Chapter 2
Supply Chain Risk Management: Bullwhip Effect and Ripple Effect

2.1 Uncertainty and Risks

Uncertainty is a system property characterizing the incompleteness of our knowledge about the system and the conditions of its development. Uncertainty is a polysemic term (poly – many, sema – a sign). Historically, the first terms related to uncertainty were accident, probability and possibility, which we relate to Aristotle. Up to the twentieth century, the mathematical basics of uncertainty factor description were founded on probability–frequency interpretation and are related to Pascal, Ferma, Bernoulli and Laplace. Modern probability theory is based on the research of Kolmogorov, who introduced an axiomatic definition of probability as a measure related to a system of axioms of a so-called probability space.

In contrast to risk, uncertainty is a more comprehensive term, considering situations that cause both positive (chance) and negative (threats) deviations from an expected outcome. Modern system theory defines uncertainty as "a gradual assessment of the truth content of a proposition, e.g. in relation to the occurrence of the event" (Möller and Beer 2004).

One of the main dangers of uncertainty is the perturbation impacts, leading to a change in a planned course of events in the supply chain functioning and (or) a threat of economic performance decrease such as lost sales or stock returns. There are different external and internal, objective and subjective perturbation impacts altering the execution conditions of a supply chain.

Let us analyse the main types of perturbation influences that can be divided into two groups:

- purposeful perturbation influences; and
- non-purposeful perturbation influences.

Purposeful perturbation influences can be antagonistic (impeding supply chain functioning) or non-antagonistic (promoting supply chain functioning). Examples

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of purposeful perturbation impacts are thefts, terrorism, piracy and financial misdeeds.

Non-purposeful perturbation influences can be natural, economic or technological. The former can be caused by phenomena of the geo-, hydro- or biosphere. Examples of an economic non-purposeful perturbation impact are demand fluctuations and the bullwhip-effect.

Hence, there are two types of uncertainty affecting supply chains: (1) risks arising from the problems of coordinating supply and demand and (2) risks arising from purposeful disruptions to normal activities (Kleindorfer and Saad 2005).

2.1.1 Sources of Uncertainty

In Fig. 2.1, a classification of uncertainty origins is undertaken.

Research on how to cope with disturbances has mostly been concentrated on the *environmental uncertainty* (i.e. demand fluctuations and the so-called bullwhip-effect) (Chen et al. 2000; Lee et al. 1997) by means of stochastic or robust optimization. Other research streams deal with uncertainty caused by *human decisions* and goals. Sterman (1989) sees wrong decisions made by human decision makers as the major cause of the bullwhip effect. Hallikas et al. (2004) considered organizational risks and proposed an approach to reduce uncertainty by means of increasing entire network transparency. Sokolov and Yusupov (2006) distinguished seven psychological types of managers and considered this criterion in the model of risk management.

Uncertainty factors are usually divided into two groups: stochastic factors and non-stochastic factors. The first group can be described via probability models. The factors described as aleatory variables (functions, fields) with known distributions are statistically defined. Aleatory variables with unknown distributions can be of two types: those with known or unknown characteristics. The following factors produce non-stochastic uncertainty:

- Purposeful opposition of a rival system, while its actions are unknown. This type of uncertainty is called behavioural.
- Phenomena interrelated with supply chain operation and insufficiently studied. This type of uncertainty is called uncertainty of nature.
- Uncertainty of human thinking. This kind of uncertainty arises when the system is being managed or investigated. It can be called personnel uncertainty.
- Uncertainty of knowledge in the system of artificial intellect.

For the formal description of non-stochastic uncertainty, fuzzy description with known membership functions, subjective probabilities for the uncertainty factors, interval description, and combined description of the uncertainty factors are used.

In analysing uncertainty, 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 the further

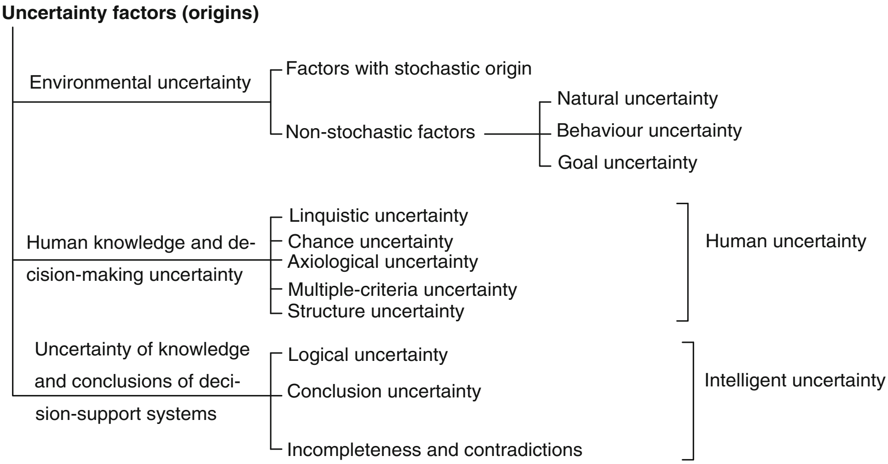

Fig. 2.1 Classification of uncertainty factors (Ivanov and Sokolov 2010)

