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**Implications of the supply chain structure
for the shock transmission within the chain**

A summary of the doctoral dissertation written under
the supervision of Associate Professor Bogumił Kamiński, PhD

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1. Introduction

The doctoral dissertation aims to assess the extent to which the characteristics of the supply chain, including the structure of connections between suppliers and customers, influence its resilience to shocks. As the degree of specialization in production is growing, connections between companies tend to play an increasingly prominent role in the economy, cf. Levine (2012). Mizgier, Wagner, and Jüttner (2015) indicate that fiercer competition, growing customer needs, accelerated globalization of markets and rapidly developing technology, have resulted in massive pressure on almost all industries to make not only intra-firm but also interfirm business processes more efficient. This in turn leads firms to outsource manufacturing and research and development (R&D) activities, source in low-cost countries, reduce inventories and slack, streamline the supply base and collaborate more intensively with other members of the supply chain.

However, there are following consequences of using the abovementioned actions as tools for the optimization of the production process. The network of connections between companies tends to grow in both density and intensity. This in turn leads to shocks affecting a single firm being transmitted to other network participants and even, in specific circumstances, having an impact on the state of the economy as a whole, cf. Gabaix (2011). Coluzzi, Ghil, Hallegatte, and Weisbuch (2010) confirm the occurrence of the cascade effects generated by exogenous events. They might be either positive, as in the case of new orders from the market, or negative – as in the case of the financial crisis, random local strikes affecting production, or natural disasters. Among the events that may disrupt the smooth functioning of the supply chain Kleindorfer and Saad (2005) distinguish the following issues: (1) operational risks (equipment malfunctions, unforeseen discontinuities in supply, human-centred issues from strikes to fraud), (2) risks arising from natural hazards (e.g. hurricanes, earthquakes, heavy rainfall, cf. Webb, Tierney and Dahlhamer, 2002), (3) terrorism and political instability. At the same time, Carvalho, Nirei, Saito, and Tahbaz-Salehi (2017) indicate that due to the key role of intermediate goods in the production process, disruptions to the orderly flow of goods and services have been increasingly recognized by policymakers as a source of aggregate risk, see also World Economic Forum (2012), European Commission (2013) and White House (2012).

In the dissertation several characteristics of the supply chain structure were scrutinized in terms of their influence on the supply chain's resilience to disruption risk. Three main reasons justify the need for thorough deliberation of the problem brought up in the study. Firstly, a detailed theoretical explanation of the transmission mechanism of shocks in supply chains may result in a better understanding of empirical observations. Secondly, enhancements of the model presented in the dissertation represent contribution to the theoretical literature on supply chain modelling. Thirdly, a thorough study of the shock transmission mechanism in supply chains may lead to a better understanding of the implications of idiosyncratic shocks at the micro level for the functioning of the economy as a whole.

The subject of the dissertation directly refers to research gaps identified in the literature on supply chain risk management. Snyder et al. (2016) indicate that the functioning of complex production networks in the face of the disruption risk is an area that requires further research. The authors claim that there is a need for new models that would improve the understanding of how disruptions propagate and how to mitigate disruptions in multi-echelon systems.

2. Research goal and hypotheses

The fundamental goal of the study is the verification of the relationship between selected characteristics defining the structure of the supply chain and the resilience of single companies and the network as a whole to shocks causing disruptions in the process of production.

Taking into account the abovementioned goal, the following definition of the shock was assumed in the dissertation. In line with Snyder et al. (2016), shocks (or disruptions) are random events that cause a company, which is part of the supply chain, to stop functioning for a certain amount of time. In case of such an event, the company fails to deliver contracted orders to its customers.

Realization of the abovementioned research goal was accomplished by verifying the following four hypotheses:

- Hypothesis 1. The relationship between the number of suppliers and customers of a company and the risk of its bankruptcy is non-monotonic.

- Hypothesis 2. If production on selected stages of the supply chain is provided only by relatively few companies, the disruption risk in the network as a whole would be relatively low.
- Hypothesis 3. The efficiency of risk mitigation strategy based on splitting orders and sales between multiple suppliers and customers depends on the geographic diversification of business partners.
- Hypothesis 4. The impact which shocks affecting particular companies in the supply chain have on the performance of the network as a whole depends on the distribution of these shocks among different stages of the chain.

