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A Delphi study on the supply risk-mitigating effect of additive manufacturing during SARS-COV-2

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ABSTRACT

Procurement has faced major challenges due to the collapse of global supply chains in the course of the SARS-COV2 pandemic, and non-critical items have become critical bottlenecks. Additive manufacturing (AM) is an emerging technology that serves as a local supply source and can mitigate some of these bottlenecks. For example, it was possible to source medical spare parts and protective equipment via AM, even when the globally arranged traditional (formative or subtractive manufacturing) supply sources failed. To that end, this research examines how supply risks change when sourced via an AM supply source rather than through supply sources that use traditional manufacturing (TM). This study assesses supply risk using a Delphi study from July to October 2020. The findings were further explored using discriminant analysis. A mix of TM supply sources with AM ('hedging') can minimise the overall supply risks. The discussion conceptualises a portfolio model to determine whether to source demands via TM, AM, or by hedging. The implications of hedged manufacturing are linked to the modern portfolio theory.

1. Introduction

In recent decades, outsourcing has increased in all industries. This increase can be traced back to intensified competition, shortened product life cycles, and increased product complexity (Harland et al., 2003; Wagner and Bode, 2006). The escalating focus of procurement organisations on efficiency (Vitasek, 2016) is further exacerbated by increasing just-in-time delivery (Blackhurst et al., 2008), supplier dependency, and global and single-sourcing (Wagner and Bode, 2006). These have also created increased supply vulnerability (Christopher and Lee, 2004). Supply vulnerability is defined by Wagner and Bode (2009) as 'a firm's susceptibility to the negative consequences of a disruption'. In addition to procurement organisations intensified exposure to disruptive events, the frequency of such high-impact events referred to as 'supply chain tsunamis' (Akkermans and van Wassenhove, 2017) (e.g., terror attacks, SARS-CoV, MERS-CoV) has increased (Coleman, 2006; Glas et al., 2021; Wagner and Bode, 2006), resulting in increased supply chain risk overall.

Although recent research on purchasing and supply management (PSM) has increasingly focused on supply risk management (Fan and Stevenson, 2018), with a more critical viewpoint (Heckmann et al., 2015), SARS-CoV-2 has revealed the persistent vulnerability of traditional supply sources (Ivanov and Dolgui, 2020), in particular, breakdowns in March 2020 due to international trade restrictions and market shortages, especially for medical and personal protective equipment (PPE). Local AM suppliers sourced equipment, such as face shields, medical spare parts, or emergency ventilators. These items were provided by organisations outside the medical industry, such as automotive companies, aerospace companies (Airbus Group, 2020; Volkswagen Group, 2020), universities, and manufacturers (Kunovjanek and Wankmüller, 2021). However, current research on AM in PSM is scarce (Hedenstierna et al., 2019; Meyer et al., 2020b; Rogers et al., 2016), especially on supply risk management (SRM) and sourcing strategy (Ivanov et al., 2021). Additive manufacturing requires a standardised capital investment good in the form of a 3D printer, as well as raw materials. Additionally, image files created with computer-aided design (CAD) are required (Li et al., 2017; Liu et al., 2014). As AM requires no tooling (Holmström and Partanen, 2010), production can start with minimal lead times for several distinctive products at the same time (Ghadge et al., 2018). Virtual drawing data can be easily sent via the Internet. Therefore, demand can be locally sourced within different geographical regions (Berman, 2012; Bogers et al., 2016). This increases the availability of supply, as the following case shows during the pandemic.

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A hospital in Chiari (Italy) faced long and uncertain lead times for ventilator valves due to the pandemic (Forbes, 2020b). Owing to complex product geometry, these valves represent a procurement object with at least medium asset specificity. This resulted in a strong dependency on the original supplier, long lead times and non-availability in times of crisis. In other words, TM and regular SRM was not able to deal with such a disruptive event. In contrast, a local engineering service provider generated a CAD file for the valve and printed 100 valves within three days. The renewed availability enabled the hospital to maintain its health services (Forbes, 2020a). This case shows that AM has an effect of mitigating supply risks.

Zsidisin (2003) defines supply risk as ' … the probability of an event associated with inbound supply from individual supplier failures or the supply market occurring, in which its outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety'. Additive manufacturing may influence supply risk, especially in response and recovery. As Natarajarathinam et al. (2009) point out, most supply chain risk research focuses on preparation and mitigation, so this is worthy of further exploration. The overarching aim of this study is to measure the impact of AM on supply risk and the hedging effect of TM and AM by means of modern portfolio theory (MPT). For this purpose, this research follows the SRM process (Hallikas et al., 2004; Harland et al., 2003) and applies a Delphi method (28 experts in two rounds) to explore risk effects of AM technology in a holistic approach. This means we explore if there is general support for risk effects caused by AM technology, taking into account a holistic view on supply risks, not only focusing on risks directly linked to AM processes (i.e. production risks). As such individual sourcing items are analysed by experts based on their risk characteristics in sourcing via an TM, AM, or hedged supply source to provide general new insights how AM could influence risk.

The results provide indications for a hedged approach of AM and TM sourcing. As such, this study is both theoretically and practically relevant. Our findings contribute to a qualitative understanding of how supply risks are affected by sourcing via AM, especially for fast response and recovery. Additionally, we provide a theoretical underpinning for the use of AM as an instrument for supply risk management through MPT. The portfolio framework of hedging TM with AM provides both academics and practitioners with strategic insights into mixed manufacturing sourcing.

The following section develops a deeper understanding of AM to formulate initial assumptions about the implications that AM could have on supply risk management and how it should be used most efficiently. Next, a Delphi study that addresses the initial assumptions is presented. This is followed by a presentation of the Delphi findings and their evaluations using discriminant analysis. Overall, the findings point to major theoretical implications that are discussed from the perspective of the MPT. The limitations and an outlook on further research conclude this article.

2. Comparison of TM and AM: initial assumptions for supply risk management

2.1. Advantages and disadvantages of AM

Additive manufacturing is a manufacturing technology that is colloquially known as 3D printing (Durach et al., 2017). Manufacturing methods have the same *raison d'être*, which produces physical end products (Feldmann and Gorj, 2017; Gebhardt et al., 2016). Nevertheless, AM varies significantly on several factors from subtractive and formative manufacturing, which are referred to in this article as traditional manufacturing methods. Physical products can be produced in an automated manner without the need for tools based on their digital representation in the form of a CAD file (Huang et al., 2013). This technology changes the interaction with physical assets using represented digital data (Aheleroff et al., 2021).

Several publications have addressed the different technological characteristics of TM and AM, as shown in Table 1. It can be seen, that both methods have specific advantages and disadvantages along with different technological characteristics. For example, the potential for manufacturing in a more decentralised manner is often discussed in the literature on AM (Braziotis et al., 2019; Khajavi et al., 2014; Mohr and Khan, 2015). Additive manufacturing provides greater potential for local sourcing (Glas et al., 2020; Meyer et al., 2020b, 2021).

An empirical analysis within a global procurement organisation based on a time-cost comparison Meyer et al. (2020a) showed that sourcing objects with the same product design via TM resulted in a cost advantage. For example, a plastic gear part produced with injection moulding technology is 55% cheaper than the same part when printed. However, sourcing via AM has lead time advantages, as seen on the left side in Fig. 1. Overall, based on considerations related to AM technology and design, as well as AM time and cost results, AM has an ambiguous advantage in terms of sourcing when compared with TM. Going a step further, this points to the assumption that AM also has an ambiguous advantage when considering supply risks. This ambiguous advantage of sourcing by AM and TM in a supply portfolio is underpinned by the following examples.

On the one hand, supply risks may be reduced due to diminished supplier dependency and an increase in local sourcing (Meyer et al., 2020b). Lead time reductions may decrease the exposure to uncertainty. On the other hand, the increased discussion about intellectual property rights on AM's potential for direct manufacturing (Berman, 2012) within the coronavirus pandemic (Mahr and Dickel, 2020) presumes an increased vulnerability for a supply organisation. CAD data might contain sensitive information that has high plasticity (Moradlou et al., 2020), and its control against opportunistic supplier behaviour may become difficult for a procurement organisation (Picot, 1993). On the one hand, this is in line with previous research which identifies suppliers

Table 1
Production-related differences between AM and TM.

