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The Ripple effect in supply chains: trade-off 'efficiency-flexibility-resilience' in disruption management

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This study aims at presenting the Ripple effect in supply chains. It develops different dimensions of the Ripple effect and summarises recent developments in the field of supply chain (SC) disruption management from a multi-disciplinary perspective. It structures and classifies existing research streams and applications areas of different quantitative methods to the Ripple effect analysis as well as identifying gaps in current research and delineating future research avenues. The analysis shows that different frameworks already exist implicitly for tackling the Ripple effect in the SC dynamics, control and disruption management domain. However, quantitative analysis tools are still rarely applied in praxis. We conclude that the Ripple effect can be the phenomenon that is able to consolidate research in SC disruption management and recovery similar to the bullwhip effect regarding demand and lead time fluctuations. This may build the agenda for future research on SC dynamics, control, continuity and disruption management, making supply chains more robust, adaptable and profitable.

Keywords: supply chain; Ripple effect; dynamics; control; resilience; robustness; disruption management; event management; quantitative analysis; information technology

1. Introduction

Major challenges in supply chain management (SCM) are uncertainty and dynamics. This requires understanding supply chain (SC) performance from dynamic perspective as composed of both efficiency and flexibility/resilience (Sheffi and Rice 2005; Tomlin 2006; Wilson 2007; Klibi, Martel, and Guitouni 2010; Hahn and Kuhn 2012; Simchi-Levi and Wei 2012; Baghalian, Martel, and Guitouni 2013). As such, current research topics include development of methods and tools for investigating the trade-off efficiency vs./(and?) flexibility/resilience.

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 SC has been extensively considered in this domain subject to *randomness uncertainty* with the help of stochastic and simulation models (Lee, Padmanabhan, and Whang 1997; Chen et al. 2000; Dolgui and Proth 2010; Ouyang and Li 2010).

However, the deviations may also result from *hazard and deep uncertainty* (Lempert et al. 2006; Klibi, Martel, and Guitouni 2010), and they have therefore different scope and scale. In recent years, the research community has started to investigate *severe SC 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 (Snyder and Daskin 2005; Wilson 2007; Lewis et al. 2013, Baghalian, Martel, and Guitouni 2013). Recent examples of such severe disruptions include the earthquake and resulting tsunami in Japan on 11 March 2011 which rippled quickly through SCs worldwide (Marsh et al. 2011; Park, Hong, and Roh 2013). As a result, Toyota lost its position as major car manufacturer in terms of production volumes for that year. Many other industries worldwide were also hard hit by the shortage of chemical components produced in Japan. Another example is the floods in Thailand which had a serious impact on the high tech sector. Intel claimed to have lost $1 billion in sales during the fourth quarter of 2011 as computer OEMs were not buying chips from Intel due to their being unable to source the hard drives needed to make new machines.

A fire in the Phillips Semiconductor plant in Albuquerque, New Mexico, has caused its major customer, Ericsson, to lose $400 million in potential revenue. Another example concerns the impact of Hurricane Katrina. This storm halted 10–15% of total US gasoline production, raising both domestic and overseas oil prices (Canadian Competition Bureau

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2006). Moreover, the world price of coffee rose by 22% after Hurricane Mitch, which also affected SCs worldwide, struck the Central American republics of Nicaragua, Guatemala and Honduras (Fairtrade Foundation 2002). A survey by the Business Continuity Institute (2011) found that 85% of companies with global SCs had experienced at least one SC disruption in the previous 12 months. The costs of such disruption can be high, leading to fewer revenues, increased downtime, delays in delivery, lost customers and damaged reputations.

The SC disruption domain has received much attention in literature and practice in recent years (Tomlin 2006; Snyder 2006; Chopra, Reinhardt, and Mohan 2007; Hendricks, Singhal, and Zhang 2009; Peng et al. 2011; Aydin et al. 2012; Sodhi, Son, and Tang 2012; Dolgui et al. 2013; Hu, Gurnani, and Wang 2013). Even though considerable advancements have been achieved, SC disruptions now occur in greater frequency and intensity, and thus with greater consequences (Wagner and Neshat 2010). SC disruptions may mean for companies losses of revenue and incur high recovery costs (Braunscheidel and Suresh 2009; Lewis et al. 2013; Kim and Tomlin 2013). Therefore, SC disruption management can be considered as a critical capability which helps to create cost-efficient SC protection and implement appropriate actions to recover SC disruptions and performance. Details of empirical or quantitative methodologies differ across the works on SC 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.
- Stabilisation and recovery policies.