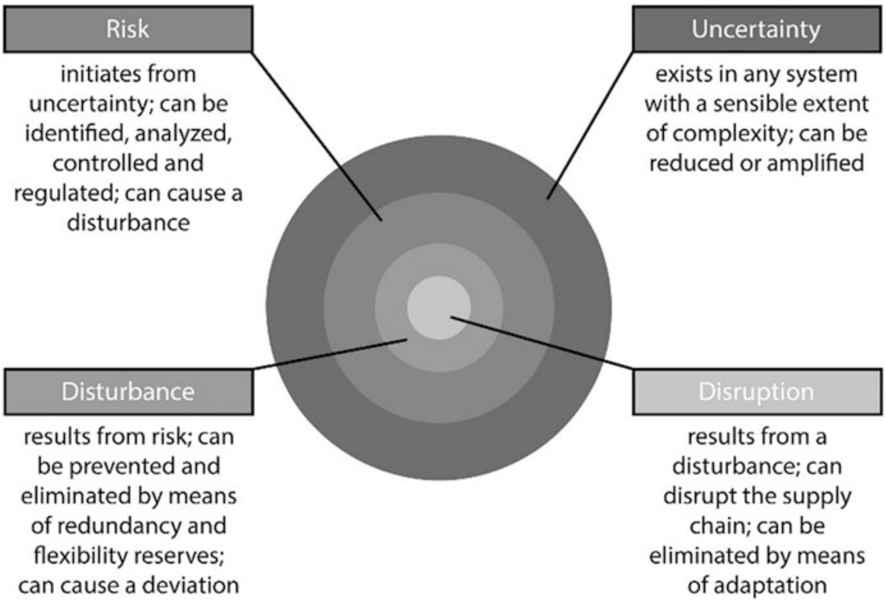

Fig. 2.2 Interrelations of uncertainty, risk, disturbance and disruption (Based on Ivanov and Sokolov 2010)

course of this and the following chapters, we will frequently encounter this constellation (see Fig. 2.2).

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. 2.2, we can broaden and narrow the uncertainty space.

Table 2.1 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

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 2.1).

In Table 2.2, some examples of disturbances and disruptions in supply chains in recent years are presented.

A survey by the Business Continuity Institute (2011) found that 85% of companies with global supply chains had experienced at least one supply chain disruption in the previous 12 months. The authors from the same institute found in a later survey (Alcantara and Riglietti 2015) that 74% of firms had experienced more than one supply chain disruption, with 6–20 disruptions per year for 15% of the companies. The costs of such disruption can be high, leading to lower revenue, increased downtime, delays in delivery, lost customers, stock return decrease and damaged reputations (Hendricks and Singhal 2005).

2.1.2 Uncertainty and Complexity

Complexity has been one of the most challenging phenomena in business and science over the last 60 years (Ashby 1956; Simon 1962; Bertalanffy 1968; Mesarovic and Takahara 1975; Casti 1979; Holland 1995; Anderson 1999;

Table 2.2 Examples of disturbances and disruptions in supply chains (Extended from Ivanov and Sokolov 2010)

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

Lissak and Letiche 2002; Richardson 2004, 2005, 2007; Pathak et al. 2007). Complexity is a multi-spectral category and one of the basic properties of systems of any nature (see Sect. 5.3).

The fulfilled analysis confirmed that a well-founded concept for uncertainty analysis in the supply chain models is a system-cybernetics one (see Fig. 2.3).

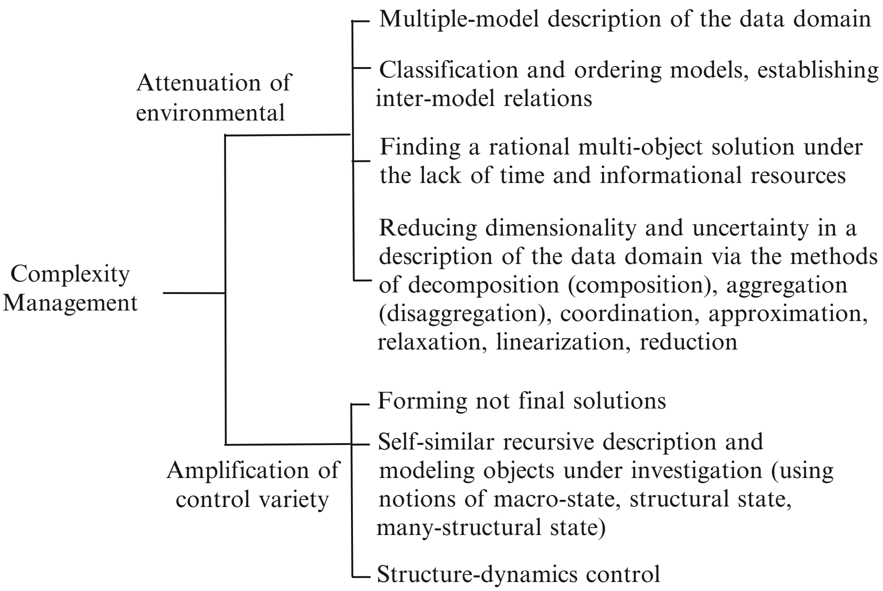

Fig. 2.3 Directions for realizing the law of requisite variety

This concept assumes that all the input signals of a dynamic system (supply chain, in our case) can be divided into two classes: control inputs and perturbation inputs. Moreover, it is assumed that the control inputs are known, and thus the supply chain and its control processes can be regarded as deterministic mathematical constructions. All of the perturbation factors are called factors of uncertainty. They belong to the environment into which the deterministic object is "plunged".

