Risk-Driven Supply Chain Design: Options and Trade-Offs in Complex Environments

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1 Introduction

Supply chain strategies develop in relation and as a response to their environment. Over the last couple of decades, the search for always greater efficiency was accompanied by the concept of agility. The advances of globalisation were to a significant part built on these pillars, as they benefitted from relative stable environments. Thus, globalisation was driven by a wide range of standardisation of supply chain structures and processes. The traditional concept of globalisation and the continued economic growth paradigm have come under scrutiny. As the world contends with greater volatility and uncertainties in the political, economic, environmental and social spheres and seeks a 'new' equilibrium in future sustainable development, supply chain strategies need to adjust. This complex environment bears great chances for success, but also failure given a greater probability and impacts of risks.

2 A Changing Context and Environment

The World Economic Forum (WEF) (2021) refers to the current environment as one of 'fractured futures'. The mentioned increasing volatile and complex environment may best be exemplified referring to the impact of the Covid-19 pandemic on risk

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perception. According to the ‘Global Risks Report 2020’, infectious disease was ranked above average in terms of impact, but as the third most unlikely global risk to happen (WEF, 2019). However, in the most recent report (WEF, 2021), infectious disease now ranks as the fourth most likely risk and the one with the highest impact. This change of risk perception reminds of other triggers of supply chain disruption like 9/11 in 2001, the financial crisis in 2007–2008 and the Japanese earthquake in 2011. The last two decades have consequently produced at least four of such events. Given such frequency, one might have expected that the likely occurrence of such disruptions forms an integral part of strategic supply chain planning.

However, despite growing complexities in our environment, supply chain strategies have so far always bounced back towards a mix of cost/efficiency and agility paradigms. Private cost continues to be the leading dimension. The Covid-19 pandemic has revealed the unpreparedness and fragility of supply chains and has triggered unprecedented and still incalculable economic and social effects. This is once again reminding us of already known limits of the traditional form of globalisation (cf. Goldin & Mariathasan, 2014). The relentless search for efficiency in supply chains resulted in a system of increased complexity, cost focus and in-transparency, and the Covid-19 crisis represented the impulse removing of the final brick causing the hollowed out *Global Supply Chain Jenga* tower to implode (Thiell & Wilmsmeier, 2020; cf. for the use of Jenga example, see Isenberg (2015)). Structural fragilities and dependencies became evident and should awake a general reassessment of supply chain structures and processes and their limitations of ‘efficiency’, ‘agility’ and even ‘resilience’ when applied in complex environments.

The, too long, idealised concept of globalisation has been and is continuing to be interrupted by the Covid-19 pandemic, not only by re-establishing physical borders but also by cutting global supply chains via political, or (often) unilateral, decisions, prioritising national interests over a global solidarity. Referring to *force majeure,* managerial decisions have been following similar pathways. These disruptions and threats of repetition created the following: (a) limiting equal access to markets, (b) fabricating an excessive vision of risk for business and society, (c) promoting excessive inventory variations and backlogs, (d) changing consumption pattern and (e) revealing quasi-monopolistic and monopsonic relationships along supply chains.

The world is at a crossroads, where climate change is increasingly affecting our economic activities, creating additional uncertainties. At the same time, there is a growing awareness on the limited capacities for preventive policy making and global governance, making our systems more vulnerable and exposed to volatility. Here volatility includes four dimensions: political, environmental, economic and social.

If we were to take the effects of the Covid-19 pandemic as an example for complex environments, until mid-2021, global supply chains were already effectively hit thrice:

First by the effects of the China lockdown, which revealed the significant dependencies on Chinese finished and intermediate products and components;

Second by the elimination of demand on the markets successively impacted by Covid-19 and going into shutdown. The results of these two effects demonstrated an artificially initiated divide in high demand increase (e.g. hoarding effects, health sector supplies) and substantial demand decrease (e.g. tourism, accessories, fashion).

Third by showing that ramp-up efforts to reach full utilisation of productive assets in a 'new normal' continue to be limited by uncertainties and recurrence of restrictions in different parts along the supply chains. Finally, the future economic knock-on effects through reduction of purchasing power, investment decision trade-offs (i.e. durable consumer goods) and a reorientation of consumerism (i.e. less quantity and diversity, a more local/national product and service geography) are still evolving.

The complexity of global supply chains and their lack of transparency and collaboration have led to little or no control over disruption causes and even less capability to trace the unfolding consequences and their underlying relationships, particularly in emerging economies (cf. Richter, 2011; Foroohar, 2014; Barbieri, 2016; Medhora, 2017). Shifting from globalisation idealism to national protectionist realism leaves emerging economies chasing shadows of the fallen *Global Supply Chain Jenga* tower (cf. Bloom, 2020; Thiell & Wilmsmeier, 2020).