In terms of the first hypothesis, the literature on supply chain risk management (including the articles focused on managing disruption risk) suggests placing orders from multiple suppliers simultaneously as one of the risk mitigation strategies, cf. Tang (2006). Snyder et al. (2016) explained that there are three following questions to be answered in order to apply the multiple sourcing strategy: (1) how many suppliers to choose, (2) which supplier to choose, and (3) how to split orders among selected suppliers. Sheffi (2001) confirmed the usefulness of this mitigation strategy in the case of disruption risk. Tang (2006) refers to the empirical study of Shin, Collier, and Wilson (2000), to claim that dual or multiple sourcing is a common business practice.

On the other hand, some companies choose to rely on a long-term relationship with a limited number of suppliers. Based on the study of Japanese-style business partnership, Dyer and Ouchi (1993) recommend limiting the number of direct suppliers to reduce costs and increase quality through greater economies of scale and less variation in inputs, see also Dyer (1996).

The issues of choosing the optimal number of suppliers and indicating the preferred character of these relationships (long- versus short-term relationships) have been the subject of numerous studies. There was no universal conclusion and the results tend to depend on specific assumptions, see e.g. Cohen and Agrawal (1999), Yu, Zeng and Zhao (2009), Namdar, Li, Sawhney, and Pradhan (2018), Berger, Gerstenfeld, and Zeng (2004), Ruiz-Torres and Mahmoodi (2007) and Meena, Sarmah and Sarkar (2011). Moreover, the studies published so far, have generally been focused on supporting the decision-making process in a single company, while implications of the shock for the performance of the network as a whole have not been comprehensively addressed.

Battiston et al. (2007), whose model has served as a starting point for the simulation tool developed and used in this dissertation, do not formally test the relationship between the number of connections the company has with its suppliers and customers and its risk of bankruptcy. They only claim that within the scope of the decision-making scenarios investigated in their paper firms would benefit from a high connectivity degree. For low connectivity degrees the shape of the relationship between the number of connections and the risk of bankruptcy is, however, less clear. It shall not be *a priori* ruled out that initially an increase in the number of business partners would translate into a higher risk of bankruptcy. From the theoretical point of view, a self-sufficient company that sells its whole production directly to the consumer market (i.e. one which does not rely on any supplier, nor any business customer), would be immune to shocks transmitted via the supply chain. On the other hand, for a sufficiently high number of suppliers and customers, a further increase in connectivity may help reduce the firm's bankruptcy risk, as the positive effects of diversification would limit the impact of the shock affecting one of the firm's business partners. Based on the results of a simulation model of interbank linkages, Nier et al. (2007) suggested the non-monotonic relationship between the extent of network connectivity and the resilience of the banking system. However, the structure of connections in the banking sector, as studied by Nier et al. (2007), differs from the one observed in supply chain networks, and therefore it is not clear the results obtained for the interbank network automatically apply to other network settings. According to the author's best knowledge, the relationship between the level of connectivity in the supply chain and the network resilience and bankruptcy risk of particular companies has not been thoroughly addressed in the literature of multi-echelon supply chain networks. The results presented in the dissertation are aimed to contribute to this field of study.

In terms of the second hypothesis, in case of a relatively limited number of firms functioning on one of the stages of the supply chain there is an interplay of two opposing effects, the result of which is not clear. On one hand, the smaller the number of firms, the more diversified would be their portfolio of business partners (as many suppliers and customers would be interested in the products or services they offer) and – therefore – the higher their resilience to shocks affecting any other company in the supply chain. On the other hand, if one of these relatively few companies was directly hit by an exogenous shock and bankrupted, the impact of this bankruptcy across the supply chain could be relatively

high due to the systemic importance of the company. Therefore, there are two dimensions: the first is related to the probability of bankruptcy of the company, and the second relates to the scale of systemic consequences in the event of its occurrence.