Category of Difference	AM	TM	Example Reference
Interaction of the virtual and physical world	***Immediate*** *production of products based on CAD data*	***No immediate*** *production of products based on CAD data*	Tuck et al. (2007)
	Only changes to CAD data *required for modifying component*	***Changes to various process steps*** *required for modifying component*	Holmström and Partanen (2010)
Specificity	***'Tool-less'*** *manufacturing*	***Numerous tools*** *required*	Eyers and Potter (2015)
	Blurred transition between *manufacturer and consumer*	***Strict separation of manufacturer and consumer***	Waller and Fawcett (2014)
	Prospect of ***decentralised*** *manufacturing*	***Centralized*** *manufacturing*	Khajavi et al. (2014)
	Synchronous *production of different products*	***Sequential*** *production of different products*	Ghadge et al. (2018)
Cost structure	***More limited cost reduction effect due to economies of scale***	***Strong cost reduction effect due to economies of scale***	Sasson and Johnson (2016)
	Consistent *costs as component complexity increases*	***Increase*** *in costs as component complexity increases*	Baumers and Holweg (2019)
Resource efficiency	***High*** *material utilisation*	***Low*** *material utilisation*	Baumers et al. (2017)
	Direct production *of functional assemblies*	***Multiple process steps*** *and single components required for the production of assemblies*	Attaran (2017)

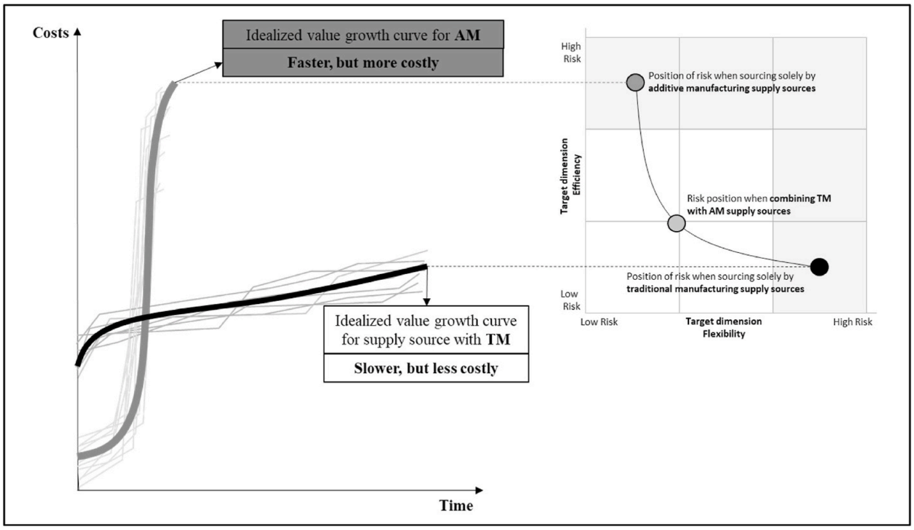


Fig. 1. Time-cost-comparison of AM and TM (Meyer et al., 2020) as an indication of the ambiguous advantageousness of AM.

as an important risk source, but with an additional risk category caused by the value of digital information exchange (3D data) with suppliers (Zsidisin and Wagner, 2010). As shown in Fig. 1, the cost/time relationship must be supplemented by a portfolio that is commonly used in supply chain risk research (Pettit et al., 2010) (and, as discussed later, in financial risk management as well). An AM supply portfolio could cause supply risks due to a competitive disadvantage in the form of diminished cost reduction capabilities (Zsidisin, 2003) due to more limited economies of scale compared to TM. This duality was addressed by our initial assumption.

2.2. Treating potential losses or gains of TM and AM: establishment of a hedge position

Many risk treatment approaches for operational risks, such as supply risks, have emerged from financial risk management (Mitchell, 1995). MPT Markowitz (1952) represents an important developmental step (Ritchie and Brindley, 2007). It assumes a risk-averse, benefit-maximising, and rationally acting investor who wants to calculate the optimal combination of arbitrarily divisible assets in the conflict of return on investment and risks. This is expressed using the efficiency line, in which there is no lower risk for the portfolio with the same return expectations. The risk is operationalised as the statistical standard deviation (σ) from the expected earnings value of the return (μ) based on historical data. Using the portfolio view, financial investments that are not fully correlated can be combined so that the overall risk is minimised owing to the diversification effect. The more negatively the two investment alternatives correlate, the lower is the portfolio's risk position. This shows that it is not the number of investments that are decisive for portfolio diversification, but their correlation. Fig. 1 shows two potential investment alternatives (large dots). If the correlation of the investments is the same ($p = 1$), no additional risk minimisation by diversification is possible by combining both investment alternatives since they have the same risk sensitivity. In this case, the total risk corresponds to the average risk of the mixed ratio of both investment shares. In the case of a different risk sensitivity with correlation $p < 1$, a minimisation of the total risk position by means of the diversification effect is achieved by combining both investment alternatives, which results in a hyperbola bent to the left. A selection of the optimal mixing ratio can be made based on investors' risk preferences. When a correlation of $p = -1$ is reached, the risk can theoretically be eliminated completely, resulting in a risk-free portfolio that has no dispersion from the expected value and can be considered deterministic. The establishment of an opposing position that correlates as negatively as possible to the current risk position is referred to as hedging (Oehler and Unser, 2001). Hedging aims to safeguard financial investments by building a 'hedge' in searching for investment alternatives that best offset potential losses or gains (Seidl, 2000). This idea may also be applied to risk positions in the sourcing portfolios. If the first initial assumption is confirmed, and AM has an ambiguous advantage compared to TM, then a combination of AM and TM has the potential to optimise the total supply risk. This may result in a multi-manufacturing sourcing strategy in which TM supply sources can be hedged against supply risk by AM supply sources (Fig. 1).

Using multiple supply sources with the same manufacturing technology has been established within the PSM literature (e.g., Costantino and Pellegrino, 2010). Several recent studies argued in favour of such usage, Khajavi et al. (2015) demonstrated that AM use within a new product launch of TM components (in which a manufacturer is exposed to high risks) could be mitigated using an overlapping production phase in which TM and AM were used in combination. Roscoe and Blome (2019) showed that a mix of centralised manufacturing systems and flexible redistributed manufacturing systems complemented one another. Tomlin and Wang (2005) showed via a newsvendor model that using a dedicated supply source along with a flexible supply source was beneficial in situations where demand was unreliable. Thus, the demand-pooling benefit of the flexible resource increases as the number of products increases, and their demand is negatively correlated.

After explicitly considering AM in sourcing, Glas et al. (2020) it was suggested that procurement should use AM to decrease the supply risk of bottleneck items within the Kraljic matrix (Kraljic, 1983). Meyer et al. (2020b) suggested that 'procurement might integrate AM into concepts that minimise supply-side risk […] hedging traditional manufacturing methods with AM is an option to address supply risks'. Meyer et al. (2020a) exemplifies based on case study research of new buy and rebuy

Initial assumption 1:

AM has an ambiguous influence on supply risk in a sourcing portfolio.

situations (Robinson et al., 1967) of a globalised procurement organisation that PSM needs ' … a diversified perspective on the use of the respective potential [on which] the mix of negatively correlating risk positions ('hedging' AM and TM) [becomes] necessary and can be used to optimise the overall performance'. Knofius et al. (2020) showed via a simulation study that AM was beneficial as a dual sourcing option for spare parts and therefore increased the effectiveness of a total sourcing portfolio. The existing literature points to the second initial assumption.

Our assumptions were tested using the Delphi technique for supply risk identification and assessment by considering alternative sourcing options (single sourcing via TM, single sourcing via AM, and hedged sourcing). Supply risks for a procurement organisation were analysed based on these sourcing alternatives for a supply portfolio, as shown in Fig. 2.

3. Delphi study methodology and procedure

The Delphi technique incorporates a multi-stage procedure that focuses on the systematic collection, consolidation, and analysis of multiple expert opinions (Gordon and Helmer-Hirschberg, 1964). It was developed in the 1950s by the RAND corporation to support the decision-making process by forecasting the development of strategic decisions and technology use in war. Since then, it has been further developed and refined across several scientific disciplines. Multiple methods of execution and fields for application exist for a Delphi study, including the use of a formalised questionnaire, interviewing of experts, anonymous individual answers, determination of a statistical group answer, communication of the group answer to each individual, and multiple repetitions of the survey (Häder and Häder, 2000). According to Grime and Wright (2016), Delphi techniques should be applied where the consequences and outcomes of complex problems, expensive endeavours, and uncertain outcomes need to be predicted. This is applicable to the use of new technologies, such as AM, in modern PSM.

The Delphi technique is highly recommended as an instrument for supply risk identification and assessment in PSM research (Harland et al., 2003, 2005; Zsidisin et al., 2000) and even in other disciplines (e.g., Hallowell and Gambatese, 2010; Haynes and Robinson, 2021; Watson et al., 2017). The use of multiple experts improves the objectivity of risk assessment (Zsidisin et al., 2000) because risks are subjective and their perceptions vary among individuals (Grudinschi et al., 2014; Juha and Pentti, 2009). Research has shown that Delphi studies provide a better outcome than conventional expert interviews (Häder and Häder, 2000) and offer better insights when traditional historical datasets are not available (Gupta and Clarke, 1996). The procedure used in the current study to identify and assess supply risks for TM, AM, and a hedged sourcing approach can be seen in Fig. 3, which distinguishes between the tasks to be performed by the monitoring group (researchers) and the tasks performed by the expert group (Grime and Wright, 2016). The adequate selection of the expert group represents the most critical aspect of a Delphi study because it strongly influences the validity and reliability of the outcome (Grime and Wright, 2016; Häder and Häder, 2000; Wolf, 2017). The process of study preparation and expert selection, data collection, group feedback, re-evaluation, final evaluation, and analysis (Wolf, 2017) will be discussed in the following section.