Within this set of attributes, most studies on SC disruption consider how changes to some variables are rippling through the rest of the SC and impacting on performance. We suggest considering this situation *the Ripple effect in the SC*, as an analogy to computer science, where the Ripple effect determines the disruption-based scope of changes in the system (Pereira 2001; Black 2006). In SCM settings, the Ripple effect should also include recovery strategies which may compensate disruptions and avoid their rippling (see Figure 1).

Ripple effect describes the impact of a disruption on SC performance and disruption-based scope of changes in the SC structures and parameters. Following a disruption, its effect ripples through the SC. 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 (Hendricks and Singhal 2005; Sheffi and Rice 2005; Tomlin 2006; Bode et al. 2011; Ivanov and Sokolov 2013; Kim and Tomlin 2013). Disruptions are highly unpredictable. Therefore, their risk and SC resilience should be estimated at the design and planning stages in the *proactive* mode (Dolgui and Prodhon 2007; Bakshi and Kleindorfer 2009; Blackhurst, Dunn, and Craighead 2011; Deleris and Erhun 2011). At the control stage in the *reactive* mode, contingency plans (e.g. alternative suppliers or shipping routes) must happen quickly to expedite stabilisation and recovery in order to ensure continuity of supply and avoid long-term impact. In implementing such recovery policies, companies need a tool supported by collaboration and SC visibility solutions for assessing the disruption impact on the SC as well as the effects and costs from redirecting material flows (Hishamuddin, Sarker, and Essam 2013).

Although the term ‘Ripple effect’ has been episodically used in the SCM domain (Deloitte Consulting 2013), it has not so far received proper attention in the scientific community so far, although many of its elements have been

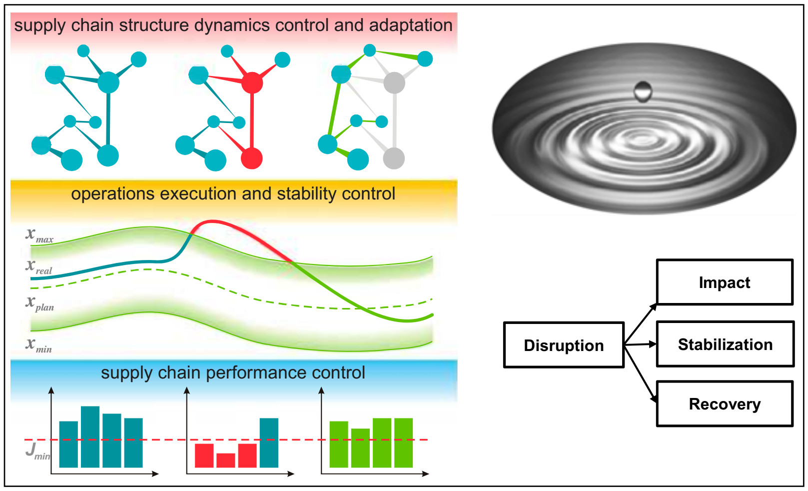

Figure 1. Ripple effect in the SC.

considered implicitly in numerous empirical and quantitative studies. This paper aims to present the Ripple effect in the SC as a new research domain in SCM. The first objective is to summarise from a multidisciplinary perspective recent development in the field of SC dynamics, control and disruption management that include management frameworks, quantitative methods and information technology (IT). The second objective is to structure and classify existing research streams and application areas of differing quantitative methods to the Ripple effect analysis, as well as to identify gaps in current research and delineate future research avenues.

This paper has resulted from long-term research and projects with companies that adopt SC disruption management techniques. The remainder of this paper is organised as follows. In Section 2, literature analysis is performed and observations regarding the Ripple effect in the SC are derived. Section 3 presents a framework for modelling and analysing the Ripple effect in the SC. Section 4 identifies gaps in current research and delineates future research needs. The paper concludes by summarising the most important insights from the research.

2. Literature review

In literature, studies on SC disruption management aim at closing the gap between theory and practice regarding uncertain nature of real environments for SC execution. Different approaches have been proposed so far since SC disruption management is really a multi-faceted issue. In literature review, we first analyse the reasons for the Ripple effect in the SC. Second, the existing frameworks for SC and operations disruption management are analysed. Third, quantitative tools for SC and operations disruption management are considered. The literature review is concluded with some observations that delineate the Ripple effect in the SC.

