Skogstad, K., Halicki, M., Uphaus, A., 2023. *The project supply chain – a model of the recent disruption brought on by the COVID-19 pandemic and the war in Ukraine*, Przegląd Geopolityczny, 43, s. 141-164.

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THE PROJECT SUPPLY CHAIN – A MODEL OF THE RECENT DISRUPTION BROUGHT ON BY THE COVID-19 PANDEMIC AND THE WAR IN UKRAINE

PROJEKTOWY ŁAŃCUCH DOSTAW – MODEL NIEDAWNYCH ZAKŁÓCEŃ WYWOŁANYCH PRZEZ PANDEMIĘ COVID-19 ORAZ WOJNĘ NA UKRAINIE

Abstract:

This paper examines the decisions companies must face while creating project supply chains, specifically concerning the number of suppliers from which to contract. This question is of importance as project supply chains are rarely described in the logistic literature. A theoretical model is developed to expound on this issue. This model is then used a basis for simulations which seek to understand under what conditions a firm may wish to insure itself against disruption by contracting with multiple suppliers. This model helps to study the impact of various disruptions, including COVID 19-pandemic or the war in Ukraine, on project supply chains. The paper finds that cost of establishing supplier relationships, the nature of the returns to scale, and the probability of a disruption are all key variables when determining how robust a firm should make their supply chain.

Keywords: disruption, model, project supply chain, disasters, simulation.

Introduction

The conflict in Ukraine and other disruptions, such as the COVID-19 pandemic, are new and unprecedented phenomena that not only companies, but entire supply chains must account for. These disruptions have the potential to significantly impede their functioning, thus reducing efficiency. One type of supply chain that is seldom discussed or studied is the project supply chain. This chain entity differs from traditional supply chains since the firms involved are tasked with implementing a single one-time project (such as a nuclear power plant or a skyscraper). Such a large chain is sensitive to various disturbances, since the purpose of its existence is to carry out a time-sensitive undertaking without the benefit of an established history. Building a project supply chain consisting of hundreds of companies that provide goods and services is a difficult and problematic task, because the main contractor responsible for the implementation of the project may find that the various links in the supply chain are disrupted at any point in time. This, in turn, may result in the project not being completed on time. It is well understood that the customer pays attention not only to the delivery time, but also to the quality, which is often the decisive factor in choosing the main contractor.

Based on the literature on supply chains and taking into account the conditions of the COVID-19 pandemic and the armed conflict in Ukraine, an attempt was made to answer the question of what decisions companies have to face when creating project supply chains. Additionally, it was decided to examine how many suppliers a main contractor should contract with for a given link in the chain. This article answers this question by creating a theoretical model that analyzes the trade-off that a company must face in a chain from having one versus many suppliers. This model allows us to study the impact of disruptions on project supply chains. The proposed model may describe the conditions under which having a single supplier is preferable to having multiple suppliers. In particular, we look at the role of prices, upfront costs, total costs, and suppliers' ability to adapt in the event of disruptions. The article uses a critical analysis of the literature with a model approach at the same time. The aim of the work was achieved by using the proprietary model with theoretical assumptions. It can be considered valuable because it is the basis for other research focused around the project supply chain.

Project supply chain and traditional supply chain

Compared to a classic supply chain, a project supply chain is much more complicated due to the number of elements as well as the complexity of the flow of goods, materials, and information. There is currently a lack of research into the nature of project supply chains and how decisions are made by firms in this supply chain. Research in this area is necessary to better understand how firms make decisions and how these decisions impact others in the supply chain. Calculations related to such topics are desirable, although undertaking them may be a challenge due to the multitude of assumptions required.

The literature on the subject mainly presents the essence of the construction supply chain, which is an example of a project supply chain, and in-depth research related to the traditional supply chain. Assuming that the construction version in many respects resembles the project version, it is possible to present a comparison with the traditional version (Tab. 1). It will also allow us to obtain a schematic of project supply chains, which has not been given much space in the literature so far, especially in terms of simulation research or financial or risk management analyzes. Secondly, it will also highlight the potential difficulties in building models.

Tab. 1. Project Supply Chain versus Traditional Supply Chain (in production)

<table>
<tr><th>The Area</th><th>Traditional Supply Chain</th><th>Project Supply Chain</th></tr>
<tr><td rowspan="4">Structure</td><td>Highly consolidated</td><td>Highly fragmented</td></tr>
<tr><td>High barriers to entry</td><td>Low barriers to entry</td></tr>
<tr><td>Fixed locations</td><td>Transient locations</td></tr>
<tr><td>Global markets</td><td>Local markets</td></tr>
<tr><td rowspan="4">Information flow</td><td>Highly integrated</td><td>Recreated several times between trades</td></tr>
<tr><td>Highly shared</td><td>Lack of sharing across firms</td></tr>
<tr><td>Fast</td><td>Slow</td></tr>
<tr><td>Supply Chain Management (SCM) Tools</td><td>Lack of IT tools to support Project Supply Chain</td></tr>
<tr><td>Collaboration</td><td>Long-term relationships;
Shared benefits; Incentives</td><td>Adversarial practices</td></tr>
<tr><td>Product demand</td><td>Very uncertain</td><td>Less uncertain</td></tr>
<tr><td>Production variability</td><td>Highly automated environment;
Standardization;
Production routes are defined</td><td>Labor availability and productivity;
Tools;
Lack of standardization and tolerance management;
Space availability; Material and trade flow are complex</td></tr>
<tr><td rowspan="2">Buffering</td><td rowspan="2">Inventory models</td><td>No models</td></tr>
<tr><td>Inventory on site to reduce risk</td></tr>
<tr><td rowspan="3">Capacity planning</td><td>Aggregate planning</td><td>Independent planning</td></tr>
<tr><td rowspan="2">Optimizing models</td><td>Infinity capacity assumptions</td></tr>
<tr><td>Reactive approach</td></tr>
</table>

Source: based on O'Brien W.J., Formoso C.T., Vrijhoef R., London K.A., 2009 pp. 2-9.