3.1. Study preparation and expert selection

The Delphi study was conducted from July to October 2020. In the preliminary stage, commonly discussed supply risks in traditional sourcing were identified within most prominent PSM literature journals, following Spina et al. (2015). *Purchasing and Supply Management, Supply Chain Management: An International Journal* and the *Journal of Supply Chain Management* were examined with the search string "supply risk". 81 articles were identified. By screening the articles, we came to a total of 25. By applying backwards snowballing (Wohlin, 2014), we identified 12 additional publications, From these sources 18 supply risks were identified, selected and consolidated by the monitoring group and provided the basis for expert risk assessment. Micheli et al. (2009) classify supply risks as either product- or demand-related, supplier, or market-related. This method of risk classification was chosen to provide an overview of the identified risks, as shown in Table 2.

The optimum number of experts to be surveyed varies in the literature. Wolf (2017) suggests a minimum of seven experts, whereas Grime and Wright (2016) suggests five to 20 experts and Häder and Häder (2000) suggest five to 25 experts. Delphi studies within PSM research include Ogden et al. (2005), who proposed five to 30 experts, and Harland et al. (2005), who proposed 30 experts. An experiment by Duffield (1993) showed that two different groups (n = 16, n = 32) in a Delphi study showed 92.9% conformity, which suggests that larger-scale studies may not be required. A total of 30 experts were chosen for the current study. Therefore, we applied a purposeful sampling strategy (Patton, 2002), which aims to select a (small) homogenous group concerned with the same phenomenon. Because this study analyses AM and hedging in the context of supply risk, it is important to consider informants with appropriate knowledge about the topic within a homogenous setting. The selection criteria for the expert group participants were profound expertise in additive manufacturing in combination with procurement or risk management expertise. This can be expressed by the following Boolean logic operator: ('Profound expertise in AM') *AND* ('Profound expertise in RM' *OR* 'Profound PSM-knowledge') and secures the individual's ability to report accurately and comprehensively on perceived latent constructs. Expert status was identified and validated based on their knowledge of AM at a professional, academic, or practical level. A Delphi allows a holistic analysis but also potentially allows to distinguis between groups. For future-oriented settings a holistic and sligthly heterogenous sample can mitigate cognitive biases (Beiderbeck et al., 2021). This study aims for a holistic analysis and does check for sub-group bias but is not intending sub-group analysis.

The objective was to map a common level of expertise and knowledge across a heterogeneous spectrum of sectors, industries, and hierarchical levels (Grime and Wright, 2016). Potential candidates were identified based on their professional career (e.g., via LinkedIn or Xing groups focusing on AM) or based on existing research partnerships (e.g., within the automotive, aerospace, and defence industries). After the screening process, 107 potential experts were invited to participate. Thirty individuals, which were located within Germany, participated in the first round of the Delphi study. Due to panel mortality, 28 participants participated in the final round of the study. Examples include a planning engineer from the automotive sector responsible for prototyping and small series production, a procurement team leader responsible for sourcing AM demands, a supply risk consultant with project experience in AM spare parts management, and a scientist with both PSM research experience and AM project experience. The distribution of experts is shown in Table 3, which shows a heterogeneous distribution

Initial assumption 2:

Hedging TM with AM has a positive effect on supply risk within a sourcing portfolio.

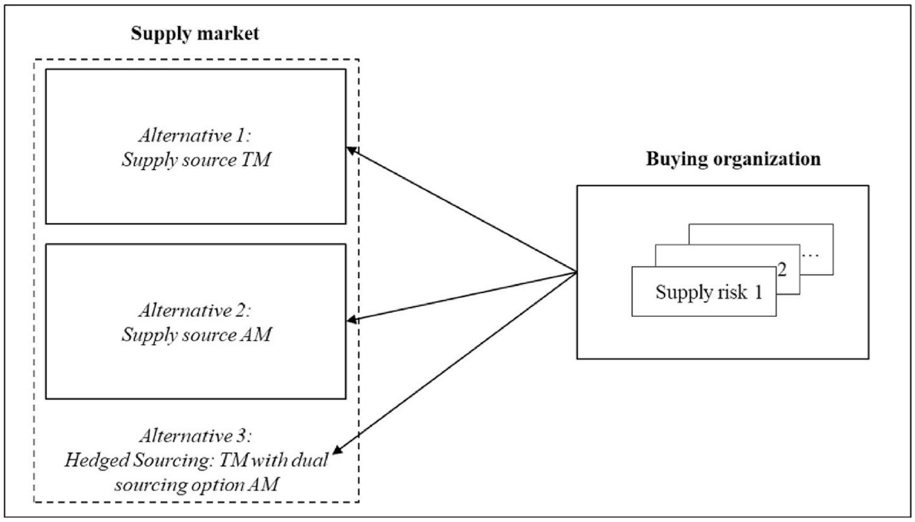


Fig. 2. Focus of the research.

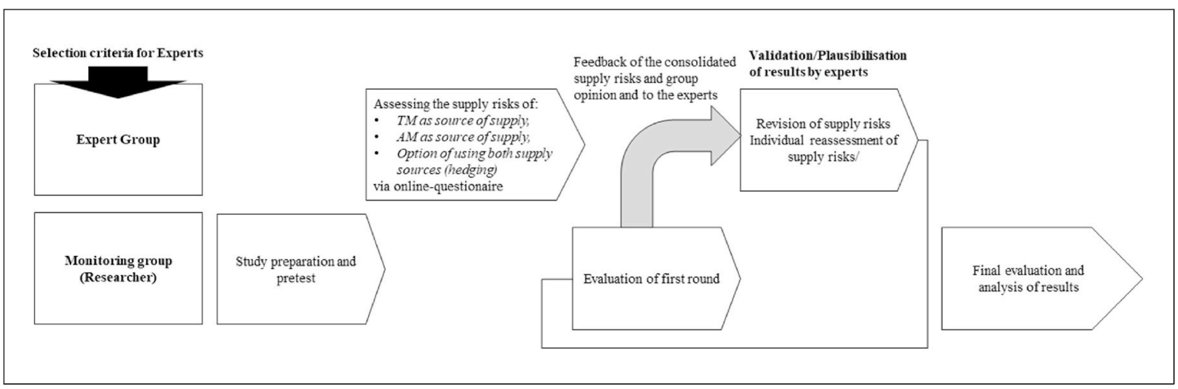


Fig. 3. Risk identification and assessment via a Delphi study.

Table 2
Overview of the identified and selected supply risks.

Classification	Supply Risk	Exemplary reference
Demand- related	*Ex-post product design changes*	Zsidisin et al. (2000)
	Volume requirement changes	Manuj and Mentzer (2008)
	Product mix changes	Blackhurst et al. (2008)
Supplier- or market-related	*Supplier dependence*	Sinha et al. (2004)
	Lack of alternative suppliers	Micheli et al. (2009)
	Supplier capacity constraints or long cycle times	Zsidisin (2003)
	Lead time risk	Micheli et al. (2009)
	Innovation capability of supplier	Matook et al. (2009)
	Market shortage	Zsidisin (2003)
	Cost reduction capabilities	Beaumont and Sohal (2004)
	Loss of knowhow or IP to supplier	Lonsdale (1999)
	Price fluctuation	Zsidisin et al. (2000)
	Technological changes or obsolescence	Svensson (2000)
	Financial risk of supplier	Zsidisin (2003)
	Sustainability risks	Micheli et al. (2009)
	Loss of insourcing capabilities	Aron et al. (2005)
	Physical distance from supply source	Giunipero and Eltantawy (2004)
	Supplier location risks or disasters	Zsidisin et al. (2000)

Table 3
Distribution of experts.

Sector		Hierarchy	
Services	10.7%	Managing director	14.3%
Public	25.0%	Division or department manager	14.3%
Science	17.9%	Group or team leader	25.0%
Industry	46.4%	Clerk	46.4%
Industry			
Automotive	18.4%	Engineering	16.3%
Energy	6.1%	Medical	4.1%
Consumables	4.1%	Logistics	6.1%
Aerospace	12.2%	Administration and defence	24.5%
Other	8,2%		

among sectors, industries, and hierarchies. It is important to mention that one expert can be affiliated with multiple industries. Prior to the actual risk assessment, a pre-test was conducted with a test group consisting of an AM-Technology expert from the automotive industry, a professor in supply management with a research focus on AM and a supply risk management expert within the defence sector to provide a consistent understanding of the questions, to eliminate potential misunderstandings, and to test the procedure.

3.2. Data collection

The data were collected using an online survey tool (UniPark). An introductory video was shown in which the task of supply risk identification and assessment was explained. The context of the SARS-CoV-2 pandemic resulting in supply shortages was explicitly mentioned to provide indications of the study's practical relevance. The experts chose a physical sourcing object of their own supply organisation (for which the later risk identification and assessment was executed). The sourcing object was chosen according to Hesping and Schiele (2015) the argument that decision making in PSM addresses the right level of analysis. The specification was that the sourcing object needed to have exactly the same design, which could be obtained within the same quality by TM as well as via AM. In terms of product design and life cycle characteristics, we examined the functional product (Fisher, 1997; Lee, 2002). Demands which were optimised in product function (individual product) were not considered, as our premise required the same product quality and design for TM and AM demand.