2.1 *Understanding reasons for the Ripple effect in the SC: sources of uncertainty*

In the last decade, reasons for disruption in SCs have been extensively investigated. Numerous studies including (but not limited to) the works of Hendricks and Singhal (2005), Kleindorfer and Saad (2005), Tomlin (2006), Craighead et al. (2007), Blackhurst, Dunn, and Craighead (2011), Bode et al. (2011), and Qi (2013) revealed four basic reasons for the increase in disruption impact on SC execution and performance. Hendricks and Singhal (2005) quantified the negative effects of SC disruption through empirical analysis and found 33–40% lower stock returns relative to their benchmarks over a three-year time period that started one year before and ended two 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, two years at a lower performance level after a disruption. Recent literature introduced different classifications of SC risks (Chopra and Sodhi 2004; Waters 2007; Tang and Musa 2011). For example, Chopra and Sodhi (2004) categorised potential SC 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.), (d) Intellectual property (e.g. vertical integration), (e) Procurement (e.g. exchange rate risk), (f) Receivables (e.g. number of customers), (g) Inventory (e.g. inventory holding cost, demand and supply uncertainty, etc.) and (h) Capacity (e.g. cost of capacity).

These reasons of uncertainty are not new within the relevant literature, but since they can also be considered as reasons for the Ripple effect, we describe them briefly (see Figure 2).

Since risks of demand and supply uncertainty are related to the random uncertainty and business-as-usual situation, we exclude them from the following analysis and concentrate on the disruption side. First, globalisation and outsourcing trends make SC more complex and less observable and controllable. According to complexity theory, such systems become more sensitive to disruptions (Casti 1979; Cohen and Havlin 2010; Arkhipov and Ivanov 2011). Special focus in this area is directed to disruptions in transportation channels (Wilson 2007; Lewis et al. 2013). Second, the efficiency paradigms of lean processes, single sourcing, etc. have failed in disruption situations (Yu, Zeng, and Zhao 2009; Wang, Gilland, and Tomlin 2010; Lu, Huang, and Shen 2011; Yang et al. 2012). As a consequence, SC became more vulnerable even to minor perturbations. Any disruption in a global SC, especially in its supply base, does immediately affect the entire SC. Third, with the increased specialisation and geographical concentration of manufacturing, disruptions in one or several nodes affect almost all the nodes and links in the SC (Babich, Burnetas, and Ritchken 2007; Kim and Tomlin 2013). Fourth, IT became the crucial element of global SCs, since disruptions in IT may have significant impacts on disruptions in material flows (Soroor, Tarokh, and Keshtgary 2009; Tang and Musa 2011; Ivanov, Sokolov, and Dilou Raguinia 2013).

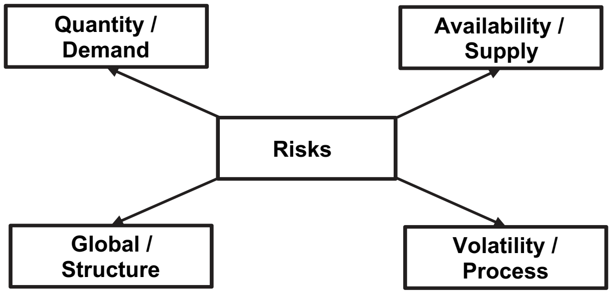

Figure 2. Risks in SCs.

2.2 *Mitigating risks and uncertainty*

Along with the risk identification, recent literature also discussed the risk mitigation strategies (Graves and Tomlin 2003; Craighead et al. 2007; Klibi, Martel, and Guitouni 2010; Pettit, Fiksel, and Croxton 2010; Simchi-Levi and Wei 2012; Ivanov, Sokolov, and Pavlov 2013; Baghalian, Martel, and Guitouni 2013). These strategies can be classified into flexibility and resilience areas (see Figures 3 and 4).

Basic areas of flexibility include system, process and product flexibility. 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 SCs are also typical in practice. Many companies also invest in structural redundancy (e.g. Toyota extends its SC 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 in the resilience framework. Therefore, elements of the flexibility and resilience are interconnected (see Figure 5).

Net profit maximisation in the SC depends on both revenue and costs. Revenue is directly influenced by service level. Variable costs in an SC include basically inventory, material, production and transportation costs. Increase in inventory, additional production capacities and alternative transportation ways or duplication of supply would increase costs. At the same time, these so called excessive 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 of scheduling (e.g. minimal lateness) can be reached better. This will positively influence the sales and service level. In Figure 6, the above-mentioned interrelations are described.

Redundancy and responsiveness elements of SC flexibility may increase both service level and costs. The optimal resilient state of an SC means that SC flexibility allows to achieve maximal service level at minimal costs. In the further course of our review, we discuss the above-mentioned trade-offs, interrelations, concepts and models.