Due to the complexity of such an organization, it is very difficult to present the project supply chain in a simplified manner, showing its essence and relations between its links. The project supply chain, as a multi-element entity, consists of hundreds of links (Kumar, Viswanadham, 2007). However, its most important link is the main contractor who coordinates the project implementation, and also makes strategic decisions exerting a strong influence on resource management. In other words, the implementation of the project depends on the attitude of the main contractor, with the participation of all other links. For this reason, an important role among these links is played by subcontractors who undertake activities on behalf of the main contractor, and who are forced to cooperate with suppliers supplying materials and services for them. Along with the financing institutions, the designer is also an important link, (Voordijk, Haan, & Joosten, 2000), that develops the design plan, and may even decide on the materials and other goods that flow through this type of chain. His position can be strong if he plays the role of a leader who selects subcontractors and suppliers considering the specifics of the project.

When characterizing a project supply chain, one should always pay attention to the fact that its most important feature is complexity, because in the case of large projects, the number of suppliers and subcontractors included in it is very large, which often causes delays in the delivery of materials and other products necessary for project implementation. This implementation can often be prolonged by the domino effect occurring related to failure to meet delivery dates between the links that make up a chain (Halicki, 2020; Korpysa, Halicki, 2022).

The decision model of the project supply chain under conditions of COVID-19 and the war in Ukraine

When examining the behavior of project supply chains, it is extremely desirable to analyze the impact of various shocks, such as the COVID-19 pandemic and the armed conflict in Ukraine on their individual links. This is especially true, due to the fact that such events can be considered highly unpredictable and have a huge impact on the operations of firms. Events considered unlikely in the past occurred and had such a strong impact on societies and economies that entire supply chains, including their project variations, were disrupted. With all this in mind, an attempt was made to build a model that allows for the study of decisions made by the links in the project supply chain in the conditions of the COVID-19 pandemic and the armed conflict in Ukraine.

The preparing and use of the model entailed the development of a set of assumptions on which it was based and which are necessary for the analysis. In order to answer the research question, a formal structure was used which, by means of a system of equations, presented the essential connections between the economic phenomena under consideration in pandemic conditions and during the armed conflict in Ukraine. It is worth mentioning that establishing supply chains, one can work either with one supplier, which is called "single sourcing", or with two or more suppliers, which is called "multiple sourcing". The first solution is used to reduce costs, but it increases disruption risks (Li, Pradhan, 2017). The second one reduces a link's exposure to many risk's types (Treleven, Schweikhart, 1988).

A review of the literature suggests that no generally accepted definition of project supply chain risk management exists, however, the literature does suggest that effective risk management in project supply chain is a system aimed at avoiding project effectiveness reduction, time delays and undesirable costs (Shojaei, Haeri, 2019). Literature research also suggests that the risk management process in the project supply chain is rarely implemented, but one cannot ignore the fact that research on this matter has been started relatively recently (Aloini, Dulmin, Mininno, Ponticelli, 2012) and is thus at an early stage(Rudolf, Spinler, 2018), so conclusions cannot be generalized here.

Most challenges related to risk management in the project supply chain, however, result from the fact that the identification of any threats to the functioning of the entire chain entity requires the participation of all links, not just the so-called triads, i.e.: main contractor, the client and the designer (Ting, Bamgbade, Nawi, 2020).

Introduction to the model

Our goal is to develop a theoretical model that examines the tradeoffs faced by a firm when deciding how many suppliers to source intermediate goods from. Suppose there exists a price-taking profit-maximizing firm that is required to purchase some intermediate goods to complete a specific project. Its problem revolves around whether to source these intermediate goods from a single supplier, or multiple suppliers.

We will make the key assumption that the marginal cost of acquiring intermediate goods from a single supplier is decreasing as more are acquired. This can be thought of as a bulk discount being provided by the supplying firm due to cost savings that they likely enjoy from a larger production run. We will also assume that the firm must pay an up-front fixed cost for establishing a relationship with a particular supplier. These two assumptions would immediately seem to suggest that the firm would only ever want to acquire intermediate goods from a single supplier, as this would minimize costs. However, this would only be true if supply chains were always functioning optimally.

It is understood that for a variety of reasons, supply chains can be disrupted. These disruptions could take the form of dramatic geopolitical events such as conflict in a foreign country or a pandemic. Considering all these possible disruptions, a firm may wish to insure itself against these possibilities by establishing and maintaining relationships with multiple suppliers. By not having "all their eggs in one basket," the firm may find that it is possible to maximize expected profits by sourcing their inputs from multiple suppliers. We begin by defining some variables so that we can better understand the nature of the tradeoffs faced by the firm (Tab. 2).

Tab. 2. Model Setup

π	Profits of the firm.
P	The price of the output.
X_i	The amount of input purchased from firm *i*.
S	The initial cost of setting up a relationship with a firm.
$C(X_i)$	The total cost of purchasing inputs X_i. Assume the first derivative of this function is positive and the second derivative is negative.
$F\left(\sum_i X_i\right)$	The production function of the firm. For simplicity, simply assume a constant returns to scale production function.
ρ	The probability that a supplier cannot supply any inputs.
α	The proportion of total inputs that can be sourced from a single firm in the event of a disruption to the other firm.