This depends on the premise that quality risks are excluded from the assessment. Therefore, the demands from the polymer (e.g., air filter box) or metal (e.g., cowling) were chosen. Component specifics such as sourcing frequency (measured as a demand level of 0–20 per month, 20 to 1000 per month, and 1000 or more per month) and asset specificity (measured as 1 = *very unspecific* to 3 = *very idiosyncratic*) were queried from each sourcing item assessed by each expert. As a matter of fact, different sourcing items face different risks, but this study is mainly interested to investigate risk differences for AM and TM supply.

Along with the 18 individual supply risks, the experts could include additional supply risks that they perceived as relevant for AM or hedging. This was useful for further supply risk identification as some additional risks for AM might not have been included in the already-treated supply risks for TM from the PSM literature and complements the step of risk identification already extracted from PSM literature.

As part of the second step of the risk management process, risks were assessed by the expert group based on the probability that the event would occur. The significance of the consequences and potential losses for the buying organisation was also assessed (Hallikas et al., 2004; Harland et al., 2003). Following the work of Hallikas et al. (2004), risks were assessed on a five-point scale based on their probability of occurrence (1 = *very improbable* to 5 = *very probable*) and their consequences for the buying organisation (1 = *very low consequence* to 5 = *very high consequence*). Each risk was assessed for TM, AM, and a hedged supply source. Additionally, each risk was assessed on the basis of its relevance (1 = *low relevance*, 5 = *high relevance*) to enable a later aggregation of the individual risks to the total risk. This contribution was based on a weighted risk assessment, which uses the degree of relevance for weighting and aggregation (Xiao et al., 2011). A high relevance indicates that individual risk has a strong influence on other risks and should be treated more carefully, whereas a low relevance indicates that an individual's risk has little or no influence.

3.3. Group feedback and re-evaluation

The researchers consolidated the risk assessments made by each expert. The methodology of the Delphi technique mandates the provision of feedback to each expert about the group estimation using a feedback sheet. This should show the group estimation as either the mean or median (Grime and Wright, 2016). As the mean could lead to a distortion of the results on a five-point scale (Wolf, 2017), the median was used. Additionally, the 0.25 quartile and 0.75 quartile were calculated for each individual risk. This was provided to the experts to show the range of variance in the submitted evaluations. The information was displayed in a box plot diagram for each individual supply risk and the expert's previous assessment segmented by probability of occurrence, consequences for the buying organisation, and the relevance of the risk within a supply portfolio. The expert was asked to either retain their original opinion or adjust it based on this information.

A feedback and adjustment loop is required to achieve a stable group option or stable estimation poles (Wolf, 2017). The Delphi technique requires at least one time the possibility for experts to adjust their estimations (Gordon and Helmer-Hirschberg, 1964; Linstone and Turoff, 1975). Although further rounds of loops are possible, no significant adjustments by the experts occur after the first feedback round and the group poles have already developed to a steady-state. (Linstone and Turoff, 1975). Therefore, the initial feedback loop was used to validate the results. Typically, the standard deviation (SD) is reduced (0.25 quartile and 0.75 quartile aligned with the median) during the 2nd round of the Delphi study (Gupta and Clarke, 1996), while the median and the poles of opinion remain stable. This can also be seen in our results (see Attachment 1). The aim of the subsequent risk assessment is not to create an expert consensus, but map their spectrum of risk assessment and reduce subjectivity by comparing and checking the individual expert assessment. However, the achievement of a stable expert opinion and, thus, no additional need to perform an additional round of expert assessment can be operationalised by means of a coefficient of variation. If this is below 0.5, an adequate consensus has been reached, and no additional rounds are necessary (Dajani et al., 1979; Shah and Kalaian, 2009). Although a single round of feedback was deliberately chosen, it was also possible to achieve a coefficient of variation 0.5 of 106/108 items (see Attachment 1).

4. Final evaluation and analysis of results

A risk map is a common way of overviewing the assessed risks (Fan and Stevenson, 2018; Hallikas et al., 2004). Fig. 4 shows the mean values of all expert assessments submitted for individual risks according to their assessed relevance within a sourcing portfolio. This is a holistic analysis of all assessments. Sample analysis provided no indication that sub-groups exist that are of relevance. There is also no indication for sub-group bias.

The findings show that supplier dependence was considered the most prominent risk, while supplier location risks such as natural hazards were perceived as largely irrelevant. Within the risk map, each individual risk is represented twice: once for exclusively sourcing via TM (black) and once for exclusively sourcing via AM (orange).

The risk evaluation of TM and AM supply sources shows a differentiated movement of several individual risks and a large spread of individual risks from AM and TM. Notably, several risks decreased, such as supplier dependency, ex-post product design changes, or the possibility of insourcing. It can also be seen that AM does not consistently have a positive effect on every risk position. Several risks, such as the potential loss of knowledge and IP and the inability to reduce costs or price fluctuations increases sharply. Other risks, such as a lack of innovative capacity or sustainability risks, remain unaffected. Overall, the results show that the sourcing of demands via AM has a different, mostly opposite risk profile to the sourcing of demands via TM.

Therefore, the results indicate that AM is not fundamentally superior to TM (and vice versa). By considering only TM and AM as supply alternatives, the 'optimal' sourcing type depends on the specific sourcing situation. However, the SARS-COV2 pandemic has shown that specific sourcing situations can change extremely sharply and quickly if, for example, a standard product 'mask' suddenly becomes a strategic bottleneck. Therefore, the experts were asked to assess the risk if *both supply sources were used at the same time* (hedging). Individual risks are represented in a risk map (see Fig. 5). It can be seen that the risks for hedging (grey) are less segregated, which means that they form a significantly more homogeneous cluster. The cluster is settled lower, as more individual risks are now within the medium (yellow) and low (green) quadrants. There was no single risk in the high-risk quadrant (red). This gives the first indication that a hedged source of supply minimises the overall risk position based on our assumptions made by the MPT.

Nevertheless, this figure provides only a first indication; a direct comparative approach is still missing. Risk (R) can be calculated as the product of the probability of occurrence (P) and the severity of its impact

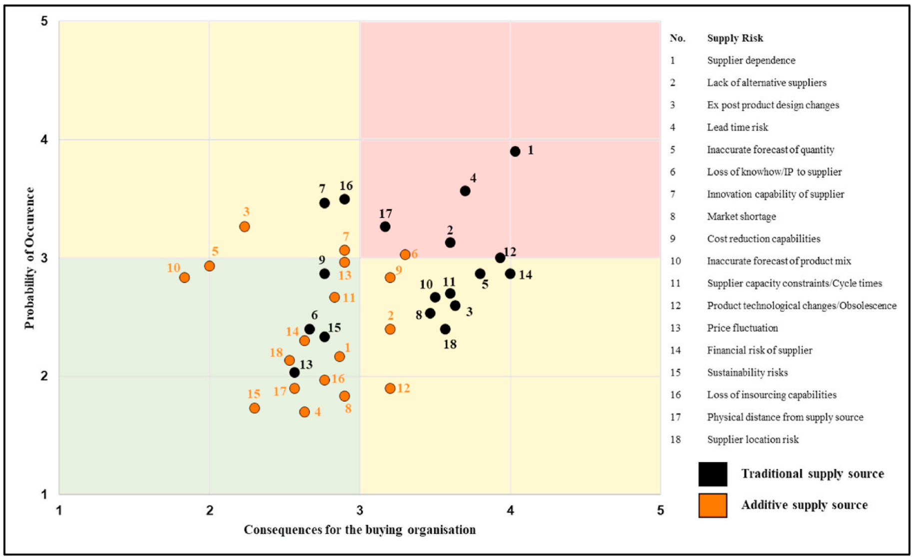


Fig. 4. Presentation of the TM and AM risk assessment within a risk map.

Fig. 5. Presentation of the risk assessment for hedged sourcing within a risk map.

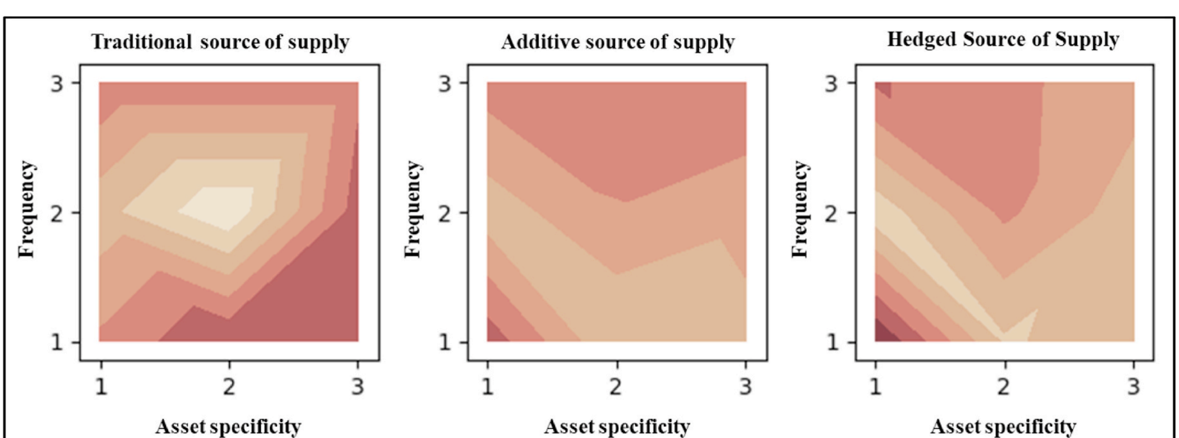


Fig. 6. Heatmap for each sourcing object.