This chapter discusses if and how to adapt or possibly restructure supply chain designs to the impulses set, risks observed and disruptions caused in complex environments. Given the dynamics of global supply chains in general, adaptation is not a new requirement for their design (Lee, 2004). What is new in the context of the Covid-19 pandemic is the magnitude and simultaneity of economy- and society-wide approaches in which also the (re-)actions of many other actors outside the direct economic system need to be considered, e.g. the role of public health, technological developments and geopolitical scenarios.

In light of more complex future environments with increased uncertainty and volatility might require designing less 'fragile', speak antifragile (Taleb, 2012), supply chains, resulting into structures with wider or even dynamic control limits, in particular looking for a re-enforcement of practices as a balanced set of different strategic options instead of the 'one-size-fits-all' solutions. Considering these developments, this chapter critically reflects on the validity of traditional cost, efficiency or agile dominant supply chain structures and proposes a framework that allows decision-makers to assess strategic design options and their trade-offs in complex environments.

3 Complexity and Risk in Supply Chain Design

This section discusses key concepts related to drive, anticipate, mitigate or respond to risks. Supply chain risk analysis has been discussed widely in literature. Christopher et al. (2003) define supply chain risk as any risk to the information, material and product flow from original suppliers to the delivery of the final product. Beyond this, numerous definitions of supply chain risks and risk management exist (Ritchie & Brindley, 2004), often with marginal differences. Supply chain risks can be categorised as supply, process, demand, intellectual property, behavioural, political/social security (Tang & Tomlin, 2008) and disruptive risks. Consequently, these risks can be separated into endogenous risks, which are caused by companies' activities along their supply chains, and exogenous risks that affect companies given their interaction with the external environment in which they operate (Faisal, 2009). The dimensions that make these risks different are unit of analysis, type of risk, likelihood, impact and frequency. While the definitions and categories of risks seem clear, the conversion towards consideration and implementation in supply chain design in practice has been limited in the past.

Industry and academic discussions on supply chain risk strategies frequently refer to agility, robustness or resilience (e.g. Elleuch et al., 2016), as most common contingency approaches. The authors argue that it is necessary to amplify the perspective by considering root causes of supply chain disruptions. Under pressure from disruptive events, most supply chains traditionally tend to adopt to even 'leaner' models, which often makes them more fragile and vulnerable (Chowdhury and Quaddus, 2016).

Research on the effect of exogenous supply chain disruptions on supply chain competitiveness started to develop more strongly after 9/11 (Sheffi, 2002; Hau & Wolfe, 2003). And past disruptive as well as the Covid-19 pandemic have been followed by a flood of studies on supply chain risk and management. Despite a growing body of research in this area, exogenous risk orientation in supply chain designs was found still to be limited given the experience effects on supply chains during the Covid-19 crisis. One reason for this can probably be explained by managers' attitudes towards risk and their belief in continued and 'unstoppable' growth, as well as efficiency and agility being a panacea for competitiveness. Such beliefs have widely (and knowingly) ignored actual possible vulnerability (Bostrom, 2019) and collapse (Bemdell, 2018) scenarios, which could expose the fragilities (Manheim, 2020) of current supply chain designs. Therefore, beyond the previously mentioned concepts, fragility as a main cause, adaptability and antifragility as main mitigation approaches are defined in the following.

Fragility is a result of context factors (external and internal) and managerial decisions of how to deal with them, specifically considering the collapse of the supply chain structure as a possible future event, as a scenario (Manheim, 2020). Vulnerability can be defined as a risk-increasing factor. Jüttner et al. (2003) define vulnerability as 'the propensity of risk sources and risk drivers to outweigh risk mitigating strategies, thus causing adverse supply chain consequences affecting the supply chain's ability to effectively serve the end customer market'. Thus, while vulnerability measures loss in case of occurrence, fragility measures the occurrence's probability. Given this relation, addressing the vulnerability of supply chains is an 'end-of-pipe' approach compared to addressing such system's fragility. Effectively, the knock-on effects of the recent pandemic met highly fragile and ultimately vulnerable supply chains, which were predominantly characterised by unpreparedness, complexity, lack of leadership and supply chain skills, lack of collaboration, lack of transparency and visibility and cost focus. Following this logic, the supply chain designs were too fragile to deliver adequate performance against the defined value propositions in the situational context of the Covid-19 pandemic.