Complexity management and system modelling can be considered as a theoretical basis for handling uncertainty in supply chains. From the perspective of complexity 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. 2.4).

By broadening the control area (Fig. 2.4b) and narrowing the uncertainty area or reverse (Fig. 2.4a), 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. 2.4).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.

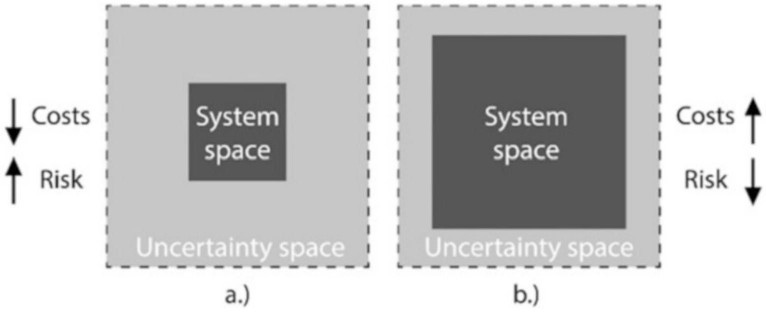

Fig. 2.4 System space and uncertainty space

2.2 Risk Management in the Supply Chain

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 and Dong 2011; Waters 2011; Gurnani et al. 2012; Heckmann 2016; Khojasteh 2017) and literature review papers (Klibi et al. 2010; Simangunsong et al. 2012; Ho et al. 2015; Fahimnia et al. 2015; Gupta et al. 2016) 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). For example, Chopra and Sodhi (2004) categorised potential supply chain risks into nine categories: (a) Disruptions (e.g. natural disasters, terrorism, war, etc.), (b) Delays (e.g. inflexibility of supply source), (c) Systems (e.g. information infrastructure breakdown), (d) Forecast (e.g. inaccurate forecast, bullwhip effect, etc.), (e) Intellectual property (e.g. vertical integration), (f) Procurement (e.g. exchange rate risk), (g) Receivables (e.g. number of customers), (h) Inventory (e.g. inventory holding cost, demand and supply uncertainty, etc.), and (i) Capacity (e.g. cost of capacity).

2.2.1 General Framework of Risk Control

Uncertainty initiates risk. At the stage of supply chain design (configuration and structure synthesis), uncertainty is a category that is mostly used in relation to risk management.

Risk management is a methodological approach to managing uncertainty outcome. 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".

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. Some literature (e.g. Sokolov and Yusupov 2006) points out the problem of 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. Sheffy 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 proposed concept of risk handling. 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. 2.5).

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

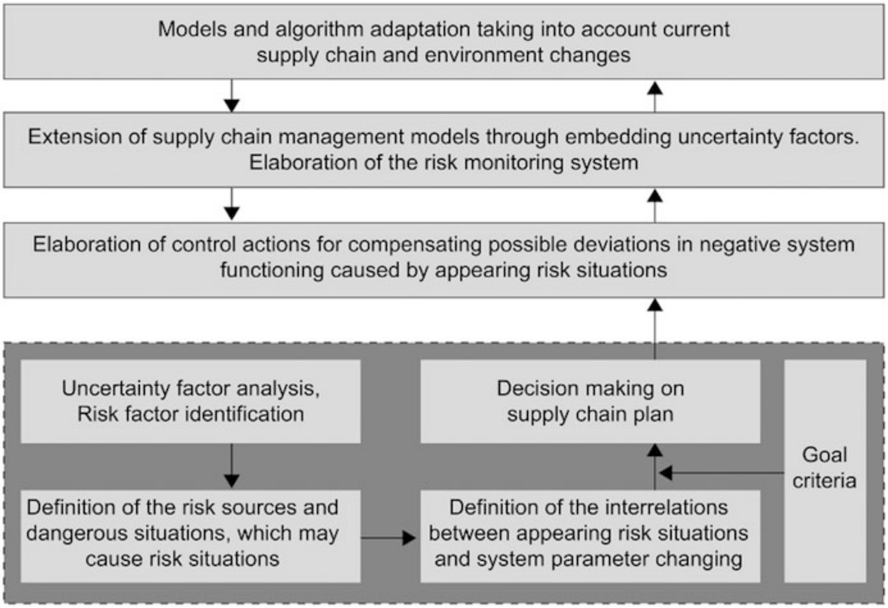

Fig. 2.5 Handling risks in supply chains

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.:

   - 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.