Source: own study

The model

For simplicity let's focus on a firm that has an option of working with two suppliers. To reiterate the setup of the model, there is a fixed cost (S) of setting up a partnership with a supplier. The cost of acquiring inputs from a supplier displays diminishing marginal costs. There is a chance (ρ) every year that a disruption to that firm prevents the inputs from that firm from being delivered. The question we are interested in answering is when is it beneficial to set up multiple supply relationships to insure against this risk?

Let's begin with the case where the firm has engaged with both potential suppliers. We will assume that these two suppliers have the same cost function, and that the firm will source an equal amount of inputs from both firms. In this case, if X represents the total amount of inputs to acquire, then we have $X_1 = X_2 = \frac{X}{2}$.Given the possibility of a supply chain disruption to one or both of the firms, all the possible scenarios can be described by the following equations:

- Scenario 1: No Disruptions (ND)

$$\pi_{ND} = PF\left(\frac{X}{2}+\frac{X}{2}\right)-\left(C\left(\frac{X}{2}\right)+C\left(\frac{X}{2}\right)\right)$$

- Scenario 2: Firm 1 Disrupted (D1)

$$\pi_{D1} = PF(\alpha X) - C(\alpha X)$$

- Scenario 3: Firm 2 Disrupted (D2)

$$\pi_{D2} = PF(\alpha X) - C(\alpha X)$$

- Scenario 4: Both Firms Disrupted (BD)

$$\pi_{BD} = PF(\mathbf{0}) - C(0) = \mathbf{0}$$

Note that in scenarios 2 and 3, an assumption is made about the non-disrupted firm's ability to increase the supply of the intermediate good. Given that the firm wishes to acquire X units of the intermediate good and given that the firm was initially supplying X/2 unit of output, the question becomes how much of the shortfall can the remaining supplier makeup. The term α describes this proportion. Assuming it faces no disruption itself, this value will be bounded below by 0.5, the original amount already being supplied. On the other end, it will not go above 1, as the firm does not wish to acquire more than this amount of the intermediate good. The larger it is, the more of the shortfall the supplier is able to produce. The probability of each scenario occurring is given by the following:

ND:	$(1-\rho)^2$
D1:	$\rho(1-\rho)$
D2:	$\rho(1-\rho)$
BD:	ρ^2

Therefore, the expected profit of the firm is

$$E[\pi] = -2S + [\rho^2\pi_{BD} + \rho(1-\rho)\pi_{D1} + \rho(1-\rho)\pi_{D2} + (1-\rho)^2\pi_{ND}]$$

We see from above that $\pi_{D1} = \pi_{D2}$. We will label this π_D. Our expected profit equation thus simplifies to the following:

$$E[\pi] = -2S + [2\rho(1-\rho)\pi_D + (1-\rho)^2\pi_{ND}]$$

Putting this aside for now, we now examine the simple case where the firm chooses to engage with only one supplier. In any given year, the possible scenarios can be described by the following equations:

- Scenario 1: No Disruptions (N)

$$\pi_N = PF(X) - (C(X))$$

- Scenario 2: Firm Disrupted (Z)

$$\pi_Z = PF(0) - C(0) = 0$$

The probability of each scenario occurring is given by the following:

N: $1 - \rho$

Z: ρ

Therefore, the expected profit of the firm is:

$$E[\pi] = -S + [\rho\pi_Z + (1-\rho)\pi_N]$$

This simplifies to the following:

$$E[\pi] = -S + (1-\rho)\pi_N$$

Now, we wish to compare the expected payoffs from our two possible scenarios. Equation 1 below shows the expected payoffs when the firm insures itself against disruption, and equation 2 shows the expected payoff when it does not.

$$E[\pi] = -2S + [2\rho(1-\rho)\pi_D + (1-\rho)^2\pi_{ND}] \quad (1)$$

$$E[\pi] = -S + (1-\rho)\pi_N \quad (2)$$

Analyzing the Model

We can begin by substituting in our profit equations into these two expressions.

$$E[\pi] = -2S + [2\rho(1-\rho)\pi_D + (1-\rho)^2\pi_{ND}]$$

$$E[\pi] = -2S + 2\rho(1-\rho)[PF(\alpha X) - C(\alpha X)] + (1-\rho)^2\left[PF\left(\frac{X}{2}+\frac{X}{2}\right) - \left(C\left(\frac{X}{2}\right) + C\left(\frac{X}{2}\right)\right)\right]$$

$$E[\pi] = -2S + 2\rho(1-\rho)[PF(\alpha X) - C(\alpha X)] + (1-\rho)^2\left[PF(X) - 2C\left(\frac{X}{2}\right)\right]$$

and

$$E[\pi] = -S + (1-\rho)\pi_N$$

$$E[\pi] = -S + (1-\rho)[PF(X) - (C(X))]$$

Since our goal is to compare these two expressions and to determine under what condition either one will be larger, we can begin by simplifying them by cancelling out common elements. Doing so, leaves us with the following:

$$E[\pi] = -S + 2\rho(1-\rho)[PF(\alpha X) - C(\alpha X)] - \rho(1-\rho)PF(X) - 2(1-\rho)^2 C\left(\frac{X}{2}\right) \quad (3)$$

$$E[\pi] = -(1-\rho)(C(X)) \quad (4)$$

So, our question becomes, when will equation 3 be larger than equation 4, implying that the expected payoffs from diversifying will be greater than that of not diversifying. Clearly, there are many factors that the firm must consider when evaluating this question, and we can see how these play out here.

<u>Initial Setup Cost (S)</u>

Firstly, we see that as the cost of establishing a supply relationship (S) increases, the more likely it is that equation 4 will be larger than equation 3. This implies that the more costly it is to set up these relationships, the less likely it will be profitable to do so. Evaluating the upfront cost of setting up this relationship will be an important component for whether or not a firm sources from a single or multiple suppliers.

