



Learning Objectives for This Chapter

- What is uncertainty and risks?
- What types of risks are encountered in the supply chain?
- Which decisions are in the scope of supply chain risk management?
- Why do the risks appear in the supply chain?
- What is the difference between the operational and disruption risks?
- What is the ripple effect in the supply chain?
- How to mitigate the disruption risks and the ripple effect?
- What is supply chain resilience?
- Which objectives are used to measure performance of supply chain and operations management in terms of risks?

15.1 Introductory Case-Study: Capacity Disruption at BASF

On October 17, 2016 as a result of an incorrect maintenance operation on a pipeline at BASF facility in Ludwigshafen (Germany), there was an explosion and subsequent fires at North Harbor, a terminal for the supply of raw materials such as naphtha, methanol and compressed liquefied gases. More than 2.6 million tons of goods are handled there each year and an average of seven ships a day moor at its docks. Two steam crackers, the starting point for producing basic chemicals, needed to be stopped because they could no longer be supplied, and 22 were only partially working. The two steam crackers could have been restarted 2 days later, but only in May 2017 was the concept for reconstruction released whereby the reconstruction

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should be completed by September 2017. Restricted production output, a daily revenue decrease of 10–15% as compared to the previous year during the disruption period, impact on the basic chemicals division (about 21% of sales), delivery delays, limited access to key raw materials, exhausted product inventories, and a forecasted impact on 6% of BASF's annual earnings were some of the consequences of this incident (Dolgui et al. 2018, and references within). Logistics was temporarily shifted from ships and pipelines to trucks and trains. BASF was in close contact with its customers to keep them informed about the current availability of products to minimize the impact on customer deliveries. Because of BASF integrated “Verbundsystem” (networking system), comprised of various plants and delivery systems for feedstocks, the incident had an impact along the global supply chain (SC). This high and long-term impact is the so-called ripple effect (Ivanov et al. 2014a, b).

BASF built a resilient SC, which is why the economic consequences of the aforementioned incident were considerably smaller than expected. BASF took process safety and risk prevention measures that included globally valid guidelines and requirements for buildings etc. and practical security trainings for employees and support staff. Along with process safety and risk prevention measures, BASF has global emergency response management. This management consists of the integration of worldwide group companies, joint ventures, partners, suppliers and customers. Emergency phones and an integrated network of control centres (e.g. internal/external fire departments and rescue service) also enable this global emergency response management to work even more closely together. BASF was prepared for the incident in October 2016, but there is still long-term impact.

15.2 Uncertainty and Risks

Uncertainty is a system property characterizing the incompleteness of our knowledge about the system and the conditions of its development. The concept of *risk* is subject to various definitions. Knight (1921) classified under ‘risk’ the ‘measurable’ uncertainty. From the financial perspective of Markowitz (1952), risk is the variance of return. From a project management perspective, risk is a measure of the probability and consequence of not achieving a defined project goal. According to March and Shapira (1987), risk is a product of the probability of occurrence of a negative event and the resulting amount of damage.

Generally, in decision theory, risk is a measure of the set of possible (negative) outcomes from a single rational decision and their probabilistic values. In the literature on supply chain management, the term “risk” is also replaced with “vulnerability”, which means “at risk”.

In analysing uncertainty and risks, four aspects are usually encountered. The first is uncertainty itself, the second is risks, the third is perturbation influence (disturbances), and the last is the perturbation impact influences (deviations). In

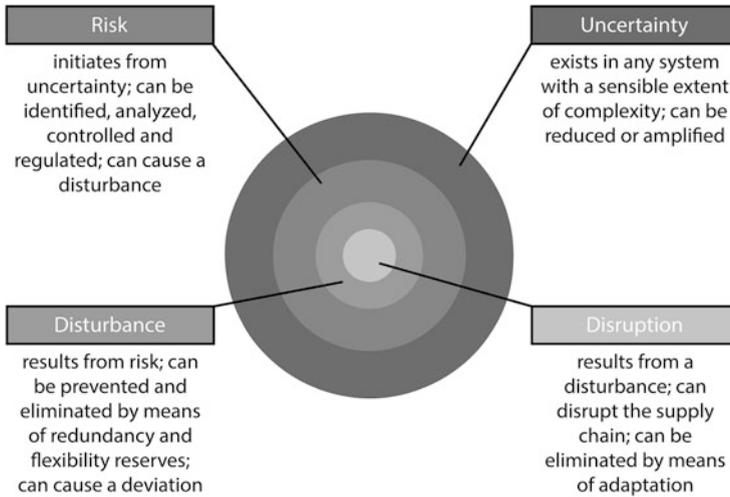


Fig. 15.1 Interrelations of uncertainty, risk, disturbance and disruption (based on Ivanov and Sokolov 2010 and Ivanov 2018)

the further course of this and the following chapters, we will frequently encounter this constellation (see Fig. 15.1).

Uncertainty is the general property of a system environment that exists independent of us for any system of a sensible complexity degree. As shown in Fig. 15.1, we can broaden and narrow the uncertainty space.

Risk arises from uncertainty. Risks can be identified, analysed, controlled and regulated. We consciously talked about uncertainty factors and the appearance of risks such as the risk of demand fluctuation as a result of the environmental uncertainty.

A *disturbance* (perturbation impact) is the consequence of risks. It may be purposeful (i.e. thefts) and non-purposeful (i.e. demand fluctuations or the occurrence of some events that may necessitate adapting the supply chain). It may cause a deviation (disruption) in the supply chain or not (e.g. a supply chain can be robust and adaptive enough to overcome the disturbance).

Operational *deviations* (or severe *disruptions*) are the result of perturbation influences. They may affect operations, processes, plans, goals or strategies. To adjust the supply chain in the case of deviations, adaptation measures need to be taken.

For the supply chain management domain, uncertainty factors and measures for their handling can be distinguished as follows (see Table 15.1).

In Table 15.2, some examples of disturbances and disruptions in supply chains in recent years are presented.

Complexity management and system modelling can be considered as a theoretical basis for handling uncertainty in supply chains. From the perspective of complexity

Table 15.1 Uncertainty factors and measures for their handling in supply chains

Decision-making level	Uncertainty factors	Handling measures
Strategic	Multiple management goals Terrorism, piracy Financial and political crises Natural disasters	Multi-criteria analysis techniques supply chain security management Liquid assets reserves Strategic material inventories Market diversification and outsourcing Product lines' flexibility and modularity
Tactical and operational	Weak coordination Stockless processes Weak control of cargo security Technological breaks Human errors	Safety stocks and time buffers Reserves of supply chain capacities supply chain coordination, monitoring, and event management

management, the problem of a system under control and uncertainty is related to an area under control and an area under uncertainty. This idea is based on Ashby's principle (Ashby 1956) of requisite variety (Fig. 15.2).