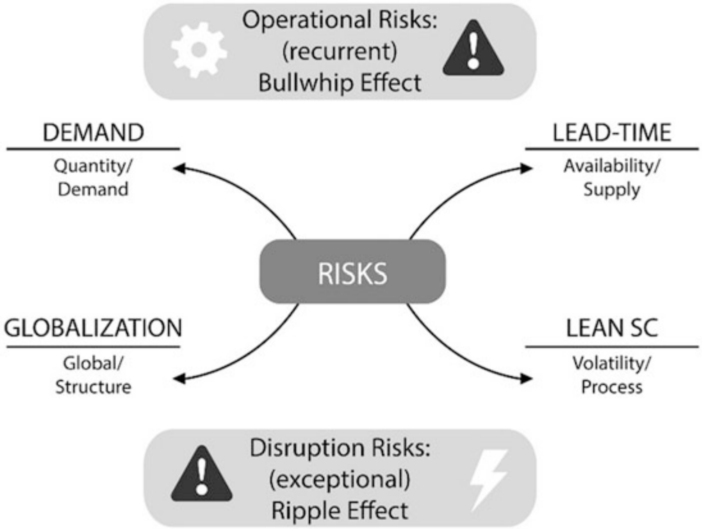

Fig. 2.6 Supply chain risks

2.2.2 Operational and Disruption Risks

The different types of risks in the supply chain can be classified into demand, supply, process, and structure areas (see Fig. 2.6).

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. First, globalization and outsourcing trends make supply chains more complex and less observable and controllable. According to complexity theory, such systems become more sensitive to disruptions. Special focus in this area is directed to disruptions in transportation channels. Second, the efficiency paradigms of lean processes, single sourcing, etc. have failed in disruption situations. As a consequence, supply chains became more vulnerable even to minor perturbations (Tsai 2016). Disruptions in a global supply chain, especially in its supply base, may immediately affect the entire supply chain. Third, with increased specialization and geographical concentration of manufacturing, disruptions in one or several nodes affect almost all the nodes and links in the supply chain. Fourth, IT became the crucial element of global supply chains, since disruptions in IT may have significant impacts on disruptions in material flows.

Recent literature and management practices provide evidence that it is mandatory to take into account uncertainty and risks in order to provide practically relevant problem statements and decision-oriented solutions. Recent literature suggests considering *recurrent* or *operational* risks and *disruptive* risks (Chopra et al. 2007). 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)

For example, the risks of demand and lead-time uncertainty are related to random uncertainty and business-as-usual situations. Such risks are also known as *recurrent* or *operational risks* (Kleindorfer and Saad 2005; Chopra et al. 2007; Meisel and Bierwirth 2014; Aqlan and Lam 2015) and are frequently considered in the framework of the *bullwhip-effect* (Ouyang and Li 2010). Supply chain managers achieved significant improvements at managing supply chains and mitigating recurrent supply chain risks through improved coordinated planning and execution, e.g., vendor-managed inventory (VMI) or collaborative planning, forecasting and replenishment (CPFR) (Chopra and Sodhi 2014; Xu et al. 2015).

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, 2017b; Ivanov 2017; Dolgui et al. 2018) subject to *structural disruptions* in the supply chain, unlike the *parametrical deviations* in the bullwhip effect (Fig. 2.7).

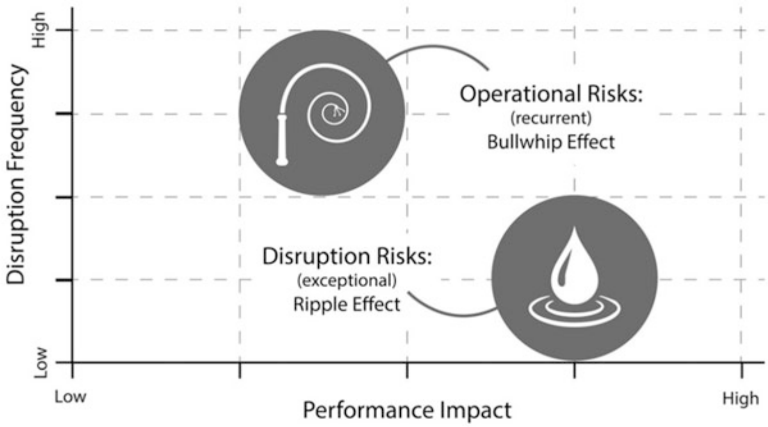

Fig. 2.7 Operational and disruption risks in supply chains

Table 2.3 Ripple effect and bullwhip effect

Feature	Ripple effect	Bullwhip effect
Risks	Disruptions (e.g. explosion)	Operative (e.g. demand fluctuation)
Affected areas	Structures and critical parameters (such as service level and total costs)	Operative parameters such as lead-time and inventory
Recovery	Middle- and long-term; significant coordination efforts and investments	Short-term coordination to balance demand and supply
Decreased performance	Output performance such as annual revenues	Mainly current performance such as daily/weekly stock-out/overage costs

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 (supply chain) has been extensively considered in this domain subject to *randomness uncertainty* with the help of stochastic and simulation models.