(I) (Christopher and Peck, 2004; Harland et al., 2003). An exact value for each individual risk can be calculated as shown in Equation (1).

$$R = P \, x \, I \qquad \text{Equation (1)}$$

A common method for risk calculation is the risk priority number (RPN), which is expressed as the product of the probability of occurrence, severity of impact, and detectability. Several modifications exist, and single risks can be aggregated into the total risk. A weighted factor can be used for risk aggregation (Xiao et al., 2011), which is expressed in the form of risk relevance (r). Therefore, the total risk calculation of an assessed sourcing object by an expert can be expressed by taking the sum of each individual risk multiplied by its assessed relevance, as shown in Equation (2).

$$R_{Sourcing\ object} = \sum_{Risk\ 1}^{Risk\ 18} r \, x \, P \, x \, I \qquad \text{Equation (2)}$$

The supply risks for each assessed sourcing object can be compared based on its denoted asset specificity and the frequency of each supply alternative. This comparison is presented with a six-colour scale interpolated in a heat map for each individual sourcing alternative (see Fig. 6). The colour represents the degree of risk; a light colour represents a lower risk, and a darker colour represents a higher risk. This figure shows that the risk for TM supply sources is highest in the case of highly specific components and specific components at all quantities. Additive sources of supply have their highest risk position with unspecific components and specific components in large quantities. It can be seen that frequency has a greater influence on the overall supply risk, while asset specificity becomes subordinate which can be seen as a result of the AM characteristics mentioned above, especially tool-free immediate operation capabilities. This provides further insights into the divergent supply risk sensitivity of an AM and TM supply source, which indicates a more negative correlation between both supply sources. For the hedged sourcing approach, sourcing objects with low asset specificity results in a high-risk position. The use of a hybrid supply channel (hedging) has the lowest risk position, especially for specific sourcing objects in medium and large quantities.

To provide a comparison for a total sourcing portfolio, all individually rated sourcing objects from the 28 experts are summarised (as shown in Equation (3)). It must be noted that only an estimation can be made about the portfolio risk; an exact risk determination would require further conditions such as knowledge of the distribution of probabilities and losses (Gleißner, 2014).

$$R_{Portfolio} = \sum_{Expert\ 1}^{Expert\ 28} R_{Sourcing\ object} \qquad \text{Equation (3)}$$

The value for the total portfolio risk was 15.826 for TM, 10.357 for AM, and 9.655 for hybrid, which shows that the lowest risk position was in fact achieved by sourcing with a hybrid approach. It seems that a hedged supply-based strategy lowers risk exposure, following the approach of supply-based strategies as a key element for resilient supply chains (Christopher and Peck, 2004).

5. Evaluation of results

The results show that sourcing via AM shifts supply risk, but is not entirely superior to TM sourcing, which validates our initial assumption 1. On the other hand, a combined approach of sourcing using TM and AM seems to minimise supply risk, as stated in our initial assumption 2. Next, an explorative discriminant analysis was performed. The results of the Delphi study will be used to check whether the supply sources TM, AM, and hedged sourcing of both can be significantly differentiated based on supply risks. A clear separability on the basis of supply risks would thus prove that the combined sourcing approach can be distinguished from TM sourcing or AM sourcing, and represents a real supply source alternative (e.g., the application by Carter et al., 2006). A discriminant analysis is a statistical structure-testing procedure, used to distinguish between two or more naturally occurring groups on the basis of characteristic variables and can also determine which variables are the best candidates for the groups. Methodologically, the following is based on Backhaus et al. (2016). First, the groups have to be defined, on which the three reference supply alternatives evaluated in the Delphi study were chosen. To formulate the discriminant function, characteristic variables are needed, which later discriminate the defined groups. For this purpose, the individual supply risks divided by the probability of occurrence and impact were used. Because the number of selected groups must not be larger than the selected characteristic variables, this is suitable for a closer analysis (Backhaus et al., 2016). Using SPSS, two discriminant functions were estimated for the three groups. The evaluation of the classification results (see attachment 2) shows that 95.6% of the cases were correctly classified. The quality criterion here is that the classification accuracy should be 25% greater than the classification probability obtained by chance, giving the model a satisfactory predictive power (Malhotra, 2010). The canonical correlation associated with these functions (see Table 12) was 0.883 for f1 and 0.812 for f2. The square of this correlation is 0.780 for f1 and 0.659 for f2, indicating that this model explains 78% (f1) and 65.9% (f2) of the variation in risk assessment disparity. Further quality criteria of a discriminant function are the eigenvalue, Wilk's lambda, chi-square, and significance (Backhaus et al., 2016). The significance of the discriminant function was examined using Wilks' statistics. The Wilks' lambda values were low at 0.075 (f1) and 0.340 (f2), resulting in a $\chi 2$ of 196.000 at 72 degrees of freedom ($p = 0.000$) for f1 and a $\chi 2$ of 82.974 at 35 degrees of freedom ($p = 0.000$) for f2. The p-values indicate that the model is highly significant and has explanatory power. This shows that the null hypothesis that the defined sources of supply do not differ from each other in terms of supply risks can be rejected (Malhotra, 2010).

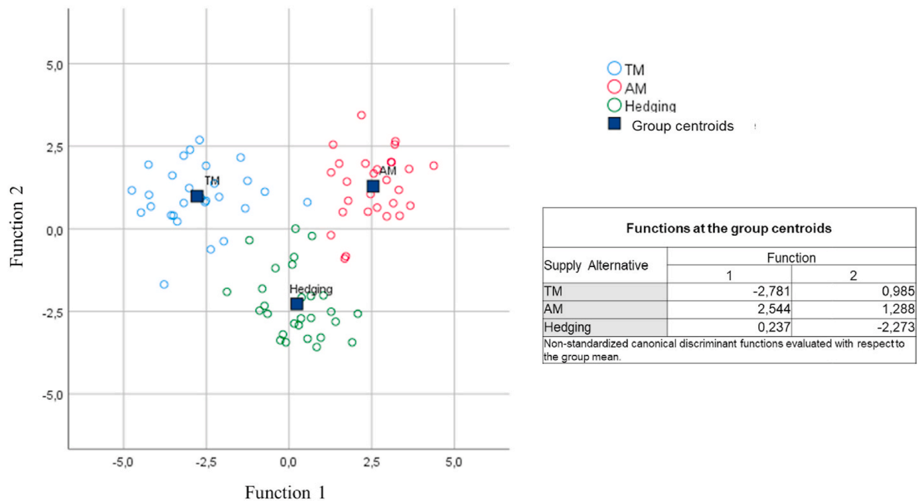
The visualization of the feature variables in the discriminant space with their group centroids (see Fig. 7) shows the distance between the group centroids. Additionally, the low overlap of the characteristic variables further validates the separability of the supply sources based on their supply risks.

Additionally, the weighting of each supply risk to discriminate the functions was analysed. First, the univariate separability of each characteristic variable was examined (see Attachment 4). Thus, apart from the characteristic variables of the probability of occurrence of the product mix changes, volume requirement changes, location risk of the supplier, financial risk of the supplier, capacity risk, the impact of missing alternative suppliers and innovation risks, as well as the supply risk of market shortages and a lack of cost reduction possibilities, a sufficient significance ($p \leq 0.05$) is given at an error probability below 5% (Backhaus et al., 2016). To analyse the relative importance of the predictor variables based on their discriminatory significance, the mean standardised discriminant coefficient was calculated (see attachment 4). This reveals that, especially for product mix changes, a long distance to the supply source, the probability of occurrence of long lead times, lack of innovation capability of the supplier, lack of alternative suppliers, the location risks of the supplier (no significance), and the lack of insourcing possibility have a high group discriminatory importance. Nevertheless, due to multicollinearity, which increases in the analysis of risks among each other, the relative weighting may be distorted (Dempster, 2002). Validation of the null hypothesis was not affected by this. Therefore, the discriminant analysis further supports the finding that supply risks can be distinguished by manufacturing type.

6. Discussion

6.1. Potential bias in risk assessment due to COVID-19

Our results indicate that hedging a TM supply source with an AM supply source has a positive influence on the overall sourcing portfolio risk position. In the context of risk assessment, it must be pointed out



Functions at the group centroids

Supply Alternative	Function 1	Function 2
TM	-2,781	0,985
AM	2,544	1,288
Hedging	0,237	-2,273

Non-standardized canonical discriminant functions evaluated with respect to the group mean.

Fig. 7. Group representation in discriminant space.

that risk perception is an elementary topic of psychometric research, in which characteristics of the individual himself (so-called ‘attention based view’ see (Lorentz et al., 2019) as well as external influences affect the risk assessment (Renn and Zwick, 1997). Generally, risk assessment faces a central tendency error (Hollingworth, 1910), meaning that risk clusters are strongly aligned toward the scale centre. In particular, the third sourcing alternative of dual TM and AM sourcing reveals this tendency. The first part of the discussion discusses our findings in light of the external influences in this study’s risk assessment.