By broadening the control area (Fig. 15.2b) and narrowing the uncertainty area or reverse (Fig. 15.2a), the system control can be adapted. Hence, the mutual relations between the system and environment spaces fall into the categories of amplification of a *control variety* and attenuation of an *environmental variety* (see Fig. 15.2). Thus, amplifying the variety of our control area and reducing the area of uncertainty, (1) a balance of control and perturbed impacts as well as (2) the maintenance of the planned execution processes and a quick cost-efficient process recovery once disturbed can be reached.

15.3 Risk Management in the Supply Chain

15.3.1 Risk Classification

Risk management in the supply chain became one of the most important topics in research and practice over the last decade. A number of books (Handfield and McCormack 2008; Kouvelis et al. 2012; Waters 2011; Gurnani et al. 2012; Heckmann 2016; Mistree et al. 2017; Khojasteh 2017; Ivanov 2018) and literature review papers (Blackhurst et al. 2005; Wagner and Bode 2008; Klibi et al. 2010; Simangunsong et al. 2012; Ho et al. 2015; Fahimnia et al. 2015; Gupta et al. 2016; Dolgui et al. 2018) provide insightful overviews and introductions to different aspects of this exciting field.

Recent literature introduced different classifications of supply chain risks (Chopra and Sodhi 2004; Tang and Musa 2011; Ho et al. 2015; Quang and Hara 2017). For example, Chopra and Sodhi (2004) categorised potential supply chain risks into nine categories:

Table 15.2 Examples of disturbances and disruptions in supply chains

Factor	Example	Impacts
Terrorism Piracy	September 11 Somali, 2008	Five Ford plants have been closed for a long time Breaks in many supply chains
Natural disasters	Earthquake in Thailand, 1999 Flood in Saxony, 2002 Earthquake in Japan, 2007	Apple computers' production in Asia has been paralysed Significant production decrease at VW, Dresden Production breakdown in Toyota's supply chains amounted to 55,000 cars
	Hurricane Katrina, 2006	This storm halted 10–15% of total US gasoline production, raising both domestic and overseas oil prices
	Earthquake and tsunami in Japan, 2011	Massive collapses in global automotive and electronics supply chains; Toyota lost its market leadership position
	Floods in Chennai, India in 2015	Production of academic literature has been stopped at many international publishing houses
Man-made disasters	Explosion at BASF plant in Ludwigshafen in 2016	15% of raw materials were missing for the entire supply chain Production of some products at BASF has been stopped for many weeks
	Fire at distribution centre of e-commerce retail company ASOS in 2005	Delivery stop for a month
	A fire in the Phillips Semiconductor plant in Albuquerque, New Mexico in 2000	Phillips's major customer, Ericsson, lost \$400 million in potential revenue
Political crises	"Gas" crisis 2009	Breaks in gas supply from Russia to Europe, billions of losses to GAZPROM and customers
Financial crises	Autumn 2008	Production decrease or closing; breaks in supply chains throughout
Strikes	Strikes at Hyundai plants in 2016	Production of 130,000 cars has been affected
Legal contract disputes	Volkswagen and Prevent Group contract dispute in summer 2016	Six German factories face production halt on parts shortage; 27,700 workers are affected, with some sent home and others moved to short-time working

Extended from Ivanov and Sokolov (2010), Ivanov (2018)

- Disruptions (e.g. natural disasters, terrorism, war, etc.),
- Delays (e.g. inflexibility of supply source),
- Systems (e.g. information infrastructure breakdown),
- Forecast (e.g. inaccurate forecast, bullwhip effect, etc.),
- Intellectual property (e.g. vertical integration),
- Procurement (e.g. exchange rate risk),

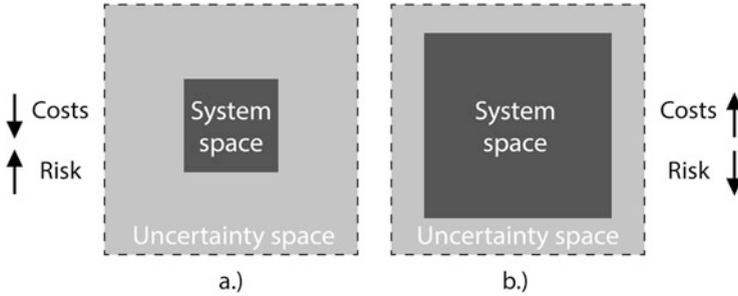


Fig. 15.2 System space and uncertainty space (Ivanov 2018)

- Receivables (e.g. number of customers),
- Inventory (e.g. inventory holding cost, demand and supply uncertainty, etc.),
- Capacity (e.g. cost of capacity).

Quang and Hara (2017) classify the following seven groups of risks:

- *External risks* which “deal with threats from an external perspective of SC that can be caused by economical, sociopolitical or geographical reasons. Examples are fire accidents, natural catastrophes, economic downturn, external legal issues, corruption, and cultural differentiation”,
- *Time risks* referring to delays in SC processes
- *Information risks*, e.g., communication breakdown within the project team, information infrastructure complications, distorted information and information leaks
- *Financial risks*, e.g., inflation, interest rate level, currency fluctuations and stakeholder requests
- *Supply risks*, i.e., risks related to suppliers, e.g. supplier bankruptcy, price fluctuations, unstable quality and quantity of inputs
- *Operational risks*, caused by problems within the organisational boundaries of a firm, e.g. changes in design and technology, accidents and labour disputes
- *Demand risks* that refers to demand variability, high market competition, customer bankruptcy and customer fragmentation

15.3.2 General Framework of Risk Management in the Supply Chain

Risk management is a methodological approach to managing uncertainty outcome. A particular feature of risk management in supply chains (unlike in technical systems) is that people do not strive for a *100% guarantee* of the result: they consciously tend to take risks. There is a contradiction between *objective risks*, those determined by experts applying quantitative scientific means and *perceived risk*, those which include managers’ perceptions.

Actually, the objective risk treatment is rooted in technical science where 100% reliability is mandatory. In socio-economic systems, like supply chains, a value of 95% as an orientation for supply chains is empirically suggested (e.g. Sheffi 2005). Different managers perceive risk to different extents, and these perceptions can change in the same manager due to changes in his environment. That is why the models for supply chains should not strive for a unique optimal solution but allow the formation of a number of alternative solutions with different degrees of potential economic performance and risk. Summarizing, we will note that risk can be considered from three basic positions:

1. risk is a likelihood estimation of a negative outcome of the event leading to losses/losses (the technological approach);
2. risk is an individual estimation by the person of the danger of a negative outcome of the event leading to losses/losses; risk is ultimately a property of any entrepreneurship (the psychological approach);
3. risk is an integral property of any process or system, the management of which is a key problem in economic performance and stability maintenance (the organizational approach).