However, deviations may also result from *hazard and deep uncertainty* (Klibi et al. 2010), and they have, therefore, different scope and scale. In recent years, the research community has started to investigate *severe supply chain disruptions* that can be caused, for example, by natural disasters, political conflicts, terrorism, maritime piracy, economic crises, destroying of information systems, or transport infrastructure failures.

The differences between the bullwhip effect and ripple effect are presented in Table 2.3.

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.

2.3 Bullwhip Effect

The *bullwhip effect* is not a new phenomenon in the industrial world (Forrester 1961). The effect can be explained as magnification of variability in orders in the supply chain. In other words, irregular orders in the downstream part of the supply chain become more distinct upstream in the supply chain. This variance can interrupt the smoothness of the supply chain processes as each link in the supply chain will over- or under-estimate product demand, resulting in exaggerated fluctuations (see Fig. 2.8).

Many retailers, each with little variability in their orders, can lead to greater variability for a smaller number of wholesalers, and can lead to even greater variability for a single manufacturer. Main reasons for the bullwhip effect can be divided into behavioural and operational areas (Lee et al. 1997; Sterman 2000):

Behavioural causes

- misuse of base-stock policies
- misperceptions of feedback and time delays
- panic ordering reactions after unmet demand
- perceived risk of other players' bounded rationality.

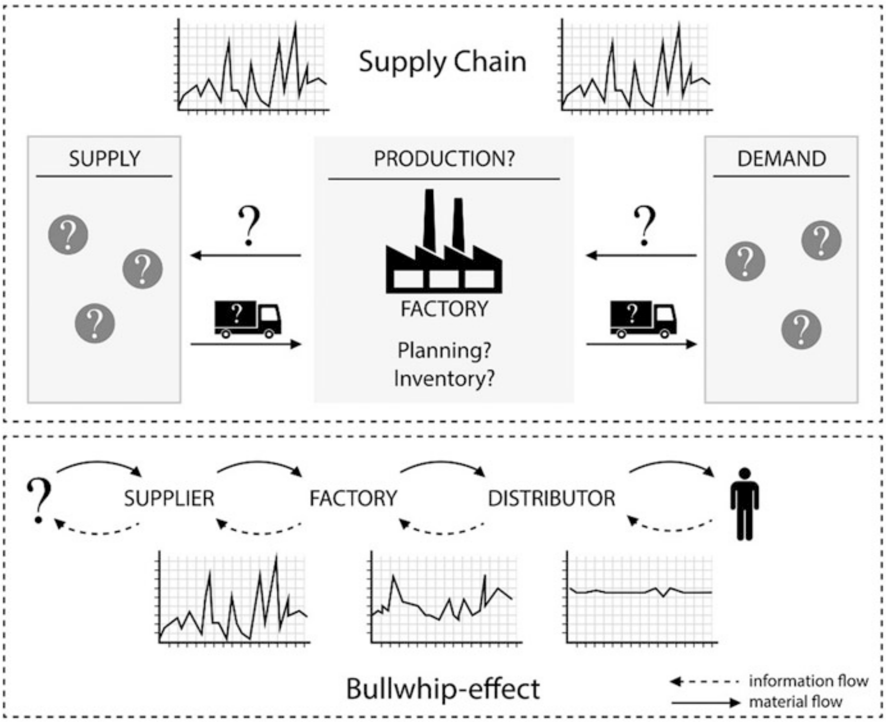

Fig. 2.8 Bullwhip-effect in the supply chain

Table 2.4 Elimination of bullwhip-effect

Reason for bullwhip effect	Countermeasures
Demand non-transparency	Information coordination
Neglecting to order in an attempt to reduce inventory	Automated ordering and monitoring of inventory in order to avoid overstock or shortage
Order batching	Coordinated and accurate lot size definition
Promotions	Use of everyday low prices instead of promotions
Shortage gaming	Validation of customer demand through historical data of customer ordering
Product returns	Policies to control returns or cancelled orders

Operational causes

- dependent demand processing (demand is non-transparent and causes distortions in information in the supply chain)
- lead time variability
- lot-sizing/order synchronization
- quantity discount
- trade promotion and forward buying
- anticipation of shortages.

Negative consequences such as higher safety stocks, inefficient production (surplus or shortage), and low or peek utilization of distribution channels can be recognized. Countermeasures for the bullwhip effect can be identified (Table 2.4).

Consider an example of how demand non-transparency leads to the bullwhip-effect. A fast-moving consumer goods company is facing slight demand variation which leads to huge variation in stocks on the supplier side. The company delivers its product to consumers through the manufacturer and three suppliers. Because of the relatively low cost of changing the production rate compared to the cost of carrying inventory, the company has decided to change its production rate in order to reduce the capital commitment in the form of finished product. The task shows the effect on the manufacturer of a 10% decrease in demand from customers.

