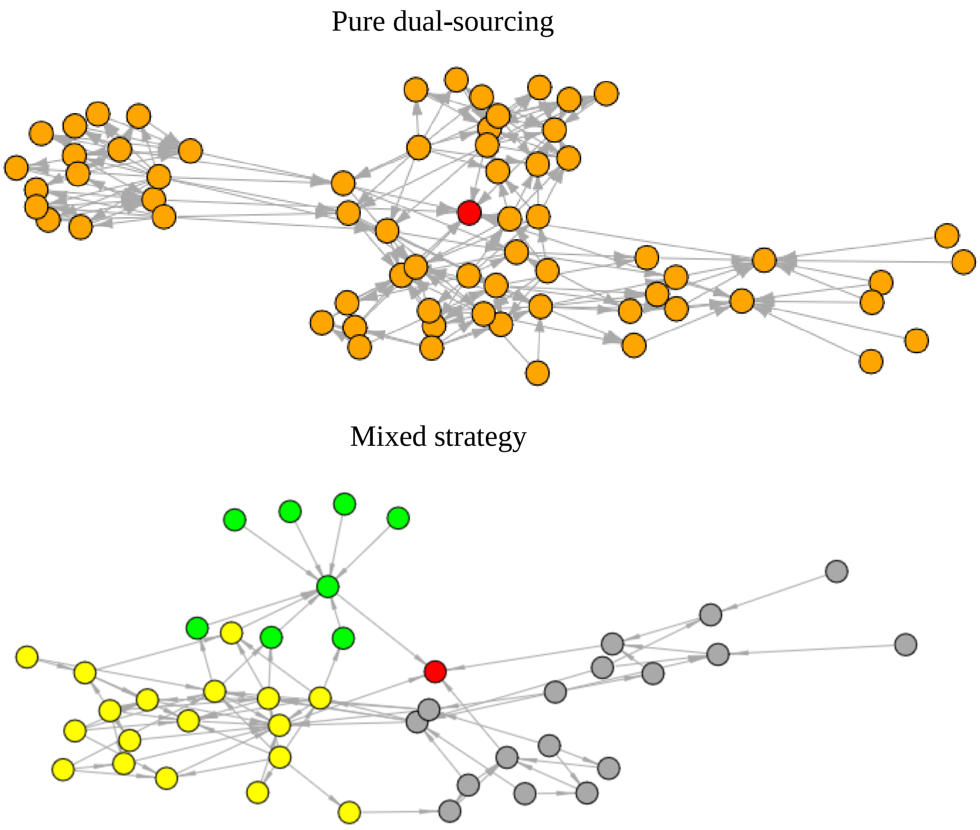

Figure 3. Final supply networks of a focal company (small).

5.2 Instance analysis and discussion

In the following part, we compare the structures of our example networks with studies presenting real supply networks in the academic literature. In doing so, we focus on three aspects. Firstly, we compare basic structural measures. Secondly, we check whether the networks show clustering behaviour, as introduced in Sloane and O'Reilly (2013) (here we focus on the small scenario). Thirdly, we compare the degree-distributions to existing data of real supply networks. Table 2 presents a part of the main network measures presented in Kim et al. (2011) and in Orenstein (2016).

	Kim et al. (2011)	Generated networks: "small"			Orenstein (2016)		Generated networks: "big"	
	Automo-tive	Single sourcing (initial)	Dual sourcing	Mixed sourcing	Food	Apparel & retail	Single sourcing (initial)	Mixed sourcing
Network size (companies)	27–34	23	60	65	1496–1769	1871–4036	700	1369
Network density	0.037–0.046	0.070	0.032	0.039	~0.002	~0.001	~0.001	~0.001
Average (in) degree	3.654–4.630	1.609	2.554	2.330	2.594–2.862	1.845–2.751	1.226	2.610

Table 2. Network measures: A comparison between values from literature and exemplary networks.

We have chosen measures that are available in all the studies. Due to different aims in the studies, a varying set of measures is presented in each study. The network size is the number of vertices. The network density is the ratio of existing edges through the number of potential edges. The degree of a vertex is the number of edges to other vertices. Subsequently the average degree is the average of the latter. All these three measures are used (among others) for the characterization of network structures. It is obvious that the measures are driven by the size of the network. That is why we present two kind of samples.