Let us describe the concept of risk management in the supply chain. In order to analyse risks, the following main categories are introduced: the risk factor, the risk source, the risk situation, and the dangerous situation. The risk factor is a global category that characterizes a system at the goal-orientation level (e.g. upsetting of the production plan, delivery breakdown, etc.). Risk sources consider certain events that may cause risk factors. The dangerous situation characterizes the state of a system when a probability of risk sources' appearance and their direct influence on this system is high. The risk situation means a condition when the active influences of risk sources cause disturbances and deviations in system functioning (see Fig. 15.3).

The problem of supply chain functioning in terms of risk consists of the following main phases: risk factors' identification → risk sources and dangerous situations' identification → identification of interdependences between risk situation appearance and changes of system functioning parameters → decision-making about compromise while supply chain configuration by aggravation of some goal criteria (e.g. cost increase while keeping the planned production volume and deadline; production volume reduction while keeping the same cost level and deadline; change of deadline while keeping the same costs and production volume, etc.) → control decision development in order to compensate for possible disturbances in system functioning caused by risk situations → development of a managed object monitoring system.

In summarizing the practical advancements in uncertainty handling within a supply chain environment, the following can be concluded:

1. Uncertainty space may be reduced by means of, e.g.:

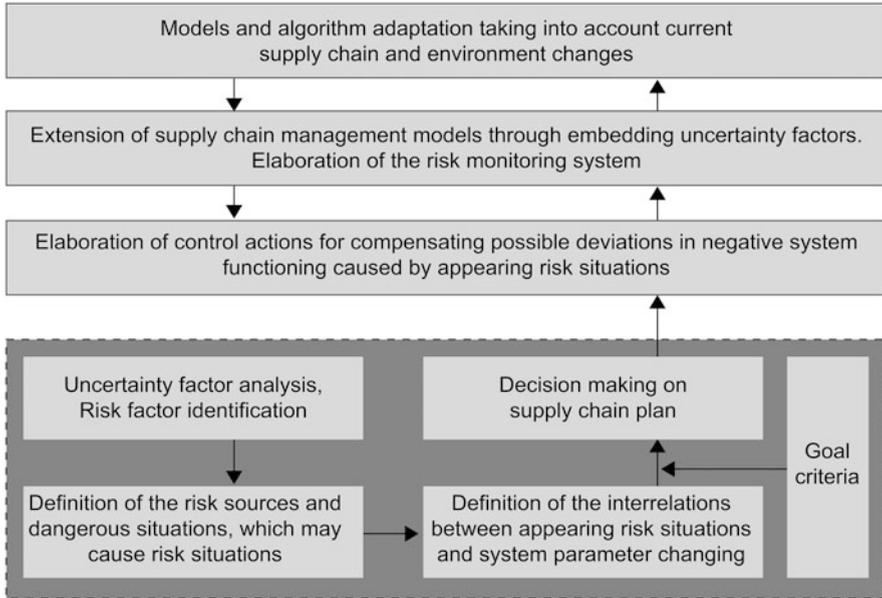


Fig. 15.3 Supply chain risk management framework

- introducing excessiveness in supply chain structures (e.g. time buffers, safety stocks, additional resources, capacity reserves, etc.);
- improving coordination and information flows to make better quality, timeliness, and accessibility;
- introducing supply chain monitoring and event management systems to react quickly to disturbances and disruptions; and
- forming a set of not final decisions, i.e. postponement and rolling/adaptive planning.

2. It is impossible to avoid uncertainty.

15.4 Operational and Disruption Risks

Klibi et al. (2010) classify uncertainties and risks in the supply chain as follows:

- random uncertainty (demand fluctuation risks)
- hazard uncertainty (risk of unusual events with high impact)
- deep uncertainty (severe disruption risks)

The different types of risks in the supply chain can be classified into demand, supply, process, and structure areas (see Fig. 15.4).

Risks of demand and supply uncertainty are related to random uncertainty and business-as-usual situation. Such risks are also known as *recurrent* or *operational risks*. Supply chain managers achieved significant improvements at managing global supply chains and mitigating recurrent supply chain risks through improved planning and execution (Chopra and Sodhi 2014).

Disruption risks represent a new challenge for supply chain managers. From 2000 thru 2017, supply chain disruptions (e.g., because of both natural and man-made disasters, such as on 11 March 2011 in Japan, floods in Thailand in 2011, fire in the Phillips Semiconductor plant in New Mexico, etc.) occurred in greater frequency and intensity, and thus with greater consequences (Chopra and Sodhi 2014; Simchi-Levi et al. 2014). Hendricks and Singhal (2005) quantified the negative effects of supply chain disruption through empirical analysis and found 33–40% lower stock returns relative to their benchmarks over a 3-year time period that started 1 year before and ended 2 years after a disruption.

Disruption risks represent a new challenge for supply chain managers who face the *ripple effect* (Ivanov et al. 2014a, b, 2017; Ivanov 2017; Dolgui et al. 2018) subject to *structural disruptions* in the supply chain, unlike the *parametrical deviations* in the bullwhip effect (Fig. 15.5).

In the last two decades, considerable advancements have been achieved in research regarding the mitigation of inventory and production shortages and response to demand fluctuations. In particular, the *bullwhip-effect* in the supply chain has been extensively considered in this domain subject to *randomness uncertainty* with the help of stochastic and simulation models.

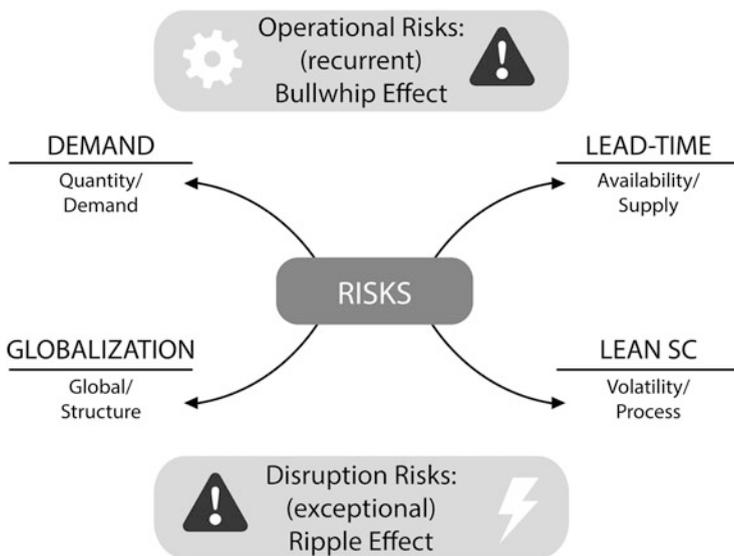


Fig. 15.4 Supply chain operational and disruption risks (Ivanov 2018)