For any supplier Eq. (2.1) is used to calculate the production rates:

$$\begin{aligned} \text{New order/production rate} &= \text{Demand new} - \text{Safety stock old} \\ &\quad + \text{Safety stock new} \end{aligned} \tag{2.1}$$

Initial data for analysis is presented in Table 2.5.

Now demand decreases by 10%. Safety stock is 25% of demand and is therefore able to cover demand of 1 week. New demand correlates with the new production rate of the predecessor supply chain member (see Fig. 2.9).

Each player in the supply chain assumes that demand forecast (or orders) for the next period is the same as in the current period. Following this assumption each supplier will be the same as in the current period. Following this assumption each supplier will be planning their production rate to cover the demand/order for the

Table 2.5 Demand data

	Demand old	Order old	Safety stock old
Customer	1200	1200	300
Manufacturer	1200	1200	300
Supplier #1	1200	1200	300
Supplier #2	1200	1200	300
Supplier #3	1200	1200	300

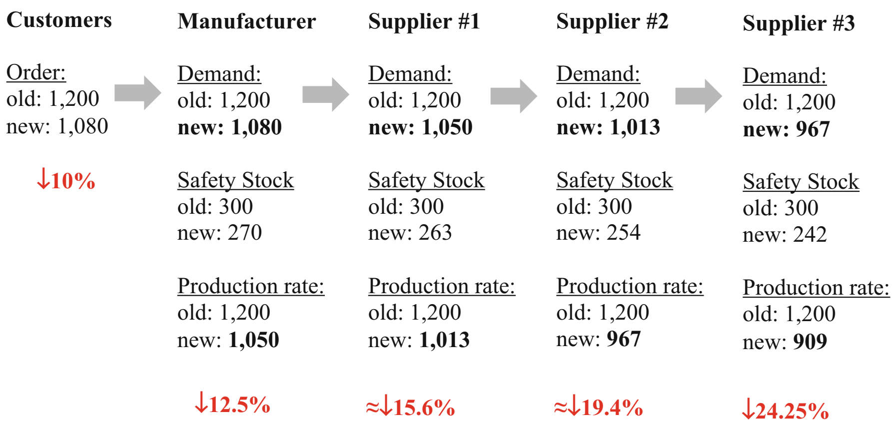

Fig. 2.9 Implications of the demand fluctuations on production rates (Ivanov et al. 2017a)

next period, which will be equal to the demand/order for the current period (e.g., new demand of supplier #3 orients itself by new production rate of supplier #2). The problem will be that only the manufacturer can see the changes in demand on the customer side. Other players in the supply chain cannot see the changes in demand because of non-transparency. For that reason the players will change their production rate and safety stocks because the predecessor changed his order without pre-informing other supply chain partners.

We can observe that demand non-transparency affects the shortage. For example, Supplier #3 will not produce the right amount of pieces for customers' orders to satisfy their demand.

It can be concluded that changes on the customer side increase order quantity through the supply chain if demand is non-transparent. In general, communication, validation of demand, information sharing, and computer aided ordering and better pricing strategy can help reduce the bullwhip effect in this situation.

2.4 Ripple Effect

2.4.1 Definition

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). The methodical elaborations on the evaluation and 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.

Ripple effects are not an infrequent occurrence. In many examples, supply chain disruptions go beyond the disrupted stage; i.e., the original disruption causes disruption propagation in the supply chain, at times still higher consequences are caused (Fig. 2.10).

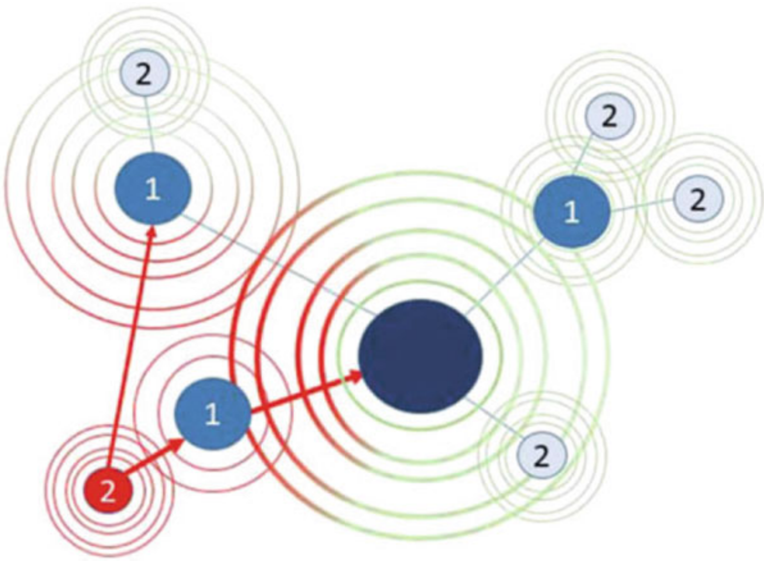

Fig. 2.10 Disruption propagation in the supply chain (Ivanov et al. 2017a)

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 (Ivanov et al. 2014a; Dolgui et al. 2018).

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).