<u>Output Price (P)</u>

Next, we evaluate the impact of higher prices. In this case, it is helpful to re-write equation 3 in the following way:

$$E[\pi] = -S + \rho(1-\rho)P[2F(\alpha X) - F(X)] - 2(1-\rho)\left[\rho C(\alpha X) + (1-\rho)C\left(\frac{X}{2}\right)\right]$$

We can see from this equation that as the price increases, the profits from diversifying will increase, so long as α is greater than 0.5. Considering that 0.5 is the amount of intermediate goods originally being purchased from this supplier, this is a reasonable expectation. Given that price does not appear in equation 4, we can be certain that as price rises, having multiple suppliers becomes more preferred. This is a rather intuitive result. Given that a disruption to supply prevents a firm from earning its full revenue, the more revenue that is potentially lost from a disruption, the more desirable it is to avoid it.

In the case of a project supply chain, one can think of the price as a measure of the cost of a delayed project. The more profit that will be lost as delays are faced, the more important it will be to take steps to avoid any potential delays.

<u>Ability to meet demand (α)</u>

Next, we turn to the impact that the α variable has on expected profits. Recall that α represents the proportion of the total desired intermediate goods that the firm can source from the single firm in the event of a disruption. Looking at equation 3, we see that α only appears in one set of brackets. This set of brackets represents the expected profits when only one supplier is disrupted. Assuming that this firm is operating with a positive profit margin, we can see that the term in brackets is positive. Additionally, given our assumption of a constant returns to scale production function, and decreasing marginal costs, we see that as α grows, this profit margin will increase. Therefore, the larger the value of α, the more profitable it will be to diversify.

This makes intuitive sense as well. Given that the firm has a desired quantity of inputs to obtain to produce the desired amount of output, any disruption that brings it away from this level will be undesirable. When a disruption does occur, α captures how easily this firm can source from the other supplier. The larger the value, the more easily it can source additional output, and the more profitable it will be. Therefore, the easier it is for a firm to increase supplies from these already established relationships, the more profitable it will be to establish them in the first place.

<u>Cost Structure ($C\,(X)$)</u>

Next, we turn to the impact of the cost structure faced by the firm. Here, we can ease our understanding by comparing the two cost components of equations 3 and 4:

$$-2(1-\rho)\left[\rho C\,(\alpha X)+(1-\rho)C\left(\frac{X}{2}\right)\right]$$

and

$$-(1-\rho)\big(C\,(X)\big)$$

We can remove the common element from these two expressions to simplify them to the following

$$-2\rho C\,(\alpha X)-2(1-\rho)C\left(\frac{X}{2}\right)$$

$$-C\,(X)$$

Focusing on the first equation for a moment. If we assume a value of α = 0.5, and a linear cost function, this equation simplifies to the following:

$$-2\rho C\left(\frac{X}{2}\right)-2(1-\rho)C\left(\frac{X}{2}\right)$$

$$-\rho C\,(X)-(1-\rho)C\,(X)$$

$$-C\,(X)$$

Meaning that the firm would face the same overall costs in both scenarios. However, if we allowed the cost structure to be non-linear, with decreasing marginal costs, then we would find the following:

$$-2\rho C\left(\frac{X}{2}\right)-2(1-\rho)C\left(\frac{X}{2}\right)$$

$$-2C\left(\frac{X}{2}\right)<-C\,(X)$$

This means that the costs faced by the firm under these assumptions would be larger when the firm had diversified its suppliers. This is as we expected. One of the main benefits to the firm from maintaining a sole supplier is that there are cost savings in terms of the average cost of an intermediate good. By sourcing from multiple suppliers, this benefit is being sacrificed. For this reason, we can see that the larger these cost savings are to the firm from having a sole supplier, the less likely they will be to diversify their suppliers.

Probability of Disruption (ρ)

Finally, we turn to the impact that the probability of disruption has on the decision of the firm to diversify. To examine the impact of this variable, we take the derivative of equations 1 and 2 with respect to ρ and $-\pi_N$.

We can show that both are negative values. The second one is obvious to see given that profits with no disruptions are positive. For the first case, we rearrange it to the following. Since $\pi_D < \pi_{ND}$, and since $\pi_D > 0$, we see that this expression is negative. So, whether diversified or not, profits will fall as the probability of disruption increases. However, the rate at which profits fall are not equal. Additionally, it is possible to show that under certain conditions, the higher the probability of disruption, the more it would pay to be diversified.

Comparing equation 1 and 2 for a moment, assume for simplicity that the value of S was zero. This would leave us with the following:

$$(1-\rho)\big(2\rho\pi_D + (1-\rho)\pi_{ND}\big)$$

and

$$(1-\rho)\pi_N$$

The question is, is it possible to show the following:

$$(1-\rho)\big(2\rho\pi_D + (1-\rho)\pi_{ND}\big) > (1-\rho)\pi_N$$

$$\rho 2\pi_D + (1-\rho)\pi_{ND} > \pi_N$$

Given that $\pi_N > \pi_{ND}$, we simply need π_D to be sufficiently large for this statement to be true. This can be achieved easily if α is sufficiently large, as this, coupled with the coefficient 2 in front, would ensure that the left-hand side of this inequality was larger than the right. Having the possibility of receiving this positive profit during a disruption can possibly more than offset the loss of having a lower profit when no disruption occurs. The basic intuition is the following. The larger the probability that a shock occurs, the larger the likelihood that the diversified firm will see it in the scenario where it is only procuring from one firm. If this firm is able to supply a sufficiently large amount, this prevents the profits in this scenario from being low. As a result, even though the profits in the non disruptive scenario with diversification are smaller than then non-disruptive scenario with no diversification, the likelihood of receiving these non-disrupted profits become smaller as ρ increases, meaning the insurance of having multiple suppliers is more likely to payoff.