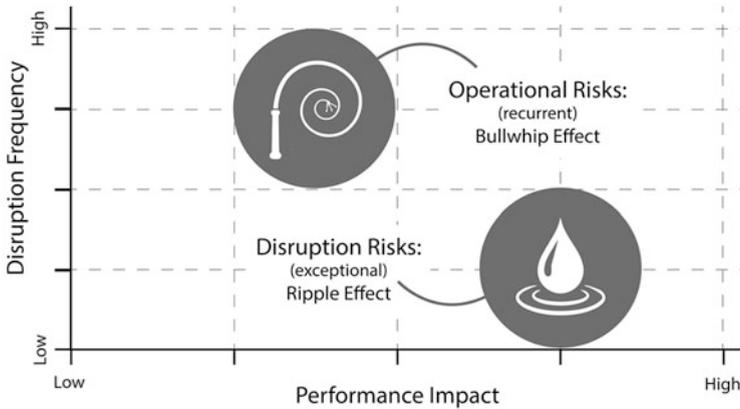


Fig. 15.5 Operational and disruption risks in supply chains

The differences between the bullwhip effect and ripple effect are presented in Table 15.3.

The Bullwhip effect considers weekly/daily demand and lead-time fluctuations as primary drivers of the changes in the supply chain which occur at the parametric level and can be eliminated in a short-term perspective. In recent years, the research community has started to investigate severe supply chain disruptions with long-term impacts that can be caused, for example, by natural disasters, political conflicts, terrorism, maritime piracy, economic crises, destroying of information systems, or transport infrastructure failures. We refer to these severe natural and man-made disasters as the ripple effect in the supply chain where changes in the supply chain occur at the structural level and recovery may take mid- and long-term periods of time with significant impact on output performance such as annual revenues. In this setting, supply chain disruption management can be considered a critical capability which helps to create cost-efficient supply chain protection and implement appropriate actions to recover supply chain disruptions and performance.

Most studies on supply chain disruption consider how changes to some variables are rippling through the rest of the supply chain and impacting performance. Studies by Ivanov et al. (2014a, b) and Dolgui et al. (2018) suggest considering this situation as *the ripple effect in the supply chain*, as an analogy to computer science, where the ripple effect determines the disruption-based scope of changes in the system.

15.5 Ripple Effect in the Supply Chain

The *ripple effect* in the supply chain occurs if a disruption cannot be localized and cascades downstream impacting supply chain performance such as sales, stock return, service level, and costs (Ivanov et al. 2014a; Dolgui et al. 2018; Ivanov 2018; Pavlov et al. 2018). The methodical elaborations on the evaluation and

Table 15.3 Ripple effect and bullwhip effect (Dolgui et al. 2018)

Feature	Ripple-effect	Bullwhip-effect
What uncertainty?	Hazard, deep uncertainty	Random uncertainty
What risks?	Disruption, exceptional risks (e.g., a plant explosion)	Operational, recurrent risks (e.g., demand fluctuation)
What can be disturbed?	Structures and critical performance (such as supplier unavailability or revenue)	Operational parameters such as lead-time and inventory
How are deviations prevented?	Proactive redundancy and flexibility	Information coordination
What happens after the disturbance?	Short-term stabilization and middle- and long-term recovery; high coordination efforts and investments	Short-term coordination to balance demand and supply
What is performance impact?	Output performance can decrease, such as in annual revenues or profits	Current performance can decrease such as in daily or weekly stock-out/overage costs

understanding of low-frequency-high-impact disruptions are therefore vital for understanding and further development of network-based supply concepts (Tomlin 2006; Liberatore et al. 2012; Sawik 2016).

Details of empirical or quantitative methodologies differ across the works on supply chain disruption management, but most share a basic set of attributes:

- a disruption (or a set of disruptions)
- impact of the disruption on operational and strategic economic performance
- stabilization and recovery policies.

Within this set of attributes, most studies on supply chain disruption consider how changes to some variables are rippling through the rest of the supply chain and impacting performance. We suggest considering this situation, *the ripple effect in the supply chain*, as an analogy to computer science, where the ripple effect determines the disruption-based scope of changes in the system.

The ripple effect is a phenomenon of disruption propagations in the supply chain and their impact on output supply chain performance (e.g., sales, on-time delivery, and total profit). It may have more serious consequences than just short-term performance decrease. It can result in market share losses (e.g., Toyota lost its market leader position after tsunami in 2011 and needed to redesign supply chain coordination mechanism). The ripple effect is also known as “domino effect” or “snowball effect”. The reasons for ripple effect are not difficult to find. With increasing supply chain complexity and consequent pressure on speed and efficiency, an ever-increasing number of industries come to be distributed worldwide and concentrated in industrial districts. In addition, globalized supply chains depend heavily on permanent transportation infrastructure availability.

The ripple effect describes disruption propagation in the supply chain, impact of a disruption on supply chain performance and disruption-based scope of changes in supply chain structures and parameters.

Following a disruption, its effect ripples through the supply chain. The missing capacities or inventory at the disrupted facility may cause missing materials and production decrease at the next stages in the supply chain. Should the supply chain remain in the disruption model longer than some critical period of time [i.e., *time-to-survive* (Simchi-Levi et al. 2015)], critical performance indicators such as sales or stock returns may be affected.

The scope of the rippling and its impact on economic performance depends both on robustness reserves (e.g., redundancies like inventory or capacity buffers) and speed and scale of recovery measures. Therefore, the risks and supply chain resilience should be estimated at the design and planning stages in the proactive mode.

At the control stage in the reactive mode, contingency plans (e.g., alternative suppliers or shipping routes) must happen quickly to expedite stabilization and recovery in order to ensure continuity of supply and avoid long-term impacts. In implementing such recovery policies, companies need a tool supported by collaboration and supply chain visibility solutions for assessing the disruption impact on the supply chain as well as the effects and costs from redirecting material flows. In supply chain management settings, the ripple effect should also include recovery strategies which may compensate for disruptions and avoid their rippling.

It has been extensively documented in literature that severe disruptions may ripple quickly through global supply chains and cause losses in supply chain performance that can be measured by such key performance indicators as revenues, sales, service level, and total profits (Schmitt and Singh 2012; Simchi-Levi et al. 2015; Snyder et al. 2016). Such risks are new challenges for research and industries that face the *ripple effect* arising from vulnerability, instability, and disruptions in supply chains (Liberatore et al. 2012; Ivanov et al. 2014a, b). As opposite to well-known bullwhip effect that considers high-frequency-low-impact *operational risks*, the ripple effect studies low-frequency-high-impact *disruptive risks* (Fahimnia et al. 2015; Simchi-Levi et al. 2015; Sokolov et al. 2016; Snyder et al. 2016).

Figure 15.6 summarize major reasons for the ripple effect.