2.4.2 Reasons for Ripple Effect

Table 2.6 and Fig. 2.11 summarize major reasons and counter-measures for ripple effect.

In the last decade, reasons for disruption in supply chains have been extensively investigated. 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, large negative effects on profitability, a 107% drop in operating income, 7% lower sales growth and an 11% growth in costs, 2 years at a lower performance level after a disruption.

2.4.3 Mitigation Strategies for Ripple Effect

Along with the risk identification, recent literature also discussed the risk mitigation strategies. These strategies can be classified into flexibility and robustness areas with regards to proactive and reactive control stages (He and Zhuang 2016).

Table 2.6 Reasons of the ripple effect and counter-measures

Reasons	Counter-measures
Complexity	Simplification of supply chain structures Structures with necessary conditions of observability and controllability
Leanness	Inventory and capacity buffers Postponement Supply chain design extension
Geographical specialization	Multiple sourcing Contingency plans
IT-failures	Decentralization Cloud services

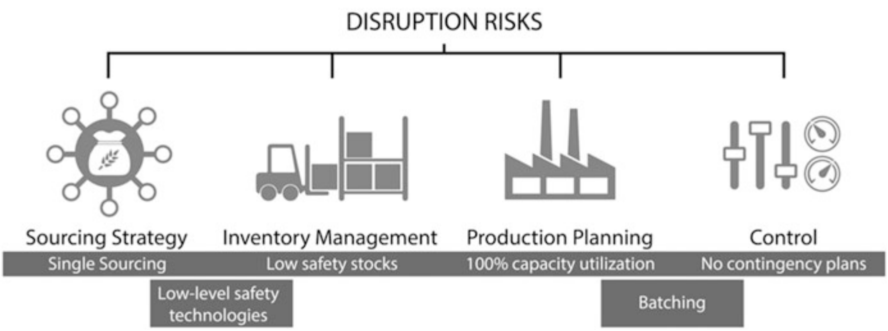

Fig. 2.11 Reasons for ripple effect

Literature has dealt extensively with methods to strengthen supply chains to mitigate uncertainty impacts.

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 *excessiveness*.

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* (Rosenhead et al. 1972). 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*.

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 (Meepetchdee and Shah 2007; Ivanov and Sokolov 2013).

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 (see also Chap. 3 for supply chain resilience).

Elements of the flexibility and robustness are interconnected (see Fig. 2.12).

Many authors, e.g., Jang (2006), Ozbayrak et al. (2006) and Tang and Tomlin (2008) consider flexibility as a solution for avoiding most of the common business disruptions on the basis of timely and responsive reaction to changes in the supply chain environment. Tachizawa and Thomsen (2007) empirically investigated the aspects of flexibility related to the upstream supply chain. Coronado and Lyons

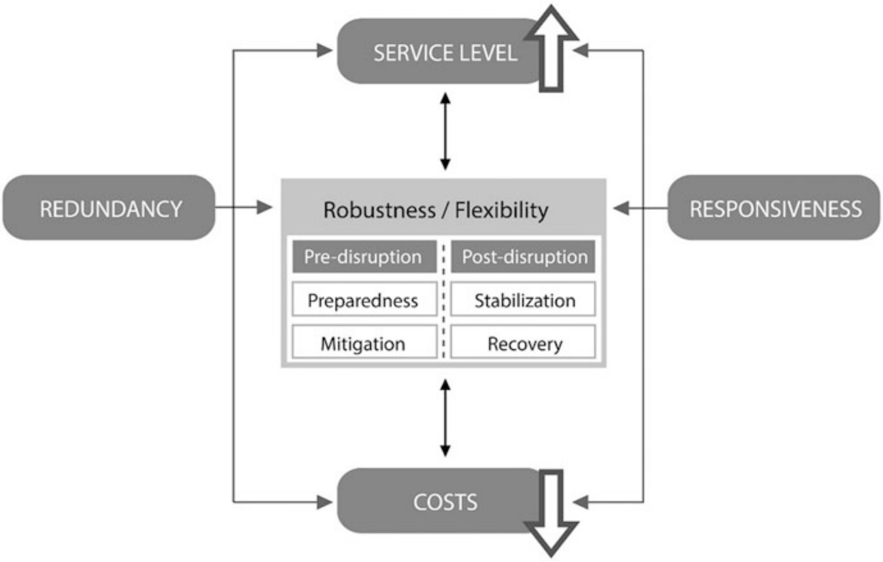

Fig. 2.12 Robustness, flexibility, and performance

(2007) investigated the implications of operations flexibility in industrial supply chains and the effect it had on supporting initiatives designed for build-to-order manufacturing. Wadhwa et al. (2008) presented a study on the role of different flexibility options (i.e. no flexibility, partial flexibility and full flexibility) in a dynamic supply chain model based on key parameters and performance measures.

Swafford et al. (2008) showed that information technology integration enables an organization to tap into its supply chain flexibility, which in turn results in faster supply chain response and ultimately higher competitive business performance. Kauder and Meyr (2009) provided a mathematical optimization framework for a mutual analysis of flexibility and efficiency of supply chain design for an automotive manufacturer. Tanrisever et al. (2012) proposed a stochastic programming model for a multi-stage supply chain regarding capacity flexibility in made-to-order production environments.