Several reasons, e.g., the SARS-CoV-2 pandemic 2020, the strong media presence of supply risks, and the experts’ own concern about supply bottlenecks, can represent characteristics for exaggerated risk perception. Since the Delphi study was conducted shortly after the collapse of global supply chains in the wake of the SARS-CoV-2 pandemic, the risk assessment may have been overestimated, especially for a TM supply source. The risk of supplier dependency for TM, in particular, is rated as very high, whereas none of the supply risks of the other procurement alternatives are even close to this level. Thus, it can be assumed that for TM in particular, the risk assessment is higher than under non-pandemic circumstances. Additionally, the distribution of experts shows that 25% are in the administrative and defence sectors. In particular, the defence sector is defined by high demands on the reliability of supply (Glas, 2012), so that a low-risk threshold prevails; thus, the assessment could be biased upwards as compared to experts from the automotive industry. Nevertheless, all have global supply chains, which were affected due to COVID-19. Consequently, the risk of TM and AM may be overestimated. Even if this is the case, this would not make our findings obsolete, because the hedging effect would be smaller, but still present.

6.2. Risk assessment evaluation

Next, we discuss the risk assessment findings in relation to previous research on the topic. Generally, the risk assessment from the Delphi study is in line with the risk assessment of previous research. For example, the assessment of supply risks by Sheffi and Rice (2005) shows that risk #17 (physical distance risk) matches their transportation risk and is equally probable and serves as in the findings of our study. Another example is the assessment of Thun and Hoenig (2011) which shows delays of transport high probability and medium impact, which coincides with Delphi study’s results. The supplier’s location risk #18 of our Delphi study matches all comparative studies, which further indicates the validity of the risk assessment. An assessment of supply risk #12 (technology risk) by Sheffi and Rice (2005) and Thun and Hoenig (2011) places it in the low probability and high impact quadrant, which in our risk assessment is located at medium probability and high impact and thus shows a slight increase. The risks of an ex-post product adjustment (#3), as well as the incorrect forecast of the number of units (#5) and product mix (#10) are located in the high probability and low impact quadrant for Oke and Gopalakrishnan (2009) and in the high probability and high impact quadrant for Thun and Hoenig (2011). In the Delphi study, these risks are located at a medium frequency and high impact. Furthermore, all three studies list the losses of the core supplier. Dependence (#1), as well as the lack of alternative suppliers (#2) in the case of a high supply share, define a core supplier (Kraljic, 1983). Thus, this can be used for comparison and is consistent with the results of Sheffi (2005) and Thun and Hoenig (2011) and further validate the results of the risk assessment of the TM supply source.

Next, we compare The Delphi risk assessment of the AM supply source with the current known barriers to AM adoption (Durach et al., 2017; Dwivedi et al., 2017; Huang et al., 2017) to further validate the results. In our risk assessment, we see an increase in the missing possibility for cost reduction (#9), and increased loss of know-how/IP (#6) in comparison to TM supply source, which corresponds with the known barriers from the literature. Qualitative limitations AM were excluded from this study because the evaluation basis of the experts represented an equal component quality.

6.3. Conceptualization of AM and TM hedging in a portfolio model

Our findings confirm the assumptions from MPT that a hedged sourcing approach of TM and AM provides a lower risk position for a supply organisation. The discriminant analysis suggests that hedging provides a valid sourcing alternative for procurement organisations (with their own risk characteristics) compared to TM and AM. Discriminant analysis further confirms that hedging can be seen as an alternative to TM or AM. This supply risk-mitigating effect of TM AM hedging could help build resilient supply chains (Pettit et al., 2010). Generally, hedging is a risk strategy in supply management, which is used for dual sourcing (Chen, 2017) or even hedging weather event exposure in the context of supply chain management (Brusset and Bertrand, 2018). Our findings support the hedging effect of MPT, which is linked to AM technology and PSM research.

Therefore, we conceptualise a portfolio model of TM, AM, and hedged sourcing based on our findings. Portfolio models, for example, Fisher (1997); Kraljic (1983); Lee (2002); Olsen and Ellram (1997) are typically used in PSM research for structuring and segmenting procurement objects or supply markets on which standard strategies are applied (Wagner and Johnson, 2004). Here, we use a portfolio model to systematise the sourcing decision of the risk-optimal arrangement of TM

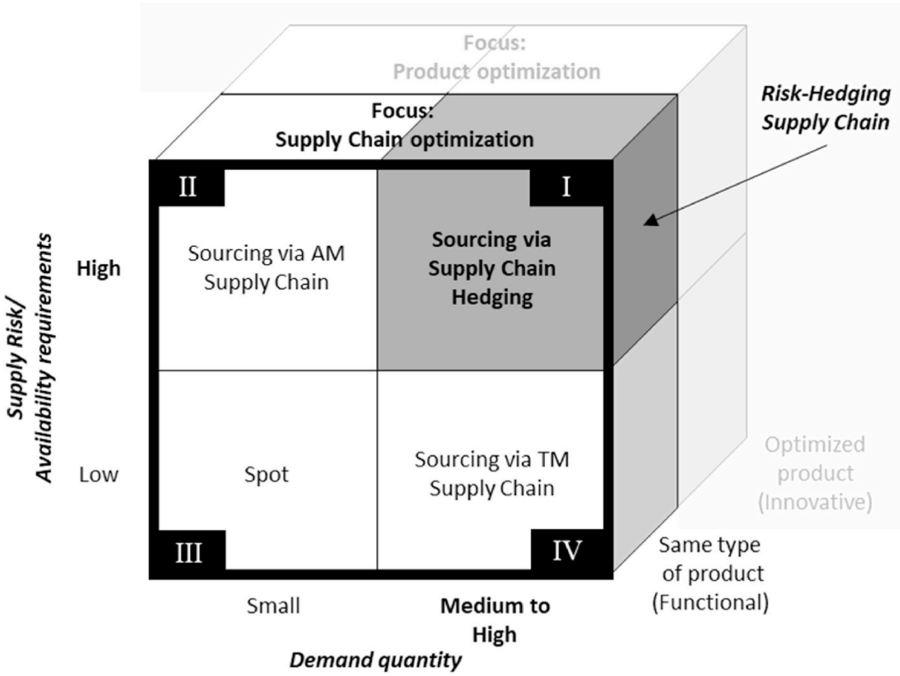


Fig. 8. Portfolio model: Risk treatment of supply risk via Hedging TM-AM.

and AM (see Fig. 8). The dimension selection was based on the empirical validation of this research (see Fig. 7).

As seen in our empirical analysis, sourcing with a TM supply chain is advantageous in the sourcing of medium to high quantities to apply scale advantages under stable circumstances (Quadrant IV), whereas sourcing via an adaptable AM supply chain is beneficial for small demand quantity under high supply risks (Quadrant II). Therefore, hedging both supply chains becomes advantageous for a high demand quantity under high supply risk (Quadrant I), whereas buying spot (Quadrant III) can be applied for low quantities at low supply risk.

Our findings from the Delphi study link MPT with AM technology and sourcing considerations. Therefore, we propose hedged sourcing of TM and AM (Quadrant I). In the following, we critically analyse the MPT within sourcing for all quadrants within the sourcing portfolio.

First, procurement objects are contrary to the assumption that the MPT has no arbitrarily divisible goods. Thus, the distribution of a required quantity to different supply sources leads to a missing order utilisation per source of supply and thus to a minimisation of economies of scale, which increases the production costs of the procurement object (Costantino and Pellegrino, 2010). This results in the use of TM for medium to high quantities (Quadrant II). Additionally, it is difficult to achieve a negative correlation because TM supply sources usually have the same risk sensitivity. Thus, diversification by the industry of suppliers is hardly possible, particularly since the sources of supply mostly hold the same pre-suppliers. In addition, transaction costs, which are elementary in the context of sourcing, are excluded. In particular, transaction cost theory is regarded as a grand external theory of procurement (Spina et al., 2015). Thus, the existence of transaction costs reduces the economics of the diversification effect (Pogue, 1970). Thus, the marginal proceeds of diversification are positive and decrease with an increasing degree of diversification. On the other hand, transaction costs increase with an increasing degree of diversification (Markides, 1996). The general principle for risk treatment strategies is outlined by Kleindorfer and Saad (2005) the trade-off between investments for risk treatment techniques, and the expected loss due to the occurrence of the risk needs to be determined. Within sourcing, high initiation costs arise for an additional source of supply, especially for medium and high product specificity due to specific tools and machines (Costantino and Pellegrino, 2010). Besides procurement, objects with low specificity are already diversified by the market since the same unspecific product is offered by many suppliers (Picot, 1991), on which no hedged sourcing logic is required for quadrant III. The criticism of the MPT in sourcing shows that the diversification effect with hedging a TM supply source AM supply source in quadrant I is mostly small and only under high transaction costs due to uncertainty, asset specificity can be initiated, especially since a high frequency of supply further increases transaction costs (Williamson, 1981).