Along with the identification of the reasons for the disruption risks, risk mitigation strategies have been developed with regards to proactive and reactive control stages (Bode et al. 2011; Ivanov et al. 2017). Let us consider them in the next section.

15.6 Supply Chain Resilience

15.6.1 Resilience Framework

Supply chain *resilience* is the “ability to maintain, execute and recover (adapt) planned execution along with achievement of the planned (or adapted, but yet still acceptable) performance is therefore the next objective property of the supply chain” (Ivanov 2018). Supply chain *resilience* is a multi-facet property that comprises a

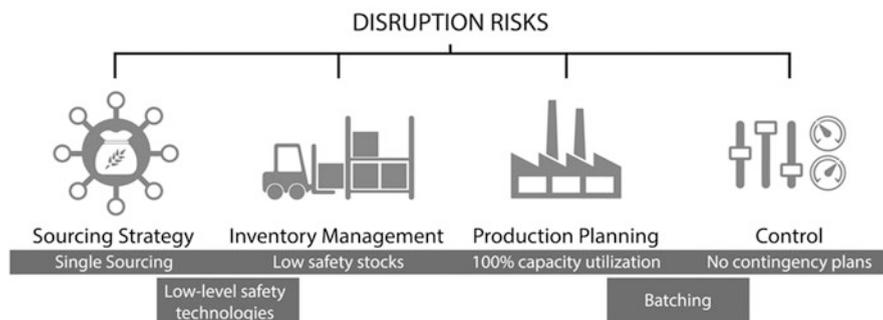


Fig. 15.6 Reasons for the ripple effect (Ivanov 2018)

number of components in both internal supply chain processes and in interaction with the environment (Fig. 15.7).

One of the main objectives of supply chain management is to increase total supply chain output performance, which is basically referred to as supply chain effectiveness (i.e., sales and service level) and efficiency (supply chain costs). At the same time, achievement of planned performance can involve the impact of perturbations in a real-time execution environment. Supply chain execution is subject to uncertainty at the planning stage and disruption at the execution stage. Cost efficiency comes with a huge hidden expense should a major disruption (i.e., a more severe impact than a routine disturbance) occur. This requires supply chain protection against and efficient reaction to disturbances and disruptions. Therefore, supply chains need to be planned to be *stable, robust and resilient* enough to (1) maintain their basic properties and ensure execution; and (2) be able to adapt their behavior in the case of disturbances in order to achieve planned performance using recovery actions.

In Fig. 15.8, we summarize relations of redundancy, robustness, resilience and flexibility (see also Ivanov and Sokolov 2013; Ivanov 2018).

First, different *reserves* (material inventory, capacities) can be referred to. Tomlin (2006) and Chopra and Sodhi (2004) analysed the issues of *risk mitigation inventory* and reserve capacity on supply chain resilience. It should be noted that risk mitigation inventory differs from classical safety stock and is considered to decouple from disruptive risks. For this issue, valuable approaches and models for supply chain design and planning under uncertainty were elaborated.

Second, new *strategies* such as leagile, agile and responsive supply chains can be applied to make supply chains more flexible in a wider sense of the word. The third method is related to better *coordination* in supply chains and refers to the concepts like collaborative planning, forecasting and replenishment. Fourth, a set of *postponed decisions* (product postponement, rolling/adaptive planning) can be used. All these approaches can be referred to as supply chain *redundancy*.

The above-mentioned redundancies generally serve for two problem areas. First, they are intended to protect the supply chain against perturbation impacts based on certain reserves. This issue is related to the supply chain *robustness*. Second, redundancies are created to amplify the fork variety of supply chain paths to react quickly and flexibly to changes of a real execution environment. This issue is related to supply chain *flexibility*.

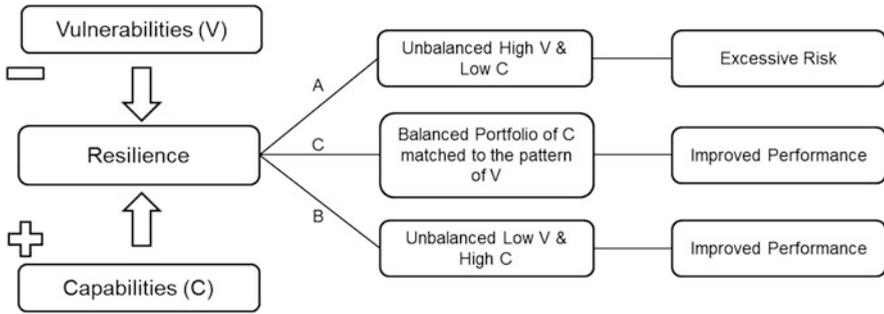


Fig. 15.7 Supply chain resilience concept (based on Pettit et al. 2010)

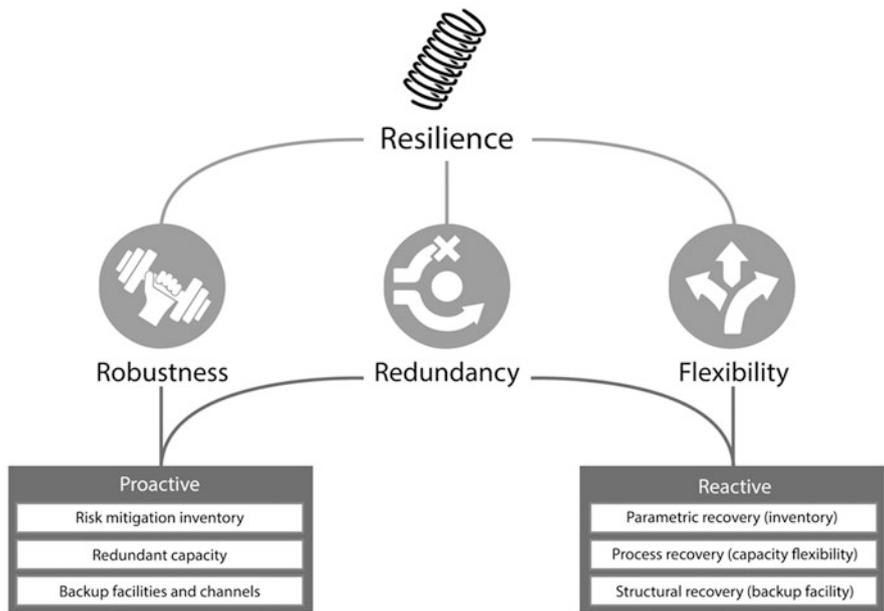


Fig. 15.8 Resilience control elements (Ivanov 2018)

The *robustness* of supply chains is a complex characteristic of a non-failure operation, durability, recoverability, and the maintaining of supply chain processes and a supply chain as a whole. This is connected with the creation of a reserves system (the introduction of resource excessiveness) for the prevention of failures and deviations in supply chain processes.