Thus, recent experiences of supply chain disruptions have shown that neither the most ‘responsive’ nor the most ‘efficient’ supply chain design (Fisher, 1997) has insured effectiveness and allowed organisations to maintain their performance level and competitiveness. The multi-disruptive impulse tested system boundaries (robustness) and effectiveness of supply chains’ internal control limits (resilience). The paradigm of robustness relates to supply chain’s ability to maintain its planned performance following a disruption event (Nair & Vidal, 2011; Simchi-Levi et al., 2018). We differentiate between ‘resilience’ and ‘robustness’ as both terms are often used interchangeably despite referring to distinct concepts in the supply chain context. Robustness refers to sturdiness and a system’s ability to respond to errors while continuing to function. Resilience in difference is defined as the system’s ability to recover its original state or move to a new, more desirable state after having absorbed disruption effects (Christopher & Peck, 2004; Spiegler et al., 2012; Hosseini et al., 2019). Since the ways the disruptions occurred and propagated along the supply chains during the Covid-19 pandemic were non-obvious, but largely dependent on the architecture and the interdependences between supply chain elements, the limits on maintaining performance and competitiveness of these two paradigms emerged.

Consequently, agility became a popular and widely used term to describe requirements for supply chains to respond to the disruptions triggered from the Covid-19 pandemic. However, agility in supply chains traditionally relates to its capability to react quickly to changes and uncertainties in demand and supply (Lee, 2002, 2004; Eckstein et al., 2015), sometimes even limited to changes of consumer expectations, but seldom related to be triggered by external supply chain risks. Resilience and agility implicitly carry the notion of flexibility in their definitions, but do not consider that the state after a disruption can be different from the original state prior to the disruption.

Following the nomenclature of Lee (2004), supply chains might be required to assess their structures under a broader view of their ‘adaptability’, including a stronger focus on strategic options and design effectiveness. Adaptability consequently sets the ‘control limits’ with a ‘wider range’ or on a different attribute level with the same range and allows the system to define new and different states after being disrupted (Christopher & Peck, 2004). These limits will then also define the system’s capability in which it can adjust under an agility paradigm.

In the context of complex environments, it is important that an adaptive supply chain can change its state as a response during the occurrence of a disruption; this response will not be defined in the original design of the supply chain. Consequently, an adaptive supply chain will create resilience and robustness in different disruption scenarios. However, the concept of adaptability does not necessarily be sufficient, if environments are volatile. Taleb (2012) proposes the concept of antifragility as such supply chain would be set to not only resist to and adapt after disruptions but also to improve to be better prepared in the future.

Fig. 1 Balancing paradigms in supply chain strategies in complex environments. Source: Authors

What is emerging is that future supply chains will require integration where different paradigms will coexist within the same supply chain (see Fig. 1). Such integration will require combinations creating multidimensional dynamic boundaries between different supply chain strategies. Here trade-offs will emerge where the combinations neither result in the lowest cost nor most resilient or most agile supply chains. Such circumstances set the stage for discussing alternative supply chain designs.

4 Conceptual and Methodological Framework

4.1 Concept

The authors propose a conceptual framework for decision-makers to define options and trade-offs for supply chain designs. The conceptual framework questions predominant designs by considering supply chain fragility and its underlying causes.

In the past, a widespread efficiency and private cost focus guided managerial practices including the adoption of lean and just-in-time practices, outsourcing, moving to offshoring (in-house and outsourcing) and reduction of the supplier base. Reviewing the traditional supply chain literature, the authors identify the following ten dimensions with opposing options for supply chain designs (see Table 1).

The following paragraphs explain each of the dimensions and give examples:

(D1) **Geographic proximity** refers to the distance between the actors in the supply chain. In comparison to a local or domestic network, a global network raises the heterogeneity of supply chain characteristics and consequently also increases supply chain complexity as well as its fragility (Levy, 1995). The piracy-related disruptions off the coast of Somalia in 2007–2012 provide an example in this field, having exposed supply chains to challenges not prevalent in many domestic regions. Under the term of ‘nearshoring’, the questions of the optimal geographic proximity became particularly relevant in the course of the Covid-19 crisis in 2020–2021,