Implications for the entire supply chain

So far, theoretically only the decision between one or two suppliers on one level has been considered. However, the risks arise from the entire upstream supply chain, all the way to raw materials. Companies are often only aware of the direct suppliers at the next level. If the decision parameters (especially the probability of failure) for the direct supplier selection already contain all information and risks of the further levels, the presented theoretical model is sufficient.

However, since the accumulation of information in the (risk) parameters of the upstream level is hardly possible and not very transparent, a theoretical consideration of the entire supply chain across all levels separately appears necessary. Furthermore, decisions at different levels can be made independently and differently across all participating companies. Supply chains are also very complex networks (Singh et al. , 2021), since a company can manufacture a large number of products (Chopra, Sodhi, 2014), products can consist of very many assemblies, assemblies of many parts, parts of other parts or raw materials. In addition, auxiliary materials, supplies, and services also go into products. Each part may also be sourced from multiple suppliers. A project is even more complex because a variety of complex products and services are needed to complete it. In this context, the project corresponds to the Original Equipment Manufacturer (OEM) equate.

Supply chains are complex and contain numerous suppliers tiers, OEM production, services, merchants and the ultimate customer. Risks can occur at any time and anywhere in them (Vieira et al., 2019). Risks also arise from barriers that can have an impact on outcomes: lack of inventory, lack of transportation, local law enforcement, scarcity of raw material, fluctuation of demand, deficiency in cash flow in the market, and lack of manpower (Gamalet al.,2022). Each barrier is relevant to each supplier, thus illustrating the complexity of the problem. Risks can have an impact on sales, reputation, and losses.

Supply chain risks and single sourcing

Supply chain risks are basically supply risks, infrastructural risks, demand risks and macro risks, which lead to a disruption of the supply chain. Interruptions can be interactional disruptions, organizational disruptions (services, internal issues, personnel), supply-side disruptions (shutdown, inventory, delays, communication), demand-side disruptions (service demand, product usage and customers) (Gatenholm, Halldórsson, 2022). This paper focuses only on supply-side risks.
There are different types of risks, which must be modeled differently:

(1) Natural disruptions such as tsunamis, volcanic eruptions or earthquakes (Singh et al., 2021; Ivanov, 2020; Chopra, Sodhi, 2014).
(2) Human made disasters such as strikes, legal disputes, economic crisis, financial crises, cyber attacks (Singh et al. , 2021; Ivanov, 2020; Sodhi, Tang, 2012)
(3) Special case: epidemic outbreaks like COVID-19 which is a global problem with new complications (Gamal et al., 2022; Ivanov, 2020).

There are risks that are limited to regions or sectors as shocks and thus affect only individual levels. These include most risks. Even wars such as the Ukraine war are usually local events and initially only affect companies in the region, leading only to partial disruptions in supply chains. Conversely, risks exist that affect the entire supply chain and not just individual levels, such as a pandemic or a global economic crisis. But ultimately, local events such as tsunamis (Sumatra, Fukushima) or wars (energy crisis due to Ukraine war) can also have a global impact. For individual companies, human made risks also arise from single sourcing and centralization of inventories have increased supply chain risks. Single sourcing is often used to increase efficiency, but requires high capacity to ensure flexibility. Establishing capacity and alternative suppliers involve very high costs, but significantly reduce fragility (Chopra, Sodhi, 2014;Beer, Liyanage, 2012).

The business impact of risks is usually a reduction in sales and revenues and an increase in costs and thus a reduction in profits (Gamal et al. , 2022). Other indirect consequences might be shortage of labor or panic buying (Singh et al. , 2021). However, the savings from single sourcing in particular are usually lower than the costs of production closures (Chopra, Sodhi, 2014;Weber, 2021).

Resilience strategies and efficiencies

Solutions proposed to reduce risks include inventory increases, capacity expansion, multi rather than single sourcing, segmentation of supply chains, and regionalization (Chopra, Sodhi, 2014). Supply chain resilience can be specifically increased by increasing flexibility, redundancies, increasing visibility and transparency, collaboration and agility (Weber, 2021). Sodhi and Tang (2012) recommend aligning interests, adaptiveness and agility as resilience strategies. Nevertheless, resilience strategies often refer to material flow and products as the most important aspects. Overall, a balance must be found between cost, efficiency, resource utilization and risk (Lahmar et al., 2015). Single sourcing strategies in particular should be analyzed again (Gatenholm, Halldórsson, 2022). In order to assess the effectiveness of resilience strategies, particularly with regard to multisourcing, it may be advantageous to extend the analysis of the theoretically presented individual decisions in series within the framework of a complete supply chain simulation with different parameters in each case, if necessary.

Simulation model

Supply chains are very complex networks with many interdependencies and high uncertainties as well as in transparencies. Simulations have the advantage of being able to analyze complex problems. Simulations can be used for recommended stress tests (Chopra, Sodhi, 2014). A simulation tool can support management decision making. Also, simulations can be performed with different scenarios (e.g. Singh et al., 2021). Ivanov (2020) distinguishes shocks such as an outbreak of an epidemic only in China, worldwide closure of production, and market restrictions of 50% with corresponding processes. Vieira et al. (2019)differentiate risks into manufacturing (internal), supply, demand, and external risks. Impact on different result factors can be analyzed in principle, e.g. production inventory dynamics, customer performance, financial performance, lead-time performance.