2.3 *Frameworks for SC and operation disruption management*

In this section, we analyse existing frameworks for SC dynamics, control and disruption management. Supply chain risk management (SCRM) is the first paradigm that becomes more and more important. SC disruptions may mean for

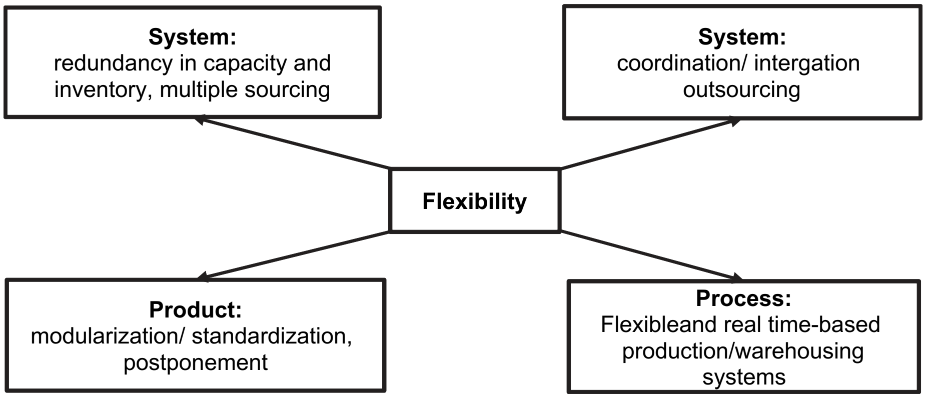

Figure 3. Supply chain flexibility.

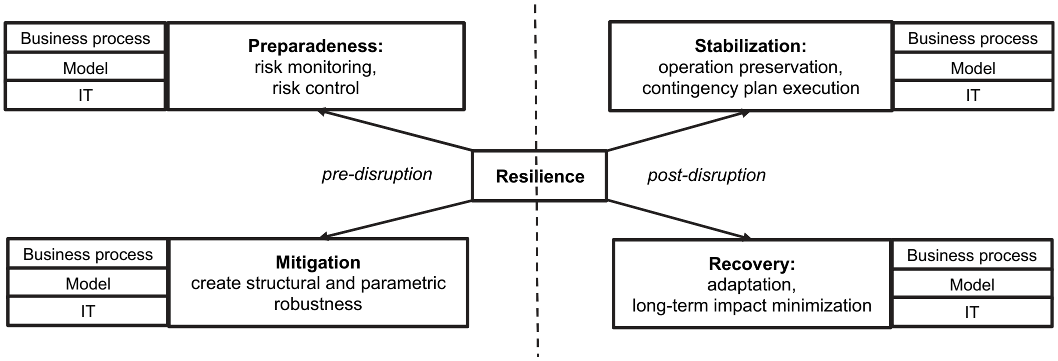

Figure 4. Supply chain resilience.

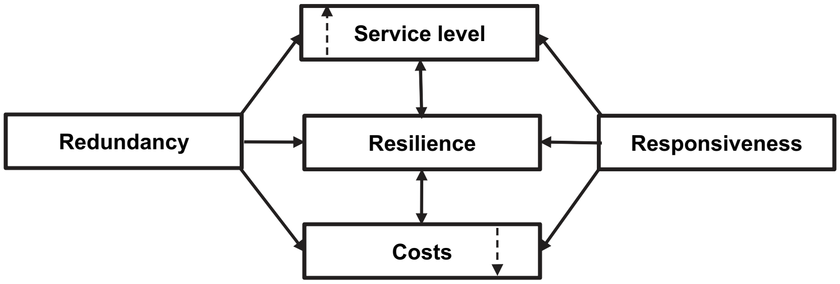

Figure 5. Resilience, flexibility and performance.

companies losses of revenue and incur high recovery costs (Sheffi and Rice 2005; Braunscheidel and Suresh 2009; Tang and Musa 2011). Therefore, SCRM can be considered as a critical capability which helps to identify the potential sources of risk and implement appropriate actions to avoid or contain SC vulnerability (Sodhi, Son, and Tang 2012). A typical SCRM comprises four risk components: identification, assessment, response, monitoring and evaluation (Vanany et al. 2009; Aydin et al. 2012; Hu et al. 2013).

The supply chain event management (SCEM) framework has been increasingly introduced in practice in the last decade (Otto 2003). SCEM aims at a timely identification of deviations or danger of deviations in SCs, analysis of deviations and alerts about what disruptions have occurred or may occur, and elaborating control actions to recover SC operability.

SCEM is composed of *five main functions*:

- monitoring of processes;
- notification about an impermissible parameter deviation;
- simulating possible adjustment actions;

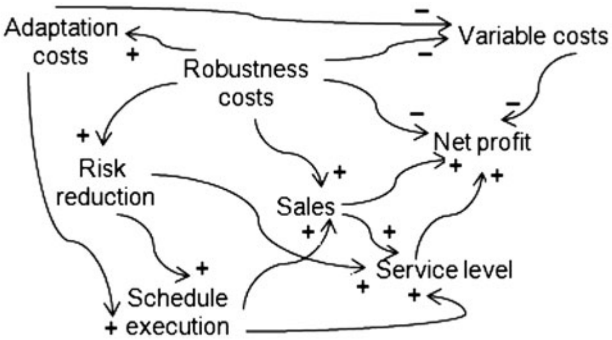

Figure 6. Components of analysis and control of SC performance.