As a starting point for the verification of the third hypothesis served the assumption made in part of the literature that supply chain disruption risk might be addressed and mitigated by increasing the number of business partners, cf. Tang (2006). The effectiveness of the abovementioned approach depends, however, on the proper selection of suppliers. The issues of supplier selection criteria, the method applied in the selection process and their impact on the performance of the company have been the subject of numerous studies, see e.g. De Boer, Labro and Morlacchi (2001), Vonderembse and Tracey (1999), Wilson (1994) and Chang, Chang and Wu (2011). In general, selection criteria considered so far have been focused mostly on the specific features of the supplier and the details of their offer (e.g. price, quality, delivery time, delivery reliability), while the network effects and geographical diversification of suppliers have not received much attention so far. In this context Masih-Tehrani, Xu, Kumara, and Li (2011) suggest, however, that the dependence nature of disruptions and its impact on supply chain performance should be taken into account. They claim that if a company ignores the effect of dependent disruptions, then in the multi-source structure, it could negatively affect the performance of the firm. Wagner, Bode, and Koziol (2009) suggest – based on empirical data from automotive suppliers – that default dependencies among suppliers do often exist and can have significant consequences. One of the implications of this observation is that a disruption risk mitigation strategy based on the diversification of suppliers without due consideration of dependencies between them might not prove sufficient to translate into the company's resilience to the bankruptcy of one of its suppliers. A company with a diversified portfolio of suppliers may still be prone to significant risk stemming from the bankruptcy of its business partners if the dependencies between individual suppliers are strong enough. Concerning the abovementioned issues, the dissertation aims to assess the relationship between the resilience of the supply chain and the geographical diversification of business partners in the network. On one hand, the selection of geographically close business partners may limit the firm's exposure to shocks originated in distant parts of the network. On the other hand, in case of a shock spreading in the direct proximity of a firm, interconnections between business partners could diminish

(or cancel) the expected diversification effects if geographical dispersion of suppliers and customers was not duly taken into account.

In terms of the fourth hypothesis, Luo (2015) studied the shock transmission mechanism in supply chains, indicating that interconnected production and financial linkages lead to the propagation of financial shocks both upstream and downstream. Based on the input-output matrix and the bond yield data in the U.S. she concludes that the upstream propagation of financial shocks is stronger than downstream propagation. The aim of this dissertation in terms of the fourth hypothesis is to investigate the relationship between the performance of the supply chain network after the occurrence of shocks that disrupt the production of selected companies and the distribution of these initial shocks in the network.

3. Research method

The selection of the research method for the purpose of the dissertation was based on the review of the literature related to the modelling of supply chain networks. The review allowed for the selection of a general model to be used as a starting point for further research. The base model was then further developed and calibrated to empirical data in order to use it as a tool for the verification of research hypotheses.

The process of selection of the analytical tool was guided by several requirements to ensure its usefulness for the dissertation. Based on research hypotheses, the method should be capable of providing insight into following research issues: (1) the relationship between the number of suppliers and customers of a company and the risk of its bankruptcy; (2) the network implications of a situation in which production on one of the stages of a supply chain is provided by relatively scarce number of firms; (3) the relationship between geographic diversification of suppliers and customers and the resilience of particular members of the supply chain and the network as a whole; (4) the relationship between the distribution of shocks among different stages of the supply chain and the resilience of the network as a whole.

Based on the abovementioned criteria, the analytical framework offered by Battiston et al. (2007) was decided to be used as a starting point for further research. Even though the original model was not directly applicable for giving answers to questions formulated in the dissertation, the following intrinsic design features made it a suitable tool for further

development. Firstly, the selected approach allowed for modelling direct connections between the participants of the supply chain network. Secondly, it allowed for both upstream and downstream propagation of shocks in the supply chain. Thirdly, the model of Battiston et al. (2007) was suitable for the analysis of a multi-stage supply chain. Fourthly, the selected approach allowed for the analysis of bankruptcy propagation in supply chain networks. The original framework of the model did not prove sufficient to allow for the verification of the research hypotheses formulated in this study. For this reason, the model has been further developed in the doctoral dissertation. Moreover, since the parameters of the model suggested by Battiston et al. (2007) have not been confronted with actual data, a calibration method has been presented and applied in the dissertation to bring the results of the simulation model closer to the empirical reality.