Table 1 Supply chain design: options

Dimension	Likely impact on SC fragility (ceteris paribus)	Opposed options	Example
D1) Geographic proximity	Increasing geographic distance leads to higher fragility	'Local sourcing' ⇔ 'Global sourcing'	Somalia piracy (2007–2012)
D2) Collaboration	Decreasing collaboration leads to higher fragility	'Partnership' ⇔ 'Arm's length'	Aisin/Toyota valve supply disruption (1997)
D3) Number of suppliers	Decreasing number of suppliers leads to higher fragility	'Multiple sourcing' ⇔ 'Single sourcing'	Japanese earthquake-tsunami-nuclear disaster (2011)
D4) Competitive priority focus	Increasing focus on cost (narrow definition of value) leads to higher fragility	'Value' ⇔ 'Cost'	Ecopetrol (2021)
D5) Degree of vertical integration	Decreasing vertical integration leads to higher fragility	'Insourcing' ⇔ 'Outsourcing'	Mattel toy recall (2007)
D6) Redundancy (volume)	Decreasing volume redundancy leads to higher fragility	'Buffered' ⇔ 'Lean'	Volcanic eruption in Iceland affecting production of BMW (2010)
D7) Risk management	Increasing focus on contingency capabilities leads to higher fragility	'Mitigation-based' ⇔ 'Contingency-based'	Covid-19 pandemic (2020)
D8) Information sharing	Decreasing information sharing leads to higher fragility	'Transparency' ⇔ 'Asymmetry'	Nokia and Ericsson chip supply from Philips in Albuquerque (2000)
D9) Intermediation	Increasing intermediation leads to higher fragility	'Integration' 'Fragmentation'	'Bullwhip effect'
D10) Redundancy (spatial)	Decreasing spatial redundancy leads to higher fragility	'Volume centralisation' ⇔ 'Volume dispersion'	Thailand floods (2011)

Source: Authors

considering that 'strategic supplies' like medical equipment should be produced in the direct proximity to the consumer markets.

(D2) **Collaboration** refers to the continuum of design options between 'arm's length' on the one hand and 'partnership' on the other hand. With increasing collaboration, supply chains are supposed to protect themselves better against disruptions by reducing opportunistic behaviour and pursuing joint approaches to plan and to execute supply chain operations with greater success than when acting isolated (Simatupang & Sridharan, 2002). The collaborative approach in which the disruption caused by the 1997 Aisin Seiki fire was solved in and by the Toyota supplier network demonstrates the power of partnership to reduce fragility: bringing in additional engineers, working overtime and sharing knowledge and other resources made it possible to reduce the expected downtime from several weeks to only 5 days (Nishiguchi & Beaudet, 1998).

(D3) With a decreasing **number of suppliers** per purchasing item, the dependency of the buyer increases. In the case of single/sole souring, the buyer places 'all eggs in one basket'. The case of the Japanese earthquake-tsunami-nuclear disaster in 2011 illustrates such case in which companies who relied on single sourcing approach considering 'low cost and high quality' experienced supply shortages, e.g. Ford had to stop taking orders for several models in the colour 'tuxedo black' that was provided by a supplier in Japan.

Such example also demonstrates that the ceteris paribus condition is crucial in the application of the conceptual framework. A general increase of fragility by focussing on one supplier can be partly compensated, e.g. by developing very strong relations including information sharing.

(D4) Guided by the **competitive priorities** of an organisation, a narrow value definition with a focus on cost increases the fragility of the supply chain. Cost-driven supply chains often improve productivity by reducing the amount and/or value of factors involved, but they may expose supply chains to higher risk of disruption. In 2020, the Colombian energy company Ecopetrol was also hit significantly by the pandemic crisis. Nonetheless, given its public-private nature and a wider value proposition, explicitly involving diverse stakeholder interests into its operations, it is concluded that Ecopetrol was better prepared to face the Covid-19 crisis than other actors in the market.

(D5) A **vertical integration** reduces supply chain fragility, considering that communication, control mechanisms and decision-making processes may work better under such condition than in a hollowed-out organisation with a high proportion of outsourcing. Tendencies towards 'insourcing', like the Apple chip plant in Munich, can in such context be interpreted as (re-)gaining control over operations previously outsourced. In a similar way, the public discussion about the diverse toy recalls of Mattel in 2007 evolved to a large extent around the use of lead paint in several toys (design problems responsible for a larger amount of toy recalls did not receive the same attention in media). While Mattel also had 'offshore in-house' operations, the disruption caused by the use of lead paint was occurring in its 'offshore outsourcing' operations.

(D6) Protecting a supply chain against disruptions with **volume redundancy** throughout its elements reduces supply chain fragility. Also addressed in the theory of constraints, inventory buffers prevent bottlenecks from running idle, avoiding a disruption of operations. In 2010, BMW experienced such disruption of its transatlantic make-to-order supply chain model from Europe to its plant in Spartanburg (USA) because of the volcanic eruption in Iceland that caused the closure of air space.