Recent literature has identified different methods to strengthen supply chains to mitigate uncertainty impacts and ensure supply chain robustness. Different robustness reserves can include material inventory, capacities buffers, etc. For this issue, valuable approaches and models for supply chain design and planning under uncertainty were elaborated.

The flexibility of supply chains is a property concerning its ability to change itself quickly, structurally and functionally depending on the current execution state and reaching supply chain management goals by a change in supply chain structures and behaviour. This is connected with the creation of an *adaptation system* (with regard to operations and resources) for the prevention, improvement, or acquisition of new characteristics for the achievement of goals under the current environmental conditions varying in time.

Basic areas of flexibility include system, process and product flexibility (Fig. 15.9).

System flexibility is composed of structural and strategy components. Companies implement product and process flexibility extensively (see e.g., new Volkswagen production system (VPS) strategy). Coordination and sourcing strategies in supply chains are also typical in practice. Many companies invest in structural redundancy (e.g., Toyota extends its supply chain subject to multiple-sourcing and building new facilities on the supply side). All these four elements of flexibility can be seen as strategies for mitigating the ripple effect at the mitigation stage and reacting at the post-disruption stage.

15.6.2 Costs of Resilience

Increase in inventory, additional production capacities, and alternative transportation methods or back-up facilities would increase costs. At the same time, these so-called redundant elements would potentially lead to an increase in sales and service level. The robustness elements would also reduce risk of perturbations which may influence schedule execution. Therefore, target objectives (e.g., on-time delivery) can be better achieved. This will positively influence sales and service level. Redundancy elements may also increase supply chain flexibility and have positive effects on both service level and costs. The resilient state of a supply chain requires a balanced robustness and flexibility which allows for achieving maximum service level with

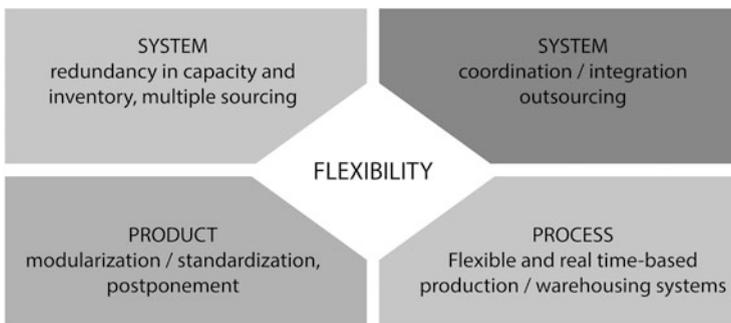


Fig. 15.9 Supply chain flexibility (adopted with changes from Ivanov et al. 2014b)

disruption risk considerations at acceptable redundancy costs. These ideas are simplified in Figs. 15.10 and 15.11.

In Fig. 15.10a, a supply chain of a retailer, a warehouse, and a factory is presented. The factory orders 100 units of a product every day from factory that is aligned with the daily production capacity of 100 units. No batching is considered in this simple example. Daily shipments are assumed. The warehouse holds risk mitigation inventory of 700 units as a proactive resilience policy. In Fig. 15.10b, factory capacity is disrupted for 7 days. Considering the risk mitigation inventory of 700 units and daily demand of 100 units, this disruption does not affect supply chain performance in terms of service level, i.e., the ratio of on-time delivered orders to all placed orders.

Now let us consider Fig. 15.11.

The disruption profile constituted in the work by Sheffi (2005) includes eight phases: preparation actions, the disruptive event, the first response, the initial impact, the full impact, the recovery preparations, and the recovery and long term impact. In Fig. 15.11, a general framework of supply chain performance and recovery analysis is depicted. The major idea here is to observe the impact of different recovery policies on supply chain performance. Figure 15.11b depicts that in case a factory stops producing for 14 days, service levels will be disrupted since risk mitigation inventory would help for 1 week only. In Fig. 15.11c, it can be observed that usage of back-up factory mitigates the ripple effect and performance decrease. However, both risk mitigation inventory and a back-up capacity increase supply chain costs.

It is evident that through the adaptation, supply chain flexibility and robustness are interrelated. From the dynamics point of view, the robustness elements can also be considered as flexibility elements and the flexibility elements can also be considered as robustness drivers. This is quite natural since both robustness and flexibility serve as “uncertainty cushions” of a supply chain. Balancing the elements of flexibility and robustness at proactive and reactive control loops, different constellations of service level, costs and stability can be analyzed methodically and well-founded and with regard to a risk covering strategy and supply chain management strategy (Fig. 15.12).

Figure 15.12 depicts an example of a typical multi-objective analysis with regards to different proactive and reactive policies. We are interested in investigating the impacts of different combinations of disruptions (i.e., two scenarios in Fig. 15.12), proactive mitigation strategies and reactive recovery policies (A, B, C, and D) on the supply chain performance in form of service level and costs. The combinations of proactive mitigation strategies and reactive recovery policies (e.g., A—higher risk mitigation inventory, B—a back-up facility, etc.) may differ in costs and service level impacts for different disruption scenarios. The task of quantitative analysis methods is to decide on what proactive and reactive policies need to be selected.

The study by Ivanov and Dolgui (2018) suggested a new approach to supply chain disruption risk management where SC behavior is less dependent on the certainty of our knowledge about the environment and its changes. The unpredictability of the occurrence of disruption and its magnitude suggests that designing supply chains with a low need for “certainty” may be as important, if not more so,