Stevenson and Spring (2007) distinguished robust network flexibility as the range of events with which the existing supply chain structure is able to cope, and the reconfiguration of flexibility regarding modification (adaptability) of supply chains. Yadav et al. (2011) analysed the flexibility of supply chain in the context of robustness regarding flexible product families and diversification. Seifert and Langenberg (2011) also considered supply chain flexibility and adaptability with product decisions.

Other aspects of flexibility are coordination and postponement. Coordination has become a key factor in mitigating the *bullwhip effect* and in overcoming information asymmetry (Datta and Christopher 2011; Ouyang and Li 2010). Moreover, it has become possible to integrate customers into supply chain considerations, resulting in the development of the build-to-order supply chain management (Gunasekaran et al. 2008). *Finally,* a set of postponed decisions (product postponement or rolling/adaptive planning) can be used (Olhager 2003) to increase supply chain flexibility.

Santoso et al. (2005) provided evidence of the importance of designing robust supply chains and mitigating information asymmetry with the help of coordination throughout. Datta and Christopher (2011) investigated the effects of information sharing and coordination mechanisms for managing uncertainty in supply chains. In addition, adaptive (rolling) planning is frequently applied to mitigate uncertainty by postponing some planning decisions for specific time intervals.

In relating supply chain flexibility to performance, different metrics such as production, capacity, volume, and logistics flexibility have been introduced (Shepherd and Günter 2006). Beamon (1999) and Naim et al. (2006) considered quantity, supply, product, transport, and innovation flexibility. Beamon (1999), Cai et al. (2009), Shepherd and Günter (2006), Stevenson and Spring (2007) emphasized that existing performance measures for supply chain flexibility are not well matched with each other and are, in some cases, contradictory or excessive.

Knoppen and Christiaanse (2007) showed that flexibility in the supply chain (unlike in manufacturing systems) is primarily interrelated with adaptation through managerial actions. Therefore, in supply chains, coordination plays an important role in flexibility and distinguishes this issue from classic automatic control theory. Simchi-Levi and Wei (2015) developed a method for worst-case analysis of process flexibility designs. Basic areas of flexibility include system, process and product flexibility (Fig. 2.13).

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-

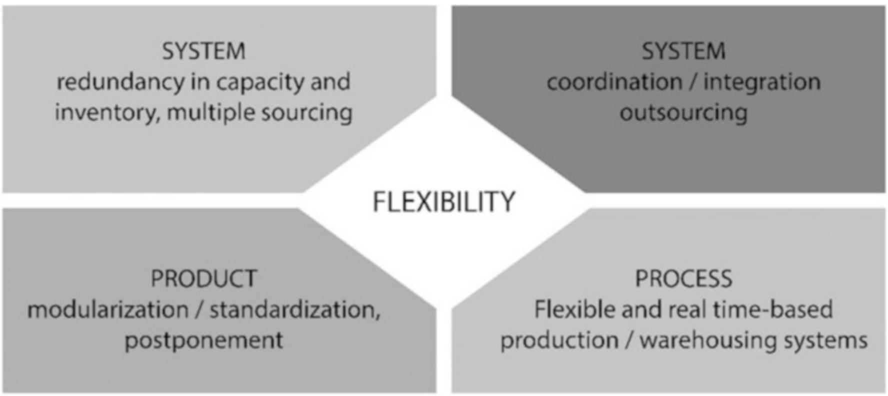

Fig. 2.13 Supply chain flexibility (Ivanov et al. 2014a)

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.

2.4.4 Information Technologies for Tackling the Ripple Effect

At the *proactive* level, APS (Advanced Planning and Scheduling) and early warning systems are used at the preparedness stage (Stadtler et al. 2015; Li et al. 2010). Despite the great advantages of recently developed supply chain optimization approaches, the models as currently implemented in APS and supply chain management information systems still do not consider important practical operability objectives such as robustness, stability, flexibility, etc. This situation creates a gap between theory and practice.

Decision-making at the *reactive* level in the case of deviations and structural dynamics is one of the main challenges in supply chain execution (Krajewski et al. 2005; Chandra and Grabis 2009; Ivanov et al. 2010; Vahdani et al. 2011; Bode et al. 2011; Peng et al. 2011). It is concerned with supply chain *control and adaptation* in different uncertainty environments where response and recovery are needed to figure out how best to allocate scarce resources to rebuilding/reconnecting supply chains to ensure process continuity and viability.

Disruptions are hardly predictable, and hence difficult to plan in advance (Kleindorfer and Saad 2005). Supply chain managers spend about 40–60% of their working time recovering from disruptions (Mulani and Lee 2002). Therefore, the supply chain control function becomes more and more important in practice. Feedback control can be supported by RFID (radio-frequency identification) technology which can be used to effectively communicate these disruptions to the other tiers, and help revise initial schedules.

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