(D7) The reliance of an organisation to react quickly to a supply chain disruption, even under the idea of agility (Lee, 2004), may not be a sufficient **risk management** approach following a supply chain fragility perspective, given that such actions primarily address the consequences of a disruption. Instead, a risk management focussing on risk mitigation would address potential disruption causes and consequently increase the stability of a supply chain. The Covid-19 crisis revealed in many organisations and industries the lack of preparedness to deal with such disruption, and the contingency approaches even caused new disruptions resulting from cancelling contracts and shutting down operations (Thiell and Wilmsmeier, 2020).

(D8) Supply chains run on information; consequently, **information sharing** leads to transparency and reduces the fragility (Lee et al., 2000). Driven by performance improvements of information technologies and the reduction of their cost, the trend towards end-to-end supply chain visibility affects today's supply chains more and more. Nonetheless, confidentiality concerns, lack of trust or target-oriented use of information asymmetries may hinder organisations to create lower levels of fragility by means of increasing information sharing. However, in a supply chain that possesses visibility, a substitution of material flows by information flows becomes more likely. Nokia's fast and overall positive response to a fire in the semiconductor plant of Philips in Albuquerque (USA) in 2000 was also a result of the way how information about this disruption was shared within the organisation and its supply chain.

(D9) Complexity of supply chains augments with every new element added to it, consequently, with an expanding **intermediation** increases the fragmentation and, ceteris paribus, the fragility (Dominguez et al. 2015). A short supply chain, in terms of few vertical elements respectively multilayers, may require a lower coordination effort within the chain, because, as a tendency, it facilitates the communication and alignment between the actors. The bullwhip effect in supply chains illustrates the relation between the number of vertical actors and the magnification of variability in the supply chain (Lee et al., 1997). Bray and Mendelson (2012) show different real-world cases, e.g. Caterpillar on how the bullwhip effect impacted supply chains.

(D10) **Spatial redundancy** refers to the impact on fragility resulting from the level of centralising volumes, e.g. having suppliers for a specific product just in one particular location in the world. This type of supply chain fragility was observable in the context of the floods in Thailand in 2011, leading to supply shortages, e.g. for hard disk drives. On the one hand, a centralisation of volume in a region with cluster-like structures results in benefits, e.g. with respect to productivity and innovation. But on the other hand, from the perspective of supply chain fragility, a spatial redundancy of productive capacity in geographically dispersed regions will reduce the impact of a disruption in moments of natural disasters or turmoil.

For each of these dimensions (D), managers need to determine where to position their supply chain design along the axis between the two opposed options mentioned in Table 1. In this process, several aspects need to be taken into consideration:

- Given the diversity of products, material and markets, it is recommended to provide such design for each product/material category.
- Once committed to an option in one of the dimensions, the array of possible solutions in other dimensions delimit, indicating an interdependent relation between several dimensions; for example: a company focussing on single sourcing (D3) may also strive for higher levels of information sharing (D8).

- The feasibility of the supply chain design should be evaluated against the resources available for managing the system (e.g. IT and human resources) and the external context of an organisation (e.g. social, economic, environmental and political).

4.2 Decision Framework

The framework for a strategic assessment of supply chain design options asks decision-makers to define the importance of opposed options in each dimension on a five-point Likert scale (1 being of 'low importance' and 5 being of 'high importance'). While the use of such a Likert scale is inevitably arbitrary, we argue that it is nonetheless a useful first step for comparing the relations and trade-offs between supply chain design options on such aggregated planning level.

To exemplify the trade-offs, the authors differentiate between two extreme cases for one commodity supply chain in an organisation as a basis for the discussion on how to design the supply chain under fragility considerations (see Fig. 2). The greater the surface of the decagon in the cobweb chart, the lower the fragility of a supply chain design. This is represented in Case A, showing some aspects which Fisher (1997) referred to as elements of a 'responsive supply chain'. Case B shows a (traditional) cost-driven supply chain design, in terms of Fisher (1997) referring to several elements of an 'efficient supply chain':

- Case A: The 'non-fragile supply chain' is characterised by the following: 'Company X' has a local 'Supplier A' (D1) for its 'Category Δ', managing the relation as partnership with open book contracts and volume commitment (D2). Besides the positive business relation with 'Supplier A', 'Company X' also has a back-up 'Supplier B' who has a similar performance and counts with 20% of the purchasing volume (D3). The production facilities of the suppliers are geographically dispersed (D10). 'Company' X' follows a wider value definition, taking into account sustainability aspects and the interests of a diverse set of stakeholders