Disruptive events are characterized by rarity, unpredictability and large performance impact. Risks thus have logical and random frameworks. However, the probabilities of interruptions are difficult to estimate but are often underestimated. One problem is the collection of accurate and credible data (Gamal et al. , 2022). Due to lack of availability of real data, random distributions and especially triangular distributions are related. Dynamic simulations over time can reveal time-dependent changes. Upfront costs for alternative suppliers and capacity expansions are of particular importance as parameters (Beer, Liyanage, 2012).The following simplified simulation refers only to supply risks and here specifically to profits as financial performance. In particular, the effects of single/multiplesourcing decisions are considered as extremely important management decisions with special consideration of upfront costs for supply chain resilience. The simulation concerns only one point in time, but can also be designed as a dynamic simulation in a next step.

Since the supply chain for a project is individual and arbitrarily complex, a corresponding simplification is required for appropriate simulation modeling and to be in a position to make appropriate conclusions. Therefore, the following simulation assumptions are made for an example project that meet the model assumptions:

(1) Only one sourced good of the OEM (project) and by each supplier should be considered. For simplicity without loss of generality input quantity remains the same on each level with $X = 20$ units.

(2) There can be one or 2 suppliers (no more) and the company must decide for single or multiplesourcing.

(3) The supply chain runs exemplarily over only 4 levels (level 4: OEM/project, level 1: basic material).

(4) All necessary information about all levels upstream are known to the supplier and especially to the OEM (this is in reality often not the case, but only preliminary for stage).

(5) The sourcing strategy single or multiplesourcing is the same for all participants across all levels.

(6) ρ and $\propto$ can change differently at all levels simultaneously.

(7) Prices at level 1 are $P(1) = 50\ MU$ (MU = monetary units) for all products and increase at each level downstream by an additional value added fraction of g=50%.

(8) The production function is assumed to be $F(X) = 5 \cdot x$ for simplicity without loss of generality. In this context, it is assumed that inputs are procured in unit quantity packages of several parts and that, for example, 5 finished products can be produced from one purchased package of 5 components.

(9) The cost function of supply chain material is assumed as $C(X) = 5 \cdot \sqrt{X} \cdot P(n)$ on level n for simplicity without loss of generality.

(10) Production and cost functions are the same for all participants and remainconstant over time.

(11) Upfront costs are the same at all levels and are assumed here to be $S = 1.000\ MU$.

(12) Overall results are measured in profits and other sustainability factors are not initially considered.

In a project supply chain, however, there is the problem that the project cannot be completed in the event of any non-delivery. The failure of a supplier can therefore lead to the failure of the entire project. Without acceptance, however, the case of penalty or zero profits may occur, which will not be explicitly considered here. Therefore, the simulation of failure probabilities seems reasonable. For the simulation, the parameters ρ and ∝ are each determined as random variableswithin given probability distributions per supplier in the supply chain. As distributions of the parameters triangular distributions are assumed with the following parameters (Tab. 3).

Tab. 3. Parameters for triangular distribution

	$\propto$ (Takeover share)	ρ (Probability of default of supplier)
a = min	0.5	0
b = max	1	1
c = most probable value	0.9	0.1

Source: based on own study.

The following situations are analyzed as scenarios:

- Scenario I: ρ and $\propto$ can change differently at all levels simultaneously
- Scenario II: ρ and $\propto$ can change at all levels simultaneously by the same amount
- Scenario III: global crisis c(ρ) = 0.8 instead of c(ρ) = 0.1 in scenario I
- Scenario IV: local crisis at level 3 only material 1: $\rho(4;1) = 0.8$
- Scenario V: ρ and $\propto$ are constant at c-level but S changes

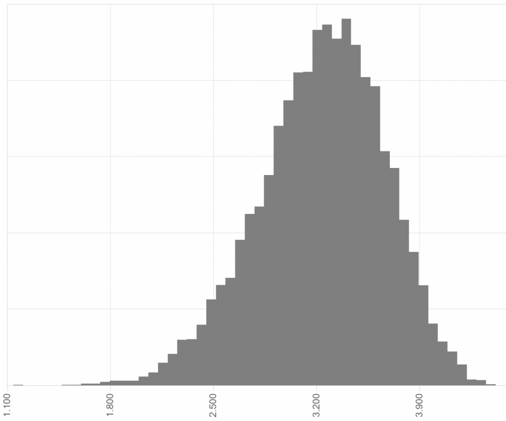
The model offers further analysis possibilities, for example, for the influence of X, S, C, F, P and g, which initially remain constant.

Results of simulation

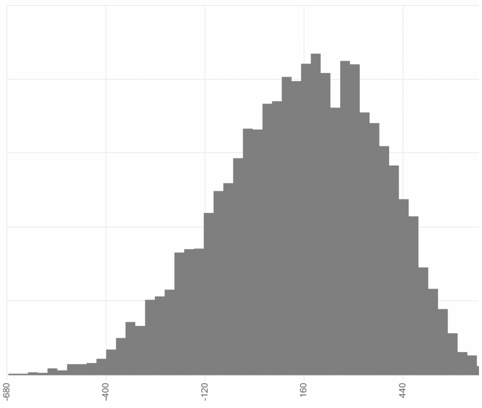
Shown are the suppliers $Sup\,(i;n,j)$ with i=1,2 alternative suppliers, $n=[1..N]$ level and $j=[1..J(n)]$ input products per level with the last result. Output products (materials) per level are $Mat(n;j)$. For single sourcing across all levels only the top branch $Sup\,(i;n,1)$ is considered, for multisourcing the whole tree. The profit is calculated for each delivery yarn according to the described model. As a result, the arithmetic mean of the profits of overall production over all participating suppliers is calculated. The simulation is performed 10,000 times.