6.4. Is there a superiority of AM-TM-hedged sourcing?

In this chapter, we explain why for quadrant I, AM-TM sourcing is the superior norm strategy. The transaction costs for initiating a hedged AM supply source are lower than for a TM supply source, which deviates from transaction cost economics (TCE), on which asset specificity represents the major variable, which can be further distinguished into the site, physical assets, human assets, and dedicated asset specificity (Williamson, 1979). AM requires no tooling (Holmström and Partanen, 2010), stores knowledge in a transferable CAD-file (Chekurov et al., 2018), can be transferred to a physical object in an automated process on-demand with little to no supervision (La Torre et al., 2016), on which 'on demand', 'on location' supply is facilitated (Sasson and Johnson, 2016). Additionally, information and data gain further strategic importance compared to the physical world on which now products of medium and high specificity can be sourced on a variety of 'open access' platforms (e.g., Thingiverse) (Friesike et al., 2018) or shared by suppliers as preparation for business continuity management (Zsidisin et al., 2005) which enables access to CAD data at lower transaction costs. Transaction costs consist of information costs, agreement costs, execution costs, and control and adaption costs (Picot, 1991). As seen in the Delphi study, AM enables more alternative supply sources (#2) compared to TM and minimises lead times (#4) on which a simplified contracting initiating a supply relationship is drastically minimised. Additionally, adaption costs are expected to shrink as the impact of supply risks such as ex-post product design changes (#3), inaccurate forecast of quantity and product mix are diminished (#5, #10), and the risk of supplier dependency (#1) which creates a lock-in effect and increases switching costs (Wagner and Bode, 2006). This results in AM's technology matrix enabling the production of multiple components, so that every 3D printer can serve as a potential supply source (Kunovjanek and Wankmüller, 2021) and diversification even of industry sectors becomes possible. This can be considered as the sourcing flexibility of AM (Eyers et al., 2018). TCE provides insights that information and communication technology enables at the same transaction costs a higher degree of geographical distribution and insourcing (Picot et al., 1996) on which the degree of diversification to TM sources of supply can be further increased. Therefore, risk sensitivity and, thereby, the coefficient of correlation of the supply sources becomes more contrary. This becomes apparent by viewing the heatmap representation (Fig. 6) of the Delphi study.

The decrease in the initiation and adaption costs of sourcing products with high specificity provides the basis for AM to even become a dual supply source, whereas the flexibility in configuration at low transaction costs enables a hedged source on which the coefficient of correlation differs significantly, and supply risk is further decreased because of the increased diversification effect.

Nevertheless, our findings provide insights that especially the risk of losing strategic knowhow and IP (#6) requires safeguarding, which increases the control costs of strategic demands. Thus, an appropriate data infrastructure for exchange and protection (e.g., decentralised databases) needs to be used preventively (Miehle et al., 2019).

7. Conclusions

This study shows how AM can be used for risk mitigation in a sourcing portfolio. Therefore, it contributes to the under-researched area of the response/recovery stream of supply chain risk management (Natarajarathinam et al., 2009). Nevertheless, this study was limited by several factors. First, the qualitative risk assessment was limited because risk perception is subjective and varies among individuals (hence, the choice of the Delphi technique as a countermeasure). Second, the results of the Delphi technique varied between the selected experts and their spheres of knowledge. Although the sample of experts was carefully chosen, it could never fully depict reality. The sample is also limited to German experts, which represents the fourth biggest country for publications within research on AM and sourcing (Meyer et al., 2020b) and thereby provides a solid sample, on the other hand Germany is strongly dependend on globally sourced physical input material and therefore was strongly affected with 63,8% of companies facing supply shortages in July 2021 (ifo Institut, 2021) causing potential bias; all this calls for broadening empirical basis.

The discriminant analysis provided insights indicating that a hedged-sourcing approach can provide a valid alternative to TM and AM. A holistic framework was provided by adapting generic risk management strategies, providing a starting point for further deep dives. The sourcing arrangement of the hedge was proposed by utilising existing knowledge from MPT, providing the basis for a multi-manufacturing sourcing strategy in PSM by using a portfolio model (Wagner and Johnson, 2004), which nevertheless has points of criticism, such as the missing illustration of temporal dynamics, restriction on exclusively two dimensions, subjectivity in the selection of the dimensions, and missing focus on the operationalisation, measurement, and dimensions' delimits (Gelderman and van Weele, 2002; Gelderman and van Weele, 2005). However, the survey Gelderman and van Weele (2005) shows the adaptation of the portfolio goes along with professionalisation of the procurement function on which competitive advantages are generated and empirical evidence as well as theoretical foundation were used for conceptualization. Our portfolio model provides guidance for sourcing managers whether source by TM, AM or to use a hedged sourcing approach.

As the potential areas of applications are demonstrated, the question arises of how to arrange sourcing with AM from a contractual point of view, which is an essential part of future research. Additionally, research should further validate proposed risk hedging strategies quantitatively (e.g., simulation) to quantify the effect of hedged sourcing for a supply organization in an "what if scenario" (Stefanovic et al., 2009) as well as qualitatively (e.g., action and case study research) to provide an in-depth analysis (Eisenhardt and Graebner, 2007) of how to establish a hedged sourcing strategy within a supply organization.

Author statement

Matthias M. Meyer: Project Administration, Formal analysis, Writing - Original Draft, Methodology, Data Curation, Visualization, Conceptualization, Investigation.

Andreas H. Glas: Project Administration, Methodology, Data Curation, Validation, Supervision, Writing - Review & Editing,

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Declaration of competing interest

There are no conflicts of interest to declare.

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Appendix

Attachment 1

Comparison of Delphi round 1 to round 2. Showing the median, lower and upper quartile of the assessed supply risk (by probability P and impact I) for each supply alternative. The Coefficient of Variation (CoV) is pooled among all experts.

SR	Round 1									Round 2									CoV		
	TM			AM			H			TM			AM			H			TM	AM	H
	.25	M	.75	.25	M	.75	.25	M	.75	.25	M	.75	.25	M	.75	.25	M	.75			
3P	2.0	3.0	3.8	3.0	3.0	4.0	2.3	3.0	3.0	2.0	3.0	3.0	3.0	3.0	4.0	3.0	3.0	3.3	33%	23%	23%
3I	3.0	4.0	4.0	1.3	2.0	3.0	2.0	3.0	3.0	3.0	4.0	4.0	1.8	2.0	2.3	2.0	2.0	3.0	20%	46%	27%
5P	2.0	3.0	4.0	2.0	3.0	4.0	2.0	3.0	3.0	2.0	3.0	3.0	2.0	3.0	3.0	2.0	3.0	3.0	31%	28%	22%
5I	3.0	4.0	4.0	1.0	2.0	3.0	2.0	2.0	3.0	3.0	4.0	4.0	1.0	2.0	2.3	2.0	2.0	3.0	19%	48%	38%
10P	2.0	3.0	3.0	2.3	3.0	4.0	2.0	3.0	3.0	2.0	3.0	3.0	2.8	3.0	3.0	2.0	3.0	3.0	32%	26%	30%
10I	3.0	4.0	4.0	1.0	2.0	2.0	2.0	2.0	3.0	3.8	4.0	4.0	1.0	2.0	2.0	2.0	2.0	3.0	22%	39%	35%
11P	1.3	3.0	4.0	2.0	2.0	4.0	2.0	2.0	3.0	2.0	3.0	3.3	2.0	2.0	4.0	2.0	2.0	3.0	40%	40%	29%
11I	3.0	4.0	4.0	2.0	3.0	4.0	2.0	3.0	3.0	3.0	4.0	4.0	2.0	3.0	3.0	2.0	2.0	3.0	26%	28%	33%
9P	2.0	3.0	4.0	2.0	3.0	4.0	2.0	3.0	3.0	2.0	3.0	4.0	2.0	3.0	4.0	2.0	2.0	3.0	36%	38%	30%

(continued on next page)

Attachment 1 (*continued*)