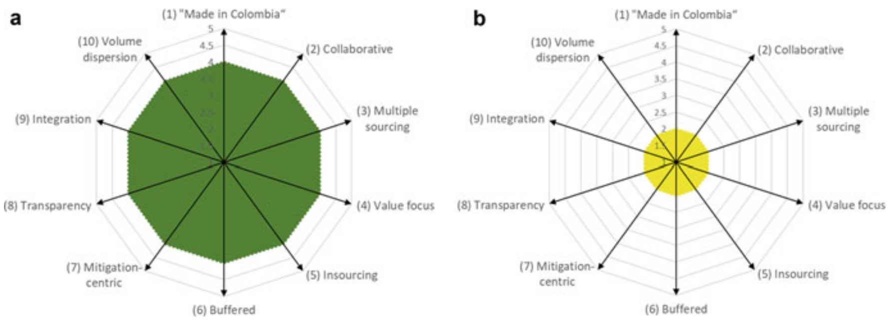


Fig. 2 Supply chain design: extreme cases (**a**) 'non-fragile supply chain design'. (**b**) 'fragile supply chain design'. Source: Authors

(D4), striving for a higher vertical integration by insourcing activities from suppliers back into the organisation (D5). To protect the supply chain elements from running idle, inventory buffers are integrated throughout the supply chain (D6). Risks are managed by focussing on the potential disruption causes (D7), and information is shared (D8) in the short supply chain (D9) in real time.

- Case B: The 'fragile supply chain' is characterised as follows: 'Company Y' has for its 'Category Φ' a 'Supplier D' located outside the country (D1). 'Supplier D' is the sole supplier (D3) for this category with its production facility accounting for 100% of 'Company Y's' purchasing volume (D10). The relationship between 'Company Y' and 'Supplier D' is characterised by a power-based battle for margins (D2). 'Company Y' strives for profit maximisation (D4), using outsourcing as an approach to achieve lower cost (D5). A 'zero inventory' policy is part of 'Company Y's' DNA (D6). Risks are managed by relying on the capabilities to react quickly and in flexible way at the moment a disruption occurs (D7). Information is in general classified as 'confidential' (8) in the long supply chain including many specialised intermediaries (D9).

Being aware that those two extreme cases in their pure form will hardly be prevalent in industry, the application of the framework makes differences visible, indicating that supply chains actually offer design options supporting the differentiation of an organisations in complex environments.

Organisations are in general part of several supply chains with different 'design profiles', leading to higher organisational complexity. Besides supporting the design of one supply chain, organisations are also well advised to review this heterogeneity of the diverse supply chain profiles following a resource-based perspective. Bundling resources to strengthen the management of certain supply chain profiles may be another trade-off supply chain managers should consider. The focus in such discussion is thus on a systemic response to complex environments rather than the assessment of just partial decision options.

4.3 Mini-Cases: Feasible Commodity Supply Chains (Colombia)

Initial tests of the decision framework in Colombia demonstrated that supply chain designs were traditionally focussing on efficiency aspects, tacitly accepting the inherent risk of resulting fragility.

In an assessment of feasible supply chain designs with a group of undergraduate students as well as a group of experienced managers in an executive education program, participants were asked for their proposal related to a future design based on a predetermined mini-case. Figures. 3 and 4 demonstrate the results of the two groups, applying reduced design options related to the question: 'Considering a typical supply chain for commodities like car spare parts, which feasible supply chain design would you propose for the future (2025)?'

As demonstrated in examples above, both groups expressed a shift from fragile supply chains towards less fragile options. Both groups propose more information

Fig. 3 Commodity supply chain design: executive education. Source: Authors

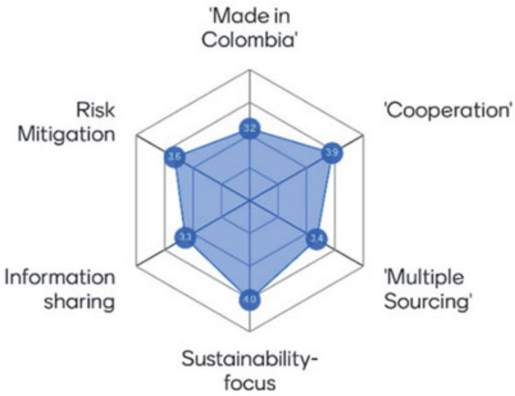
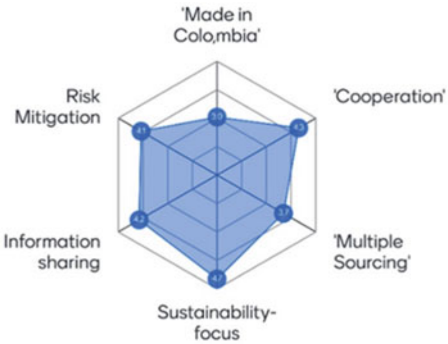


Fig. 4 Commodity supply chain design: undergraduate. Source: Authors



sharing, and more collaboration. Furthermore, the participants exhibited a tendency towards a more holistic value perspective, considering sustainability aspects and a stronger focus on risk mitigation instead of contingency approaches. Overall, the undergraduate group demonstrated a stronger desire towards less fragile designs in all dimensions.