- selecting a control action to eliminate the deviation; and
- measuring on the basis of performance indicators.

SCEM is based on three main drivers. First, the tracking and tracing (T&T) systems, RFID and mobile devices are used to provide current information about a process execution. Second, the method of management by exception is used to filter information and to compare actual parameter values with planned ones. Third, the method of event-oriented planning is used to reveal sensitive adjustment actions in the case of negative events.

Events are a critical point in the SCEM concept. Events can be negative ('a track has a one-hour delay'); or positive ('a shipment launch is still possible today'). A basis for the alerts and disruption recovery is a tolerance area of execution parameters' admissible deviations. In SCEM, a certain tolerance area of admissible parameters' deviations is set-up to relate events, alerts and adjustment launching.

If parameter values are outside of this area's borders, alerts take place. However, two important questions still remain open: (i) how to determine the borders of the tolerance area; and (ii) what adjustments should be made to overcome a particular disruption. In the literature, we were unable to find any formalised approach to determine the tolerance area. In practice, these decisions are made on the basis of weakly founded heuristics or just expert analysis.

Altay and Green (2006) proposed a framework for analysis of *OR/MS research in disaster management*. This framework distinguishes the following stages:

- Mitigating,
- Preparedness,
- Response and
- Recovery.

The mitigation stage considers processes to reduce the risk of deviations already at the planning stage. The preparedness stage includes processes of monitoring and risk control. The response stage is devoted to processes of how to react in the case of disturbance (i.e. the 'first response' solution). The recovery stage includes processes for adaptation (i.e. it must decide on replanning, correction or continuation of the planned execution). This classification can be used for structuring existing research on quantitative methods and IT.

A recovery from an unexpected event is illustrated in literature through functions that describe different scenarios. Sheffi and Rice (2005) identified eight typical stages of disruption: preparation; disruption event; first response; initial impact; full impact; preparation for recovery; recovery; and long-term impact. Among these stages, recovery is the longest and most important stage.

Numerous other frameworks for SC resilience and disruption management have been proposed by different authors in recent years. For example, empirical framework of global supply resiliency is proposed by Blackhurst, Dunn, and Craighead (2011) based on recently published study on the severity of SC disruptions (Craighead et al. 2007). Pettit, Fiksel, and Croxton (2010) develop a framework where three possible SC states are distinguished: excessive vulnerabilities relative to capabilities will result in excessive risk (state A), excessive capabilities relative to vulnerabilities will erode profitability (state B) and SC performance improves when capabilities and vulnerabilities are more balanced (state C). A good overview of such frameworks can be found in Zsidisin and Ritchie (2009) and Kouvelis et al. (2012).

2.4 *Quantitative methods and information technology*

Previous quantitative studies considered SC disruptions from three perspectives (Klibi, Martel, and Guitouni 2010; Klibi and Martel 2012; Schmitt and Singh 2012; Ivanov and Sokolov 2013):

- how to synthesise SC configurations, master plans and schedules in order to maximise/ensure the planned performance (both efficiency and effectiveness);
- how to remain stable and robust even in the case of disturbances; and
- how to adapt/recover in the case of disturbances/disruptions.

In answering these questions, a variety of quantitative methods have been applied so far. Recent studies in both business and technical literature emphasised that SCs need to be considered with regard to dynamic aspects, real-time performance and perturbed execution environments (Daganzo 2004; Santoso et al. 2005; Meepetchdee and Shah 2007; Springer and Kim 2010; Ivanov, Sokolov, and Kaeschel 2010; Baghalian, Martel, and Guitouni 2013). These studies indicated different approaches to analysing the impact of uncertainty on SC performance, based on the categories of stability, robustness, flexibility, resilience, etc. Nevertheless, there is considerable variation in the definitions of terms related to SC dynamics, uncertainty and performance (Klibi, Martel, and Guitouni 2010). For example, in business literature these categories are frequently used equivalently in general contexts, while in systems and control theories they have a very specific technical meaning. This section aims to enumerate and appraise various methodologies that have been applied to the domain of the Ripple effect in the last two decades. In particular, we ask of each technique: to which extent does it reveal the dynamics of processes involved? This question is important since only through the understanding of execution dynamics, we can gain full appreciation and knowledge of the factors leading to the Ripple effect.