Scenario I: ρ and α can change differently at all levels simultaneously

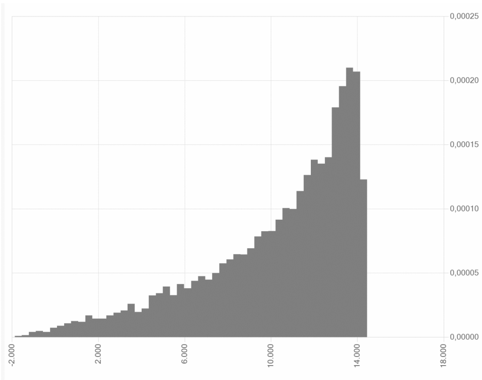
Fig.1. Simulation result scenario I



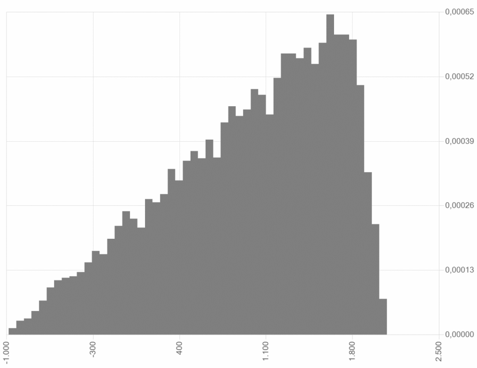
1a: Multisourcing profit Scenario I average



1b: Singlesourcing profit Scenario I average



1c: Multisourcing profit Scenario I OEM



1d: Singlesourcing profit Scenario I OEM

Source: based on own study

The average profit in the last run only is 3,146 MU in multi-sourcing and is thus, as expected, significantly higher for the selected parameters than for single sourcing with -89 MU. This is also true for all levels individually. The distribution of the average profits of all participating suppliers appears approximately normal, while that of the OEMs is right skewed. The profit distribution is also visibly shifted to the right in the multisourcing case, i.e. it has a higher mean value as position parameter. Significant gains seem to be possible with the parameter constellation only with a multisourcing strategy, while singlesourcing even leads to partial losses. OEM has significantly higher profits, due in particular to higher prices. This can also be shown on the basis of the average values:

Tab. 4. Average profit scenario I

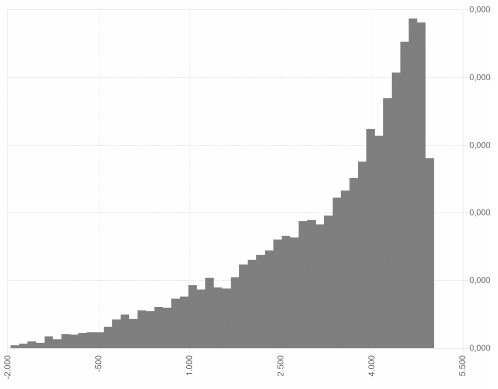
all in MU	multisourcing	singlesourcing
average	3,234	148
OEM	10,279	959

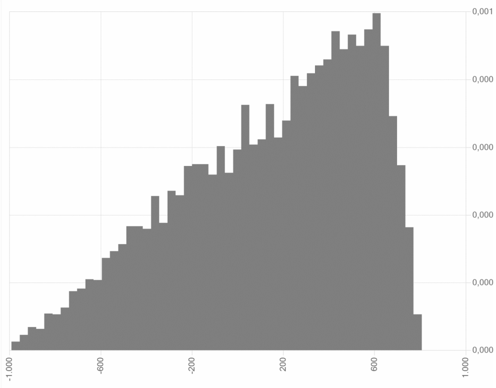
Source: based on own study

Consequently, a multi-sourcing strategy seems to be mandatory in this case.

<u>Scenario II: ρ and α can change at all levels simultaneously by the same amount</u>

Fig. 2. Simulation result scenario II





2a: Multisourcing profit scenario II average

2b: Singlesourcing profit scenario II average

Source: based on own study

The distribution for average profits looks different and more right-skewed. This seems logical and similar to the distribution of the single OEM. The averages of result are similar as in scenario I.

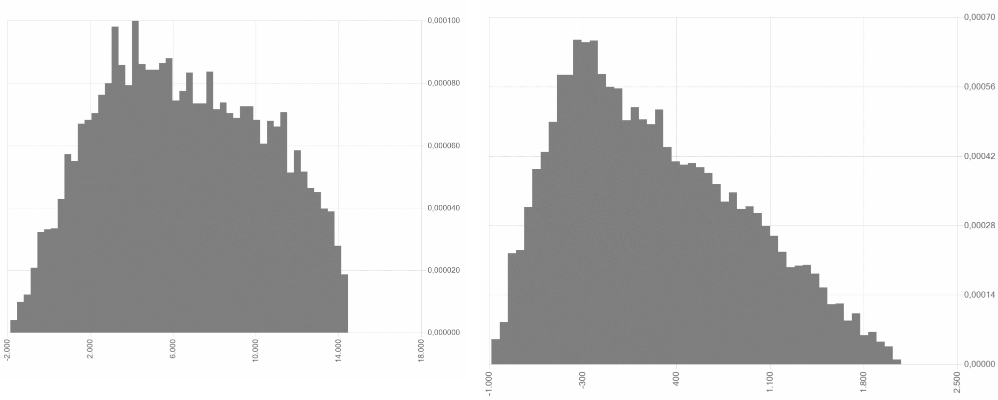
Tab. 5. Average profit scenario II

all in MU	multisourcing	singlesourcing
average	3,228	145
OEM	10,236	950

Source: based on own study

<u>Scenario III: global crisis c(ρ) = 0.8 instead of c(ρ) = 0.1 in scenario I</u>