The following developments of the original model have been put forward and applied in the dissertation. Firstly, in the original model the number of firm's suppliers and customers was the same for all companies in the network. For the purpose of the dissertation, the model has been developed to allow for heterogeneity among firms in terms of the number of business connections. Based on empirical evidence, Pareto distribution has been used in the case of both in-degree and out-degree, see Bernard, Moxnes, and Saito (2019). Secondly, in the original model the same number of companies was operating on each stage of the supply chain network. For the purpose of the dissertation, the model has been developed to allow for stages of the supply chain, in which production is provided by a limited number of companies. Thirdly, in the original model firms always connect to those suppliers and customers in the network that are closest to them in terms of the geographical distance. For the purpose of the dissertation, the model has been developed to allow for the pre-determined level of geographical diversification of connections with business partners. Fourthly, in the original model the distribution of exogenous shocks was the same for companies on all the stages of the supply chain. For the purpose of the dissertation, an alternative structure of exogenous shocks has been suggested. Specifically, shocks affecting a particular stage of the network have been temporarily suspended to allow for a better understanding of the shock transmission mechanism.

Besides the developments specified above, the dissertation contributes to the literature also by providing a general method for calibration of parameters in the model formulated by Battiston et al. (2007).

Only after developing the original model in a manner specified above and calibrating its parameters based on empirical data, the analytical tool could be successfully employed to address the issues considered in the dissertation.

4. Main results

The main contribution of the dissertation is twofold. Firstly, an analytical tool has been presented that allows for studying the implications of the supply chain structure for the shock transmission within the chain. Secondly, the following conclusions can be formulated that result from the application of the analytical tool.

In terms of the first hypothesis, the study aimed to verify the shape of the relationship between the number of suppliers and customers of a company and its bankruptcy risk. Specifically, it has been confirmed that the relationship is non-monotonic. The results of the research show that an increase in the number of business partners may initially lead to higher bankruptcy risk. Initially, the negative effects of higher exposure to shocks coming from the supply chain are not compensated by the positive effects of diversification. As the company increases its level of network connectivity beyond specific optimum, positive effects of diversification start to prevail, resulting in diminishing bankruptcy risk. Values of presented measures (bankruptcy risk, growth of production volume) depend not only on the level of network connectivity of a specific company but also on the average connections density in the network as a whole. To study the implications of the average density of connections in the supply chain, performance indicators of a company with a particular number of suppliers and customers can be compared for different network settings (i.e. for networks of different average connections density). A higher average number of connections in the network tends to result, on average, in lower bankruptcy risk and better performance for particular firms. Research results should be interpreted with full awareness of the limitations arising from the form of the model used in the dissertation. For example, the model does not take into account that making subsequent connections would result for a firm in an increase in the cost of handling them. When making decisions regarding the expansion of the network of connections, both aspects should be taken into account.

In terms of the second hypothesis, the study aimed to verify the implications of a scenario in which production on selected stages of the supply chain is provided only by relatively few companies for the stability of the system as a whole. The results of the research confirm the hypothesis that a relatively low number of firms on one of the stages of the supply chain may imply relatively low disruption risk in the network as a whole. Supply chains with a relatively low number of companies on one of the stages tend to be more resilient to bankruptcies, as companies tend to be better diversified and therefore less vulnerable to bankruptcy risk. While interpreting the results one shall bear in mind the limitations of the approach applied in the dissertation, i.e. issues that have not been taken duly accounted for in the simulation model. For example, the state in which there is a limited number of firms in the market may imply higher bargaining power of these companies. Making use of this dominant position by imposing one-sided terms of contracts may result in lowering the resilience of other companies in the network.

In terms of the third hypothesis, the study aimed to verify if the efficiency of the risk mitigation strategy based on splitting orders and sales between multiple suppliers and customers depends on the geographic diversification of business partners. The results of the research suggest that there is a non-monotonic relationship between the level of geographic diversification of firms' business partners and the resilience of the supply chain as a whole. On one hand, a low level of geographical diversification implies that disruptions in a specific part of the supply chain may induce bankruptcies in a close neighbourhood of a disrupted firm, but the transmission of the negative shock to more distant parts of the supply chain remains limited. On the other hand, in the supply chain that is fully diversified geographically, negative consequences of the shock are spread throughout the entire network, and incidents of bankruptcy avalanches in particular parts of a supply chain happen less frequently and the overall bankruptcy ratio is relatively low. Although full geographical diversification of connections in the supply chain might result in greater resilience of the network, such a scenario does not seem empirically plausible, see Bernard et al. (2014) and Bernard, Moxnes, et al. (2019).