2.4.1 *Mitigation and preparedness*

Two basic approaches to hedging SC against the negative impacts of different disruptions – *proactive* and *reactive* have been developed to coping with uncertainty in recent years (Santoso et al. 2005; Tomlin 2006; Chopra, Reinhardt, and Mohan 2007; Schütz, Tomasgard, and Ahmed 2009; Knemeyer, Zinn, and Eroglu 2009; Klibi, Martel, and Guitouni 2010; Georgiadis et al. 2011; Peng et al. 2011; Bode et al. 2011; Cardona-Valdes, Álvarez, and Ozdemir 2011; Vahdani, Zandieh, and Roshanaei 2011; Lim et al. 2012; Baghalian, Martel, and Guitouni 2013). Reactive approach aims at adjusting SC processes and structure in the presence of unexpected events. Proactive approach creates certain protection and takes into account possible perturbations while generating SC structures and execution plans.

Graph theoretical approaches have been applied to analysis of SC structures at the structural level of first-stage design variables. For example, Wagner and Neshat (2010) propose a method of quantifying risk using the permanent of an adjacency matrix based on graph theory. However, the dynamic characteristics of the SC execution over time and the consequences remain without consideration. Arkhipov and Ivanov (2011) introduced a complexity measure for SC design based on the entropy approach.

At the parametric level, recent literature has also identified different methods to strengthen SCs in order to mitigate the impact of uncertainty at the *planning* stage. These methods are mainly based on mixed-integer programming, stochastic and robust optimisation, fuzzy optimisation and system dynamics (Santoso et al. 2005; Villegas and Smith 2006; Klibi and Martel 2012; Hahn and Kuhn 2012; Pishvaee, Razmi, and Torabi 2012; Baghalian, Martel, and Guitouni 2013).

A broad research area is the analysis of SC stability and robustness. For these issues, classical control theory (CT) has been extensively applied (Ivanov, Sokolov, and Dolgui 2012; Ivanov and Sokolov 2013). Modelling SCs and operations using differential equations holds great appeal for the control theorist (Riddalls, Bennett, and Tipi 2000; Sarimveis et al. 2008; Ivanov 2010; Ivanov et al. 2012). This is because many of the influential characteristics of the problem can be succinctly expressed in dynamic form. Then, a vast array of tools and methodologies from CT can be invoked to gain insight into the system dynamics. The rationale for this approach is that models of modest complexity, which are therefore amenable to analytical study, can provide an insight into the factors that are common to much larger 'live' systems. Differential equation models also have the advantage of being conduits into the adaptation/recovery domain, which offers a framework particularly suited to the study of systems in which oscillations are a salient attribute (Riddalls, Bennett, and Tipi 2000).

The understanding of stability and robustness depends much on the system considered as well as on methods and goals of systems analysis (Daganzo 2004; Meepetchdee and Shah 2007; Qiang et al. 2009; Ouyang and Li 2010; Ivanov, Sokolov, and Dolgui 2012). Basically, Lyapunov's stability in different forms (e.g. asymptotic or exponential) for mechanical systems or the BIBO (bounded-input-bounded-output) stability for control systems can be distinguished (Liao, Wang, and Yu 2007). Lyapunov's stability is directed by the natural movement of objects, and studies their reaction to small deviations from the equilibrium state. BIBO stability studies the influence of external disturbances on control and output variables. Mesarovic and Takahara (1975) consider stability as the property of ensuring continuity of system behaviour. The study by Narendra (2005) underlines the basic effects of considering stability in the context of adaptive systems.

Although BIBO stability analysis can be a useful tool for Ripple effect analysis, it is subject to many restrictions if applied in the classic form. First, the classic models imply natural movement of objects. Second, they typically consider very small deviations of control and output variables. Third, stability analysis can help in estimating SC volatility in any concrete state. But it is not enough to stabilise the SC – the SC should also bring profits; hence the inclusion of performance considerations (i.e. the robustness analysis) is required as the next step. Finally, classic stability analysis is concerned with funding equilibrium states for mechanical and automatic systems. As a consequence, such methods are hardly suited to analysis of processes where an individual entity has an impact on the fundamental state of the system.

With the robustness and stability analysis, integration of *non-stationary operability performance objectives* in SC synthesis (planning) decisions becomes possible. For example, a model of SC risk under disruption with performance measurement and robustness analysis is reported by Qiang, Nagurney, and Dong (2009). However, in many cases it is impossible to avoid disturbance. Therefore, adaptation is needed to change SC schedules or inventory policies in order to achieve the planned output performance. In this setting, SCs can be robust and stable only on the basis of decisions that are taken by *people* (unlike a pendulum, which returns to the stable state due to natural laws, without adaptation). In SCs, the *adaptation* (and more precisely, human-driven coordinated adaptation) is the precondition of stability and robustness (Ivanov and Sokolov 2013).