Despite the motivation of changing supply chain designs, these initial experiments also identified specific impediments due to the Colombian context. Barriers were in particular identified with respect to the competitiveness of local industries in comparison with global supply chains, making the option 'Made in Colombia' less feasible.

Such results indicate that the decision of supply chain design will require the consideration of the specific context of the decision-maker and the relevant ecosystem, including factors like cognitive limitations or personal biases of the decision-makers as well as resource limitations and competitive priorities of the ecosystem.

Considering past globally significant supply chain disruptions like the ones caused by the financial crisis in 2008 or the Japanese earthquake in 2011, such context factors may also reveal that the actual implementation of changes may be restricted by an 'inertia to change', e.g. resulting from the following factors:

- Path dependence: our traditional and existing structures, resources, processes and business habits may limit the scope of actions, in particular when the effort and the outcome of change are uncertain.
- Definition of value and performance: we may still be significantly influenced by considering cost and profit as main optimisation criteria for our supply chain designs. But new designs should also consider a shift from cost-dominant to emphasising other characteristics and attributes, e.g. security of supply, time, quality, robustness, transparency, dependency levels, ecological footprints, social impact as well as changing stakeholder preferences in the course of time.
- Opportunity cost of change: changes may involve, at least temporarily, opportunity cost, interpreting change as an uncertain investment into the future. One may ask if companies are willing to obtain lower margins, if customers accept higher prices or how will stock markets react when there are 'profit warnings' reported by organisations.

The impulse of the financial crisis in 2008 and the Japanese earthquake in 2011 on the contemporary debate about supply chain designs was strong, but not strong enough to initiate significant changes away from cost- and efficiency-driven supply chain designs. The next years will show if the Covid-19 pandemic crisis will change our way of doing business or if the 'new reality' will be a clone of the 'old reality'.

5 Conclusions

Over the last two decades, supply chains were affected by many severe disruptions, and the 'lessons learnt' just seemed to have short time horizons of prevalence. Sometimes denoted as 'once-in-a-lifetime' events, this millennium showed us with 9/11 in 2001, the financial crisis in 2008, the Japanese earthquake-tsunami-nuclear disaster in 2011 and currently the Covid-19 pandemic crisis already four of such events. The consequences of complex environments on future supply chain designs are still unquantifiable, probably most likely underestimated and neither limited to, ripple, nor domino effects, but rather *multi-ball pinball game situations*. With a strategic planning time horizon of 5–10 years, organisations may be well advised to integrate the potential occurrence of a significant disruption into their plans and the supply chain design.

In this regard, this chapter reflected on possible supply chain design responses to current and future complexity and provides decision-makers with a framework for a strategic assessment of their supply chain design, considering their fragility in complex environments.

The capabilities to manage such complexity, fragility and risk have the potential to become key factors influencing the way supply chains are designed and managed in the future. Supply chain professionals will need to identify and interpret how complexity and fragility may jeopardise the perceived optimum of existing supply chain designs. The opportunity costs of maintaining and relying mostly on contingency approaches might become too high in the future.

Agility and resilience will remain important strategic options, particularly in the context of supply chains driven by private cost. However, the future will ask managers for a more holistic interpretation of value, in a first step internalising social costs and later satisfying the stakeholder expectations in terms of sustainability. This will require supply chain professionals to adapt a risk management culture that expands their response options in complex environments by determining the fragility trade-offs between contingency- and mitigation-oriented supply chain designs.