In terms of the fourth hypothesis, the study aimed to verify if the impact which shocks affecting particular companies in the supply chain have on the performance of the network as a whole depends on the distribution of these shocks among different stages of the chain. The bankruptcy of a company or its failure to deliver the contracted products to

customers constitutes a shock that is transmitted both downstream (i.e. to customers) and upstream (i.e. to suppliers). Transmission downstream results from the failure to deliver the contracted amount of intermediate goods down the supply chain, while the customer firm has already allocated resources (hired labour and capital) to further process the goods it was expecting to receive. Transmission upstream results from the failure to pay for delivered intermediate goods up the supply chain, while the supplier has already incurred all the production costs. The results of the research suggest that the negative effects of the initial shock expire as they are transmitted to further stages of the network, i.e. propagation intensity is weaker for firms that are located further away in terms of supply chain distance from the firm initially hit by the exogenous shock. For a firm, operating close to full capacity may imply higher negative consequences of supply chain disruption and result in higher ratio of bankruptcies in the network as a whole.

5. Concluding remarks

Results of the research presented in the dissertation may be useful especially for three following types of entities: (1) a firm that is part of a supply chain; (2) a regulator that is interested in assessing the stability of a supply chain; (3) an investor who is interested in comprehensive information on the risk profile of a specific company or a specific industry.

In the first case, a company (e.g. its owner or risk management unit) may use the information on its location in the supply chain, as well as information on the number and geographical diversification of firm's suppliers and customers to make a better assessment of firm's exposure to supply chain disruption risk. Initial assessment can be obtained by directly relying on general results presented in the dissertation. Moreover, it is also possible to make a more accurate assessment that would be tailored to the needs of a company. This would require adjusting the structure of the simulated network, so that it mimics a specific supply chain and calibrating model parameters to adequate empirical data. The results of such an analysis may be used not only to determine the level of supply chain risk in a specific company. They may also provide the management of a firm with recommendations concerning actions that would result in mitigation of supply chain disruption risk (e.g. by changing the number of suppliers or customers or by changing the level of geographical diversification of business partners).

In the second case, regulator might receive more accurate information on the risk profile of a specific supply chain. Based on the knowledge of the number of firms on particular stages of supply chain and (even approximate) information on the structure of connections between suppliers and customers in the network, research method presented in the dissertation may be used to simulate the shock transmission mechanism in a specific network. General conclusions can be drawn with no additional analytical effort, by relying on the results presented in the dissertation.

In the third case, (potential) investors might deepen their understanding of the level of supply chain risk affecting a company or a group of companies that are part of a specific network. A better understanding of the company's risk profile can then be used to assess whether the supply chain risk is properly included in company's share price, thus reducing uncertainty associated with the investment.

The results of the study presented in the dissertation may constitute the starting point for further work on the shock transmission in production networks. Future research could involve reducing or even eliminating the limitations resulting from the approach used in the dissertation, including by even more precisely basing the model specification and values of its parameters on empirical data and by repealing the assumption concerning the stability of the structure of connections in time. First of all, access to micro-level empirical observations – and thus the ability to calibrate model's parameters to data – is currently limited. With the development of computing power and with the increase in the availability of micro-level data on connections between individual firms in different countries, the possibilities of bringing the analytical tool presented in the dissertation closer to empirical data will improve. Recalculating the results after taking this information into account can lead to improved accuracy of the results. Secondly, future research may include the development of the research tool by enabling endogenous formation of connections in the network. Applying this approach would require designing decision rules for individual companies that will direct the process of changing the contractor. This might be achieved by allowing individual firms to choose their contractor based on the price criterion or the criterion of supplier's reliability. Such a modification would allow for the verification of the hypothesis whether companies choosing suppliers based on maximization of short term profit (i.e. price criterion), rather than the criterion that incorporates supplier's reliability, contribute to a deterioration of the long-run stability of the network as a whole.

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