The ability to maintain, execute and recover (adapt) the planned execution along with achievement of the planned (or adapted, but yet still acceptable) performance is therefore the next objective property of the SC. This property is related by most authors to SC *resilience* (Bakshi and Kleindorfer 2009; Cimellaro, Reinhorn, and Bruneau 2010; Blackhurst, Dunn, and Craighead 2011). Chen and Miller-Hooks (2012) consider resilience as an indicator of recovery capability related to intermodal freight transport. Jüttner and Maklan (2011) bridge SC resilience and financial crisis. The main challenge is to extend resilience strategies providing adequate protection from disruptions without reducing SC effectiveness in business-as-usual situations. The costs of adaptation should also be considered along with the costs of redundancy creation.

For resilience analysis, the simulation-based studies dominate (Datta and Christopher 2011). A Monte Carlo approach based on a generalised semi-Markov process is taken to assess the disruptions caused by a specific type of hazard on an SC (Deleris and Erhun 2011). This model estimates the probability distribution of the loss in the SC output caused by the occurrence of hazards within the SC. Zegordi and Davarzani (2012) present an SC disruption analysis model based on coloured Petri nets for better visual representation. Schmitt and Singh (2012) presented a quantitative estimation of the disruption risk in a multi-echelon SC design using simulation. The disruption risk is measured by ‘weeks of recovery’ as the amplification of the disruption.

At the IT level, APS (Advanced Planning and Scheduling) and early warning systems are used at the preparedness stage (Stadtler and Kilger 2008; Li et al. 2010). Despite the great advantages of recently developed SC optimisation approaches, the models as currently implemented in APS and SCM 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.

2.4.2 *Recovery*

Decision-making in the case of deviations and structure dynamics is one of the main challenges in SC execution (Krajewski, Wei, and Tang 2005; Chandra and Grabis 2009; Ivanov, Sokolov, and Kaeschel 2010; Vahdani, Zandieh, and Roshanaei 2011; Bode et al. 2011; Peng et al. 2011). It is concerned with SC *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 SCs to ensure process continuity and viability.

Disruptions are hardly predictable, and hence are difficult to plan in advance (Kleindorfer and Saad 2005). SC managers spend about 40–60% of their working time recovering disruptions (Mulani and Lee 2002). Therefore, SC 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. A possible algorithmic basis for optimisation of adaptation actions provides CT (Sarimveis et al. 2008; Ivanov, Sokolov, and Dolgui 2012; Ivanov and Sokolov 2013).

The very extensive area of research on SC adaptation is model predictive control (MPC) (Wang et al. 2007). In MPC, a system model and current and historical measurements of the process are used to predict system behaviour at future pre-determined times. A control-relevant objective function is then optimised to calculate a control sequence that must satisfy the system constraints.

Applications of MPC to multi-echelon production–inventory problems and SCs have been examined previously in the literature. Perea et al. (2000) modelled multi-plant, multi-product polymer processes through difference equations, and schedule optimisation in an MPC framework. In the study by Puigjaner and Lainez (2008), a multi-stage stochastic model has been employed. Vahdani, Zandieh, and Roshanaei (2011) developed a hybrid multi-stage predictive model for SC collapse recovery analysis in light of continuity management.

Ivanov and Sokolov (2012) and Subramanian et al. (2013) presented studies on integration of CT and scheduling methods for SCM and considered optimal programme control (OPC), distributed and cooperative control along with the MPC. These studies discussed the possibilities of translating mathematical scheduling models into state-space form and design rescheduling algorithms with desired closed-loop properties.

2.5 *Observations*

Based on the analysis in Sections 2.1–2.3, we can make some preliminary observations on the reasons for the Ripple effect and counter-measures, frameworks, quantitative methods and IT (see Tables 1–5).

The first observation is that the stages of planning and control have rarely been discussed as a united framework. The recovery process has received less attention than have pre-disruption activities. As a consequence, control decisions are frequently isolated from the planning level and mainly based on expert knowledge with a weak application of quantitative analysis tools and IT.

While disruption rippling through the SC has received empirical evidence, there is a lack of quantitative studies involving modelling and simulation to empower decision-makers to better face disruptions in SCs. To the best of our knowledge, no formal models take into account stabilisation of SCs including costs of stabilisation and recovery. It is quite natural, since the application of any quantitative techniques presumes control business process models that are still missing in many companies.

Management science and operations research along with system dynamics and control theory contain a number of useful methods that can be used for analysis and for mitigating the Ripple effect. Different methods are suited to different problems. No single technique is likely to prove a panacea in this field. While mathematical optimization is placed at the strategic and tactical level at SC design and planning stages, they fail to throw much light on the dynamic behaviour of the SC as a whole. The implications of strategic SC design and tactical plans on SC performance at the execution and recovery stage can be enhanced by using models based on the dynamics of the execution processes (Ivanov, Sokolov, and Dolgui 2012).