Management Perspective on Risk-Driven Supply Chain Design: Options and Trade-Offs in Complex Environments

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Well-designed product supply chains just like well-functioning international financial markets are based on the premise that success requires the efficient allocation of capital necessitating high levels of market visibility. That visibility should include the likelihood of certain negative or instability causing events occurring and their consequences for the supply chain. These occurrences, including climate- or health-related examples, or others caused by geo political events, are not rare, so why are they not quantified and factored into supply chain design? Clearly, some are but what happens when critical information or data is not available or is obscured because it cannot be quantified? This problem is relevant when you consider that supply chain practitioners are being asked to design or manage their global operations with large chunks of data missing. Following the logic of Thiell and Wilmsmeier's suggestions for redesigning supply chains as set out in this chapter leads to the question – how do we fill the information gap? They argue that supply chain practitioners are not correctly allocating capital when assessing future risk, because of either 'inertia to change' (in particular reliance on the traditional cost-based model), an inability to deal with an increasingly complex environment or a lack of understanding in how to assess risk and possible negative outcomes. The solution is a change to supply chain design. How can we get supply chain practitioners any time soon to sit down, redesign and plan based on different 'dimensions' beyond efficiency? This begs the question how does a useful academic thesis translate to change at the strategic and operational level? What steps might be taken by the academic community and private sector to find a solution?

It is obvious that some data or information deficiency comes into the 'too difficult' category and some 'too remote or unlikely'. Perhaps neither of these excuses should now be accepted if a general set of tools could be developed refined by location, industry and so on.

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Thiell and Wilmsmeier highlight methods for making choices through opposing options grouped under ten dimensions such as proximity (local vs. global) and collaboration (partnership vs. arm's length), all critical in the increasingly complex supply chain. However, if the global supply chain is susceptible to forces and events outside the supply chain manager's control, the real conundrum is how to quantify the risk associated with each to aid planning and thus investment. To redesign the supply chain requires evidence of the consequences of choices and risks taken. The insurance industry constantly refines its underwriting risk and models possible liabilities. While risks are well known when assessing insurance pricing for say car insurance (pre automation), it is less the case when assessing the effects of dramatic climate events or global viruses shutting borders. But the supply chain cannot wait to be forced to redesign based on its insurance costs or ultimately consumer rejection of its products on environmental grounds. There should be a strategic assessment of the options for redesign, the costs and benefits based on known or calculated risks.

A few years ago, F&L conducted a survey of its network by dividing the supply chain into its constituent actors and asking each actor how they ranked certain preferences including service, reliability, cost and so on. Each actor suggested they ranked non-cost factors more highly and suggested every other actor prioritised cost! As well as a lack of understanding of their supply chain partners' preferences, this cost focus was always short term and never included unquantifiable or more remote risks. In the same way, until recently, decarbonisation measures were avoided because they were not understood and emissions could not be measured. Now GLEC (Global Logistics Emissions Council) and others have provided the tools and action is being taken to reduce greenhouse gas emissions.

Redesign will come about when different stakeholders within the supply chain and beneficiaries of it provide pressure. They cannot do so without data, here being the calculated cost of risks taken. At one level of the supply chain, the CEO has little incentive to consider shifting a manufacturing base to a more expensive (in normal operational terms) but lower risk environment, especially given the transition costs, when the risks cannot be quantified and his personal KPIs focus only on short-term profits.

A significant problem for defining a model for risk is that many of the consequences or costs of an occurrence may be borne by society. During the Covid crisis, some businesses have benefitted from significant sales increases and enhanced margins, whereas society and in some cases the wider environment have suffered negative consequences, many of which we will not fully understand for some time.

The obvious argument runs that design changes have costs and cost increases run through the supply chain. Therefore, if we wish to be more

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resilient, more stable in a volatile world, will the consumer or taxpayer accept the cost or will we simply be undermined by competition? Before we get to the position where we have no choice and dramatic events force supply chain changes, we need to agree how to judge the costs of such risks and reskill the supply chain to manage and take the opportunities of change.

Taking Thiell and Wilmsmeier's ten dimensions, academics could usefully analyse the projected risk factors associated with choices, based on specific company sectors (product inputs and other variables) and location. They should then work with supply chain specialists to consider how these theoretical risk factors would affect the supply chain and the possible costs or production/sales impact. The aim could be to develop a database of relevant impact ratios for particular supply chains assisting the redesign without starting from scratch. This would be a more suitable version of the market entry risk factors that companies often utilise, but specifically adapted for the supply chain. There are academic models that forecast the likelihood of natural erosion on rail and road routes, landslides and resultant impassable routes. Logistics managers know the effects and costs of a failure in a key route or corridor—many have suffered the effects of the 2017 Rastatt tunnel collapse and the more recent landslide closing the Rhine Valley rail route.

There will be significant opportunities arising from change and understanding how complex supply chains can be both more stable and agile. Staying flexible enough to adjust to events and yet stable enough to give confidence to customers or consumers will define the winners. Who will provide the data and model to make our impact ratio database possible? That is surely a worthwhile collaborative challenge for the academic and private sector communities.

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