SR	Round 1									Round 2									CoV		
	TM			AM			H			TM			AM			H			TM	AM	H
	.25	M	.75	.25	M	.75	.25	M	.75	.25	M	.75	.25	M	.75	.25	M	.75			
9I	2.0	3.0	3.0	2.3	3.0	4.0	2.0	3.0	3.0	2.0	3.0	3.0	3.0	3.0	4.0	2.0	3.0	3.0	28%	30%	25%
1P	3.3	4.0	5.0	1.0	2.0	3.0	1.3	2.0	3.0	3.8	4.0	5.0	1.0	2.0	3.0	1.0	2.0	3.0	26%	56%	43%
1I	4.0	4.0	4.8	2.0	3.0	4.0	2.0	3.0	4.0	3.8	4.0	5.0	2.0	3.0	3.0	2.0	3.0	3.3	22%	38%	33%
14P	2.0	3.0	3.0	1.3	3.0	3.0	2.0	2.0	3.0	2.0	3.0	3.0	1.8	2.0	3.0	2.0	2.0	3.0	24%	42%	28%
14I	3.0	4.0	5.0	2.0	3.0	3.0	2.0	2.0	3.0	4.0	4.0	5.0	2.0	2.0	3.0	2.0	2.0	3.0	21%	37%	36%
15P	2.0	2.0	3.0	1.0	2.0	2.0	2.0	2.0	3.0	2.0	2.0	3.0	1.0	2.0	2.0	2.0	2.0	3.0	26%	39%	23%
15I	2.0	3.0	4.0	2.0	2.0	3.0	2.0	3.0	3.0	2.0	3.0	3.0	2.0	2.0	3.0	2.0	2.0	3.0	35%	42%	33%
4P	3.0	4.0	4.0	1.0	2.0	2.0	1.0	2.0	3.0	3.0	4.0	4.0	1.0	2.0	2.0	1.0	2.0	2.3	21%	45%	46%
4I	3.0	4.0	4.0	2.0	3.0	4.0	3.0	3.0	4.0	3.0	4.0	4.0	2.0	3.0	3.0	3.0	3.0	4.0	19%	41%	27%
17P	2.3	3.0	4.0	1.0	2.0	2.8	2.0	3.0	3.0	3.0	3.0	4.0	1.0	2.0	2.0	2.0	3.0	3.0	29%	37%	26%
17I	2.0	3.0	4.0	2.0	3.0	3.0	1.3	2.0	3.0	3.0	3.0	4.0	2.0	2.0	3.0	1.0	2.0	2.3	29%	37%	44%
18P	2.0	2.0	3.0	2.0	2.0	3.0	2.0	2.0	3.0	2.0	2.0	3.0	2.0	2.0	3.0	2.0	2.0	3.0	28%	32%	31%
18I	3.0	4.0	4.8	2.0	2.0	3.0	2.0	2.0	3.0	3.0	4.0	4.0	2.0	2.0	3.0	2.0	2.0	3.0	30%	37%	31%
8P	1.3	2.0	3.8	1.0	2.0	2.8	1.0	2.0	3.0	2.0	3.0	3.3	1.0	2.0	2.0	1.8	2.0	2.0	44%	53%	40%
8I	3.0	4.0	4.0	2.0	3.0	4.0	2.0	3.0	4.0	3.0	4.0	4.0	2.0	3.0	4.0	2.0	3.0	4.0	29%	38%	32%
13P	1.0	2.0	3.0	2.0	2.0	4.0	1.3	2.0	3.0	1.0	2.0	3.0	2.0	3.0	4.0	1.8	2.0	3.0	40%	30%	41%
13I	2.0	3.0	3.0	2.0	3.0	4.0	2.0	2.0	3.0	2.0	3.0	3.0	2.0	3.0	4.0	2.0	2.0	3.0	27%	31%	33%
7P	2.3	3.0	4.0	3.0	3.0	4.0	1.0	2.0	2.8	3.0	4.0	4.0	3.0	3.0	4.0	1.0	2.0	2.0	27%	34%	42%
7I	2.0	3.0	3.0	2.0	3.0	3.8	2.0	3.0	3.0	2.0	3.0	3.0	2.0	3.0	3.0	2.0	3.0	3.0	33%	33%	36%
16P	2.0	4.0	5.0	1.0	2.0	2.0	1.0	2.0	2.8	2.8	4.0	5.0	1.0	2.0	2.0	1.0	2.0	2.3	38%	41%	50%
16I	2.0	3.0	4.0	2.0	3.0	3.0	2.0	3.0	3.0	2.0	3.0	4.0	2.0	3.0	3.0	2.0	3.0	3.0	35%	38%	35%
2P	2.0	3.0	4.0	2.0	2.0	3.8	2.0	2.0	3.0	2.0	4.0	4.0	2.0	2.0	3.0	2.0	2.0	2.3	39%	42%	35%
2I	3.0	4.0	4.0	2.3	3.0	4.0	2.3	3.0	3.8	3.0	4.0	4.0	3.0	3.0	4.0	2.0	3.0	3.0	23%	28%	27%
6P	2.0	2.0	3.0	2.0	3.0	4.0	2.0	2.0	3.0	2.0	2.0	3.0	2.0	3.0	4.0	2.0	2.0	3.0	41%	33%	40%
6I	2.0	3.0	3.0	3.0	3.0	4.0	2.0	3.0	3.0	2.0	2.0	3.0	3.0	3.0	4.0	2.0	3.0	3.0	33%	31%	31%
12P	2.0	3.0	4.0	1.0	2.0	2.0	1.0	2.0	2.0	2.0	3.0	4.0	1.0	2.0	2.0	1.0	2.0	2.0	39%	48%	47%
12I	4.0	4.0	5.0	3.0	3.0	4.0	3.0	3.0	4.0	4.0	4.0	5.0	2.8	3.0	4.0	3.0	3.0	4.0	26%	29%	25%

Attachment 2
Discriminant analysis classification results

Source of supply		Predicted group affiliation			Total
		TM	AM	Hedging	
Amount	TM	29	0	1	30
	AM	0	27	2	29
	Hedging	0	1	30	31
%	TM	96.7	0	3.3	100
	AM	0	93.1	6.9	100
	Hedging	0	3.2	96.8	100

Note: 95.6% of the cases originally grouped were correctly classified.

Attachment 3
Eigenvalue and wilks Lambda

Eigenvalue				
Function	Eigenvalue	% of Variance	Cumulated %	Kanonical correlation
1	3.550[a]	64.6	64.6	0.883
2	1.942[a]	35.4	100.0	0.812
Note: The first 2 canonical discriminant functions are used in this analysis.				
Wilks-Lambda				
Test of Function(s)	Wilks-Lambda	Chi-Quadrat	df	Significance
1 to 2	0.075	180.293	72	0.000
2	0.340	74.998	35	0.000

Attachment 4
Equality test of group means and standardized discriminant coefficients

Predictor variables	Mean per supply alternative			F	Significance	Stand. discriminant. coefficient per function		Mean discriminant-coefficient
	TM	AM	Hedging			1	2	
10I Product mix	3,64	1,79	2,32	34,975	**0,000**	−0,977	−0,314	5661
10O Product mix	2,54	2,82	2,71	0,895	0413	0,613	0497	4362

(*continued on next page*)

Attachment 4 (*continued*)

Predictor variables	Mean per supply alternative			F	Significance	Stand. discriminant. coefficient per function		Mean discriminant-coefficient
	TM	AM	Hedging			1	2	
17I Distance	3,21	2,54	2,07	10,189	**0,000**	0476	0,735	4328
4O Lead time	3,64	1,68	1,96	46,025	**0,000**	−0,726	0154	3993
7O Innovation	3,39	3,14	1,89	20,693	**0,000**	0330	0,873	3979
2O Alternative	3,11	2,36	2,25	5599	**0,005**	0633	0,293	3908
16O Insourcing	3,64	1,89	2,04	20,579	**0,000**	−0,380	−0,644	3608
17O Distance	3,39	1,89	2,57	23,603	**0,000**	−0,575	−0,219	3425
18O Location	2,46	2,18	2,29	1218	0,301	0529	−0,128	2954
12I Technology	3,93	3,21	3,14	5633	**0,005**	0349	0,419	2850
14I Finance	4,00	2,64	2,50	20,076	**0,000**	0102	0,833	2744
14O Finance	2,79	2,29	2,54	2470	0,091	0319	−0,340	2488
13O Price fluctuation	2,04	3,00	2,18	9158	**0,000**	0190	0,525	2349
2I Alternative	3,61	3,18	2,93	4405	0,015	−0,279	0335	2276
8I Market shortage	3,46	3,00	3,14	1419	0,248	0059	−0,715	2215
11I Cycle time	3,57	2,86	2,71	7034	**0,002**	−0,353	0175	2212
8O Market shortage	2,61	1,89	1,93	4758	0,011	−0,095	−0,552	1952
5O Quantity	2,79	2,89	2,89	0,173	0841	−0,202	−0,342	1916
1O Dependence	3,93	2,14	2,21	21,464	**0,000**	−0,331	−0,032	1719
3O Design.	2,61	3,21	3,18	5318	**0,007**	0249	−0,176	1702
4I Lead time	3,68	2,64	3,18	9130	**0,000**	−0,053	−0,521	1663
12O Technology	3,07	1,86	1,71	15,196	**0,000**	−0,068	0482	1635
18I Location	3,61	2,46	2,39	14,560	**0,000**	−0,089	0425	1583
15I Environment	2,75	2,29	2,46	1779	0,175	0047	−0,435	1404
16I Insourcing	3,00	2,75	2,54	1454	0,240	0233	0,091	1392
15O Environment	2,36	1,68	2,29	10,424	**0,000**	−0,165	−0,204	1362
13I Price fluctuation	2,50	2,93	2,54	2298	0,107	0154	−0,217	1345
6O Knowhow IP	2,46	2,89	2,50	1415	0,249	−0,213	0109	1345
5I Quantity	3,79	2,00	2,39	29,633	**0,000**	0148	0,204	1281
6I Knowhow IP	2,61	3,25	2,89	3241	**0,044**	−0,112	0236	1184
7I Innovation	2,68	2,93	2,61	0,889	0415	0,020	−0,385	1136
9O Cost reduction	2,93	2,86	2,64	0,572	0567	0,082	0212	0,976
9I Cost reduction	2,71	3,07	2,64	2135	0,125	0148	−0,078	0939
1I Dependence	4,00	2,86	2,96	10,458	**0,000**	−0,040	−0,262	0905
3I Design.	3,46	2,25	2,61	13,204	**0,000**	0084	0,000	0416
11O Capacity	2,71	2,71	2,50	0,432	0651	−0,024	−0,002	0123

Numbering of supply risks based on Fig. 4. Abbreviation of the probability of occurrence (O) and impact (I).

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