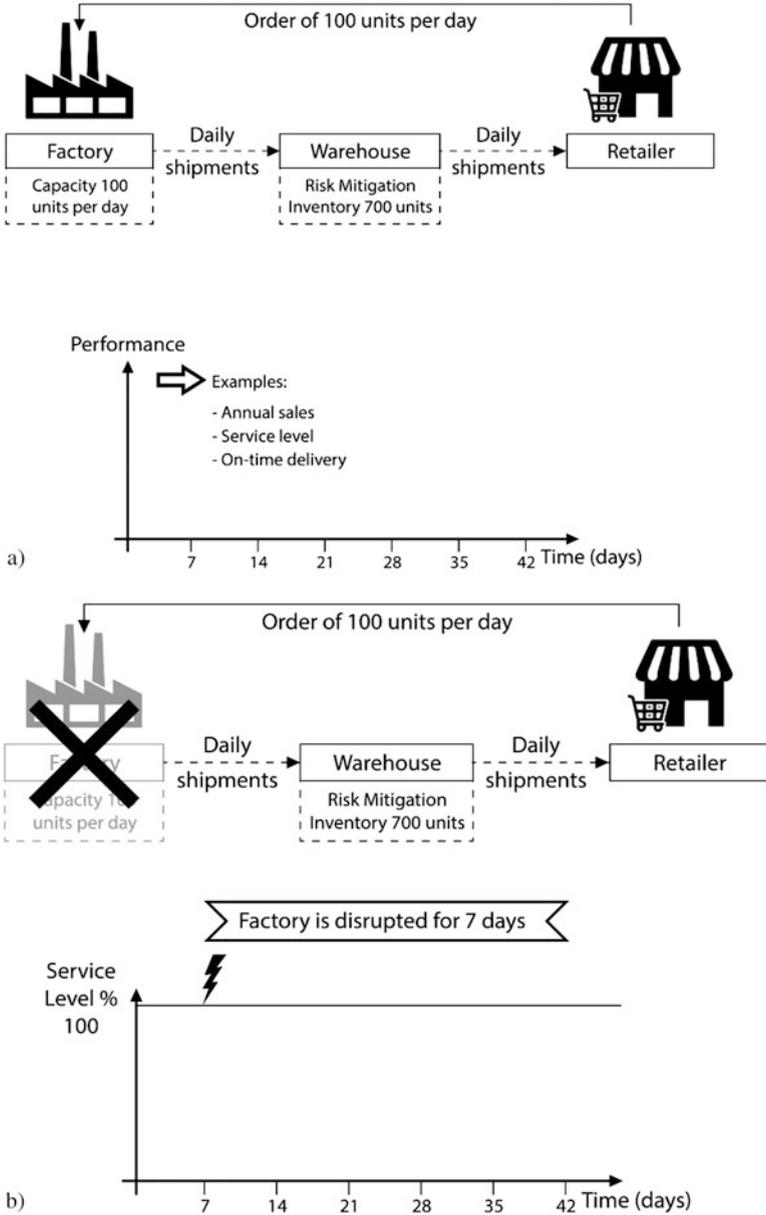


Fig. 15.10 Supply chain with a proactive policy (risk mitigation inventory) (Ivanov 2018). (a) Supply chain without disruptions. (b) Supply chain with a disruption

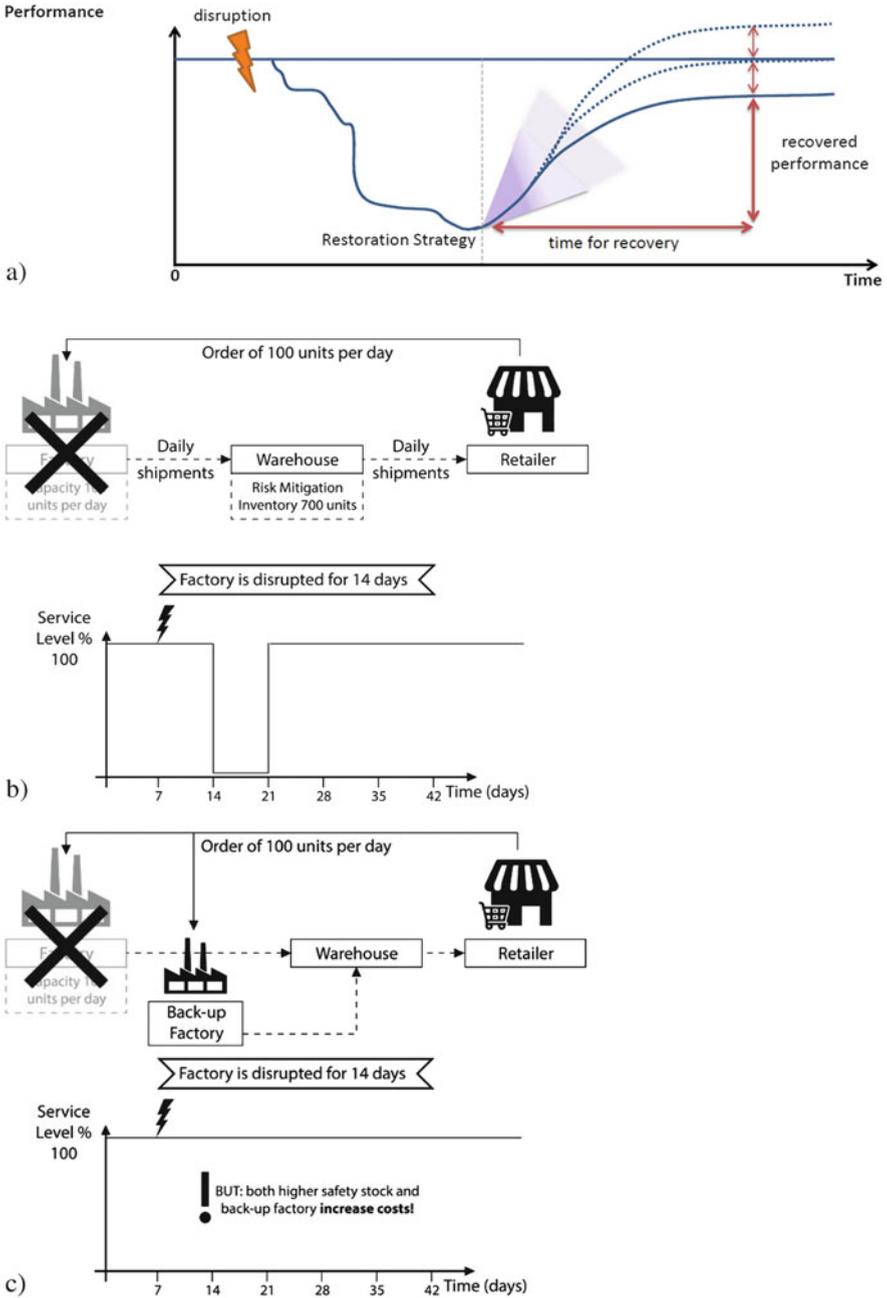
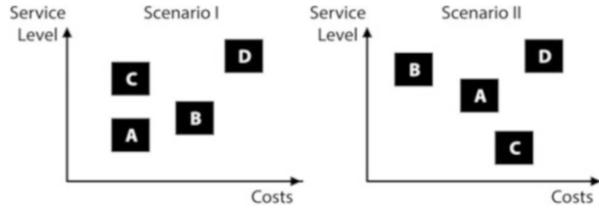


Fig. 15.11 Supply chain with a proactive policy (back-up facility) (Ivanov 2018). (a) General performance and recovery analysis framework. (b) Disrupted supply chain performance. (c) Back-up facility as a reactive flexibility strategy

Fig. 15.12 Efficiency vs effectiveness trade-off in supply chain resilience management (Ivanov 2018)



than predetermined disruption control strategies. In this setting, this study calls for the development of a new perspective in SC disruption management, i.e., low-certainty-need (LCN) supply chains. Structural variety, process flexibility, and parametrical redundancy are key LCN supply chain characteristics that ensure efficient disruption resistance as well as recovery resource allocation. Two efficiency capabilities of the LCN supply chain are low need for uncertainty consideration in planning decisions and low need for recovery coordination efforts based on a combination of lean and resilient elements.