It is visible that most structural measures fit well. Nevertheless, when comparing the initial gozintograph network with the modelled supply network, the formation model shapes the network in the right direction. This becomes apparent by comparing the initial graphs (pure single sourcing) with the generated networks (mixed or dual strategy).

Similar to Sloane and O'Reilly (2013), our example networks for the "mixed strategy" deliver the same results conducting a clustering investigation; that is, a clear structuring. Conducting a clustering algorithm (edge-betweenness), in this example (mixed strategy for the small case) three subgroups can be identified (marked as green, grey and yellow in the above figure). Our example shows clustering effects that originate in mutual dependencies between suppliers. For the pure dual-sourcing such a clear structuring into clusters is not observed.

In their qualitative study, Hearnshaw and Wilson (2013) state that supply networks should show a fit-gets fitter mechanism. Such a mechanism is apparent in the degree distribution by a strong decrease of the density of vertices with a higher degree. A widespread method depicting this is to plot the cumulative degree distribution. In such a plot the cumulative density on the y-axis is scaled logarithmically. The scaling of the x-axis depends on the distribution pattern. Kito et al. (2014) found that the best fits to their data of the degree distribution are provided by an exponential distribution or a log-normal distribution. This corresponds with the results of the generated networks. Figure 4 presents the cumulative degree distribution for two generated networks. Both networks are generated using the described "mixed strategy". One network represents the small network and the other the big network (compare table 2). Surely the presented example networks show the predicted fit-get fitter mechanism as proposed by Hearnshaw and Wilson (2013). The red lines represent a logarithmic regression line, which indicates an exponential distribution, as proposed by Kito et al. (2014).

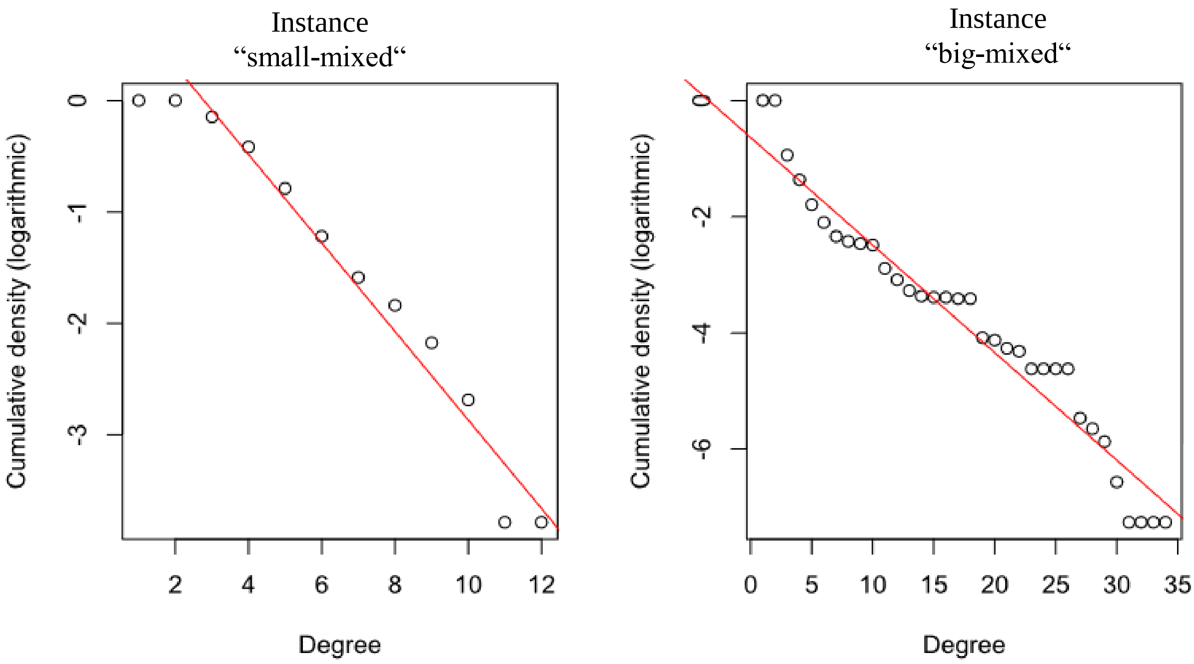

Figure 4. Cumulative degree distribution for the created networks.