Fig. 3. Simulation result scenario III



3a: Multi-sourcing-profit scenario III OEM

3b: Single-sourcing-profit scenario III OEM

Source: based on own study

Now the focus should be on the profit OEM (the project). The distribution for OEM profits looks different and now more left-skewed. This seems logical while ρ distribution is right-skewed yet. The averages of result is now different to scenario I:

Tab. 6. Average profit scenario III

all in MU	multisourcing	singlesourcing
average	1,642	-275
OEM	6,511	233

Source: based on own study

All profits have fallen sharply (e.g. for OEM multi-sourcing 6,511 instead of 10,279 which is -37%) and single sourcing even results in losses across all suppliers on average yet.If a global crisis with the same effects is assumed everywhere on each level only for comparison, the parameters $\rho = 0.8$ and $\propto = 0.9$ can be fixed. $\propto$ could also be assumed to be lower, since the alternative suppliers would probably not be able to supply such a high replacement percentage in real terms. For the OEM, the result would be slightly better than for the average of the companies due to the increasing prices over all levels.

Tab. 7. Average profit scenario IIIb

all in MU	multisourcing	singlesourcing
average	324	-638
OEM	3,430	-383

Source: based on own study

Scenario IV: local crisis at level 3 only material 1: $\rho(4;1) = 0.8$

In this scenario, a local problem is analyzed. As an example, only one purchase of material 1 by the OEM/project (level 4) from Ukraine in times of war (level 3) with a fixed probability of failure of 0.8 is considered, whereby all other general conditions correspond to scenario I but $\propto$ was fixed to 0.9 over all companies for comparison.

Tab. 8. Average profit scenario IV

all in MU	multisourcing	singlesourcing
average	2,995	-187
OEM	3,430	-383

Source: based on own study

Compared with scenario IIIb, the result for the OEM remains equally poor, as expected, since both parameters were fixed at the same level. The average result is significantly better, as the probability of failure fluctuated within the parameters of the triangular distribution of scenario I. Thus, local crises obviously have significant consequences for companies at the next level in each case.

Scenario V: ρ and $\propto$ are constant at c-level but S changes

In scenario V, the dependence of the results on the upfront costs is to be shown. If all other parameters are kept constant, the theoretical model shows a direct linear dependence of the results on the upfront costs. If ρ and $\propto$ are simulated again as in Scenario I, the clear dependence can be seen. Consequently, in this case, the results for multiple sourcing are nearly always better than those for single sourcing regardless of the upfront costs. Supply chain resilience may therefore depend on the other parameters and the structure of the specific project.

Discussion

When establishing a project supply chain, a firm must carefully consider how many suppliers from which it should procure intermediate goods. Standard economic theory would suggest that, in the absence of any disruptions, fewer suppliers is preferred, as it avoids any upfront fixed costs of establishing a relationship with a supplying firm, and cost savings can be achieved through possible bulk discounts from suppliers. However, recent events have shown that relying on single suppliers can be problematic. The recent disruption to global supply chains brought on by the COVID-19 pandemic and the war in Ukraine, have demonstrated that sole source supplying may be increasingly risky moving forward. In this model, this can be shown by a larger value of ρ, the probability that a disruption will occur. Although cost savings do still potentially exist from using a sole source supplier, the probability of realizing the higher profits associated with this choice, may be less probable.

The decision on whether or not to make the switch to multiple suppliers will depend critically on two additional factors. The first is how much profits will be potentially lost in the event of a disruption. If profit margins are small, and can be easily made up in future years, then the benefit of diversification may be small. On the other hand, for a project supply chain, that may have to meet a critical deadline to avoid large fines, or a large amount of lost revenue, the cost of delay may be relatively large. The second factor is with regards to how quickly and easily suppliers can fill the void left by the disrupted firm. If a supplier is already operating at capacity and is unable to surge its output to meet the increased demand, there may be little to no benefit of having established the relationship in the first place. On the other hand, if a firm can surge its output to meet demand, then this would justify the cost of establishing and maintaining the relationship.

The simulation confirms the theoretical results for the selected parameters. By adjusting the parameters and adding real supplier structures and levels, the simulation model can also be used for general risk simulation with regards to the decision as to whether single or multi sourcing makes sense. For the case of pandemics, the probability of failure can be increased and for the simulation of local risks, the parameters can be changed at the appropriate point. This is especially true for project supply chains. All in all, a theoretical and empirical decision support model for the single/multiple sourcing question was developed and tested, which should also be applied to assess risks in real situations.

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Streszczenie:

W artykule zawarto odpowiedź na pytanie, z jakimi decyzjami muszą się zmierzyć przedsiębiorstwa tworząc projektowe łańcuchy dostaw, w zakresie liczby dostawców głównego wykonawcy. Odpowiedź na to pytanie jest celem artykułu, została ona udzielona na podstawie modelu teoretycznego. Model ten pozwala zbadać wpływ wielu zakłóceń, takich jak pandemia COVID 19 lub wojna na Ukrainie, na projektowe łańcuchy dostaw. W artykule przeanalizowano rolę cen, kosztów a także zdolności do funkcjonowania w warunkach zakłóceń. Dodatkowo przeprowadzono symulacje w celu uzyskania wyników badań o ustalonych parametrach. Pokazana symulacja może być również wykorzystana do innych symulacji ryzyka, celem jego analizy, czy też jako narzędzie wspomagające decyzje dotyczące tego, czy budować łańcuch z jednym źródłem dostaw czy z wieloma.

Słowa kluczowe: zakłócenie, model, projektowy łańcuch dostaw, katastrofy, symulacja.