15.7 KPI for Supply Chain Risk

Quantification of SC risk is based on KPIs (key performance indicators) that can be classified into operational and disruption risk KPIs with regards to bullwhip and ripple effects, respectively (cf. Fig. 15.4).

15.7.1 Operational Risks

Disney and Towill (2002) suggested the use of *inventory variance ratio* (InvVarR) to quantify the magnitude of bullwhip effect as the relation of inventory variance and demand variance ratio at a generic node (Eq. 15.1).

$$InvVarR = \frac{\sigma_{inventory}^2 / \mu_{inventory}}{\sigma_{demand}^2 / \mu_{demand}} \quad (15.1)$$

where variances of demand and inventory are denoted by σ , and μ are the average values of demand and inventory.

The *order rate variance ratio* (OrdRVarR) operates in a similar way, see Eq. (15.2).

$$OrdVarR = \frac{\sigma_{order}^2 / \mu_{order}}{\sigma_{demand}^2 / \mu_{demand}} \quad (15.2)$$

where variances (σ) are computed according to Eq. (15.3):

$$\sigma_{demand}^2 = \frac{\sum (x_{demand} - \mu_{demand})^2}{(n - 1)}; \sigma_{orders}^2 = \frac{\sum (x_{orders} - \mu_{orders})^2}{(n - 1)} \quad (15.3)$$

where x is the demand or orders in a period, μ is the average demand or orders, and n is the number of periods. If variance ratio measure is >1 , then variance amplification is present and the risk of the bullwhip effect occurring arises. If the variance ratio measure is $=1$, then no bullwhip effect amplification is present. If the variance ratio measure is <1 , then smoothing or dampening is occurring (cf. Heizer and Render 2014, p. 499). Some extensions of the metrics (15.1) and (15.2) for multi-echelon SCs have been proposed, e.g., in Vicente et al. (2017).

15.7.2 Disruption Risks

Ivanov (2018) suggested the use of ripple effect *performance impact* (PI) (Eq. 15.4).

$$PI = \frac{Sales_{plan}}{Sales_{disruption}} \quad (15.4)$$

The PI index represents the relationship between the KPI planned (e.g., revenue or sales) in a disruption-free mode and the real KPI in the case of disruption. Ideally, $PI = 1$. If the PI measure is >1 , then disruption reduces SC performance. If PI measure is <1 , then the SC planning was performed in a non-optimal manner.

Consider an example of PI computation for the six SC designs (SCD) in Table 15.4.

It can be observed in Table 15.4 that SC designs no. 4 and 6 can be considered the most robust since their PIs are the lowest among the SC designs considered and $=1.13$.

Supplier reliability is a further important disruption risk KPI and can be computed as shown in Eq. (15.5)

$$SR = \frac{Quantity_{received}}{Quantity_{ordered}} \quad (15.5)$$

Equation (15.5) can be modified by considering on-time deliveries only. Other relevant metrics are order fill rate and lead time variance.

Time-to-recovery (TTR) and *Time-To-Survive* (TTS) also belong to disruption risk KPIs. TTS is considered as the maximum time that the SC could operate and match supply with demand after a disruption. In contrast, TTR is the time it would take for a particular node to be restored to full functionality after a disruption (Simchi-Levi et al. 2015). TTR/TTS are used to “identify bottleneck suppliers for which it’s critical to obtain accurate TTR information and distinguish them from other suppliers where even plus or minus 30% error in TTR information will have very little impact on the supply chain.” (Simchi-Levi 2015).

Table 15.4 PI computation results

	Initial	SCD 1	SCD 2	SCD 3	SCD 4	SCD 5	SCD 6
Maximum revenue in disruption-free scenario	82,550	82,550	82,550	82,550	82,550	82,550	82,550
Revenue in the disruption scenario	54,600	67,600	67,600	70,200	72,800	70,200	72,800
PI	1.5119	1.2211	1.1759	1.1759	1.1340	1.1759	1.1340

For particular analysis purposes, additional KPIs for disruption risks can be used, e.g., VAR (Value-at-Risk), CVAR (Conditional Value-At-Risk), resilience, robustness, flexibility, adaptability, and reliability of SCs (Goh and Meng 2009; Schmitt and Singh 2012; Kim et al. 2015; Chen et al. 2017; Mizgier 2017; Ivanov 2018; Pavlov et al. 2018; Sokolov et al. 2016). Modern software such as anyLogistix, DHL Resilience 360, and RiskMethods facilitate the computation of these and further KPIs at the risk assessment, monitoring, identification, recovery, and control stages.

15.8 Key Points and Discussion Questions

In this chapter, SC risk management has been introduced. Fundamentally, there are four important categories that need to be analyzed in this domain, i.e., uncertainty, risk, disturbance (the so-called perturbation impact), and disruption (operational deviations).

- Can you explain how these four elements are mutually connected?
- Can you summarize uncertainty factors and the corresponding handling measures?
- Can you explain the seven different supply chain risks?

We have seen that demand, globalization, lead-time, and Lean supply chains can be considered as different types of risk in SCM. This means SCs are exposed to recurrent operational risks and exceptional disruption risks. Summarize in your own words factors relevant to operational risks under the Bullwhip Effect. Do the same for disruption risks and explain the Ripple Effect and give some examples of the Bullwhip- and the Ripple Effect.

- Where does information coordination help, and when would you suggest building up inventory buffers?
- Is the explosion of a factory an operational or a disruptive risk? Is an explosion an exceptional or a recurrent risk?
- What are low-frequency-high-impact risks? Are these operational or disruptive risks?

- What are high-frequency-low-impact risks? Are these operational or disruptive risks?
- What are effects of the Ripple Effect that can be diagnosed in reduced SC performance?
- What are two other good expressions that you know for the Ripple Effect?
- Can you summarize major reasons for the Ripple Effect and can you give examples for recovery strategies or policies?
- What KPIs can we use to quantify operational and disruption risks?

SC managers do not only deal with SC risks. They also need to put strategies in place to manage SC resilience. SCs need to be planned such that they are stable, robust, and resilient, i.e. so they can cope with uncertainty in the planning stage and are able to deal with disturbances and disruptions during SC execution.

- Can you give examples for proactive and reactive measures that will lead to SC resilience?
- What are approaches to support SC redundancy?
- What are the four elements that enable companies to implement SC flexibility?

SC flexibility and robustness are interrelated. As we have seen, risk mitigation inventory or considering a backup location, and purchasing items from an alternative supplier, respectively, are useful strategies. These robustness and flexibility strategies have certain costs. Companies should therefore balance their robustness and flexibility investments and possible losses from disruptions to reduce the Ripple Effect and mitigate decreased SC performance, which would lead to lost sales, penalty payments, and is significantly negative from a reputational point of view.

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