All of the considered aspects show that the presented formation model generates supply networks with structural characteristics similar to existing real supply networks.

A limiting factor remains the fact that the number of networks for comparing the network structure is low. Hence, further research can potentially reveal necessary minor adjustments to the described formation model. It should be emphasized that the backbone of formation process, and conseuqently the network structure, is the gozintograph and the market structure, i.e. the number of firms offering the particular product. For the presented study, the gozintograph is a input factor whose basis is designed manually. An extension of the presented model could include a gozintograph formation process. On this basis, dynamic aspects, such as the development of the supply network over time, could also be included; this would broaden the fields of application of this model enourmously. Although the structure of the gozintograph of products and the market structure of components are much more easily researchable than a particular supply network structure, there has not been a lot of research regarding this topic (an exception is Nuss et al. (2016)). On that account, additional research investigating the structure of gozintographs is required. In the meantime, for the analysis of particular industries and static analysis, the presented model offers a good way of modelling realistic supply networks.

6 Conclusion and outlook

Due to the developments of globalization, digitisation and increasing product complexity, supply networks are becoming increasingly complex (Harland et al., 2003). Managing supply networks efficiently and effectively is an important and urgent challenge; this is mainly because ineffective processes often threaten the existence of companies or are very expensive. Because of this the field of supply process management needs new methods. Methods that consider network aspects. To develop the methods, it is necessary to have realistic large scale sample networks, as well as a deep understanding and knowledge of the underlying supply network structures. To achieve this, concepts of formation of supply networks are valuable. In particular, data of large-scale network structure is not available in the quantity that academic research requires. By using a formation model, such as the proposed one in this study, a large variety of different supply network structures can be derived. It is important to consider that the structural character of supply networks varies widely and depends on several external characteristics. As a result, the proposed formation model can derive, by variation of the external characteristics (in this case, mainly the sourcing strategy and the product structure, given by the gozintograph) a large variety of different supply network structures. Hence, the proposed formation model fits the needs of academic researchers.

With a view to creating realistic large-scale supply networks, this study has presented a formation model that generates supply networks with structural patterns as they are identified in real supply networks, as shown in section 5.

Modelling the formation processes of supply networks is challenging due to the special characteristics of supply networks. Concepts from other fields such as the preferential attachment model do not depict the characteristics supply networks must have. It is important that supply networks contain different kind of flows and vertices. The particular characteristics of supply networks are a result of the interrelations between these different kinds of entities. This becomes particularly apparent in the field of supply disruptions. Here, the different kind of materials that are transmitted within the supply network must be considered. Consequently, this study provides, as its basis, an analytical description of the various entities that supply networks consist of.

The advantage of this approach of a formation model is that for a given product structure realistic supply networks can be derived. The supply networks are largely unknown, whereas the product structure and its industrial background are known.

The presented formation process enables researchers to generate large-scale supply networks. Consequently new methods do not need to stay on a methodological level. Such methods can be simulative approaches (using petri nets as presented in Fridgen et al. (2012)) or system dynamics concepts (e.g. discussed in Schieritz and Grobler (2003)). Such concepts aim – among other things – to investigate cascading failures (e.g. Zeng and Xiao (2014), Han and Shin (2016)), which derive a fundament for dynamic reactions against disruptions. Another kind of approach represents the use of structural measures such as centrality measures (as presented by Mizgier et al. (2013) or Yan et al. (2015)). Using an exemplatory supply network consisting of six suppliers, Mizgier et al. (2013) identified correlations between centrality measures of nodes and the consequences of disrutpions at the same nodes. This field of research in partiuclar can instantly benefit from using the aproach presented in the present study.

Another aspect is that, by extending the model by additional information flows that are not restricted to the flow of material, this network modelling approach can lay the basis for inter-enterprise information management research and consequently improve supply chain management information systems, in particular.

Finally, modelling these networks and comparing them to real-world cases, this framework will support the process to understand the parameters shaping the structure of supply networks and the time effects, which have not previously been in academic focus. Understanding these parameters is the fundament for successfully developing more effective and more efficient process management methods in the field of complex supply networks.

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