3. Dynamic framework for Ripple effect analysis

The methodical basis of the proposed framework for analysis of the Ripple effect in the SC is the interpretation of an SC as a dynamic controllable system described through differential equations. The justification for this choice is based on the feedback properties of control theoretic methods which allow incorporating planning and control stages. In addition, continuous time representation can be favourable with regards to its accuracy.

Consider the following notations in line with the paper (Ivanov and Sokolov 2013):

- Current execution plan (e.g. an inventory policy or a schedule) calculated subject to demand D and material supply S; we define it generally as the control vector $\mathbf{u}_{pl}(t)$ within the area of allowable control inputs $\mathbf{Q}(\mathbf{x}(t), t)$.
- Redundancy of the SC plan (e.g. excessive inventory, alternative suppliers, etc.); we define redundancy parameters as the vector $\boldsymbol{\alpha}(t)$.
- Perturbations; we define it generally as the perturbation vector $\boldsymbol{\xi}(t)$ within the area of accidental perturbation $\Xi(\mathbf{x}(t), t)$ and intentional perturbation $\tilde{\Xi}(\mathbf{x}(t), t)$.
- Current state (i.e. inventory level); we define it generally as the state vector $\mathbf{x}(t)$.
- Disruption (i.e. change in the SC planned execution); we define it generally as the disruption vector $\mathbf{z}(t)$.
- Adaptation (i.e. the active control actions to change planned SC behaviour); we define generally (a) the adjustable control actions vector as $\mathbf{v}(\mathbf{x}(t), t)$ within the area of allowable real-time regulation control inputs $\mathbf{V}(\mathbf{x}(t), t)$ and (b) parameters being affected by the disruption and to be adjusted as the vector $\boldsymbol{\beta}$.
- Output performance (e.g. service level, costs, etc.); we define it generally as the planned performance vector $\mathbf{y}(t)$ and current performance vector $\mathbf{y}'(t)$ with performance measures $\mathbf{J}_{\boldsymbol{\Theta}}{}^{\mathrm{T}}$ at the end of the planning horizon.

Table 1. Reasons of the Ripple effect and counter-measures.

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

Table 2. Frameworks for the Ripple effect analysis in the SC.

Frameworks and Stages			
SCRM	SCEM	Altay/Green	Sheffi
Identification	Monitoring	Mitigating	Preparation
Assessment	Notification	Preparedness	Disruption event
Response	Simulation	Response	First response
Monitoring	Control	Recovery	Initial impact
Evaluation	Measuring		Full impact
			Preparation for recovery
			Recovery
			Long-term impact

Table 3. IT for the Ripple effect analysis in the SC.

Planning	Monitoring
APS systems	Early Warning Systems
Decision-support systems	SC Visibility Systems
	RFID

Table 4. Dimensions of the Ripple-effect.

Dimension	Content	Quantitative methods
Structural	Structure dynamics; parameters (inventory, capacities, etc. remain unchanged)	Graph theory
Parametrical	Structure changes are defined first (design variables); then parameter variation (control variables) is analyzed	Robust optimization Stochastic optimization Fuzzy optimization System dynamics
Structural-parametrical	Simultaneous analysis of structural and parametrical changes	Control theory (for continuous variables) System dynamics

According to the given notations, the general model formulation for the Ripple effect in the SC can be presented as dynamic system (1)–(6):

$$\dot{\mathbf{x}}(t) = \tilde{\boldsymbol{\varphi}}(\mathbf{x}(t),\ \mathbf{u}(t),\ \boldsymbol{\xi}(t),\ \alpha, \boldsymbol{\beta}, t) \tag{1}$$

$$\dot{\mathbf{y}}(t) = \tilde{\boldsymbol{\psi}}(\mathbf{x}(t), \mathbf{u}(t), \boldsymbol{\xi}(t), \alpha, \boldsymbol{\beta}, t) \tag{2}$$

$$\mathbf{u}(t) = ||\mathbf{u}_{pl}^{\mathrm{T}}(t), \mathbf{v}^{\mathrm{T}}(\mathbf{x}(t), t)||^{\mathrm{T}};\ \mathbf{u}_{pl}(t) \in \mathbf{Q}(\mathbf{x}(t), t);\ \ \mathbf{v}(t)(\mathbf{x}(t), t) \in \mathbf{V}(\mathbf{x}(t), t), \tag{3}$$

$$\boldsymbol{\xi}(t) \in \boldsymbol{\Xi}(\mathbf{x}(t), t);\ \ \boldsymbol{\beta} \in \mathbf{B}, \tag{4}$$

$$\mathbf{x}(t) \in \mathbf{X}(\boldsymbol{\xi}(t), t), \tag{5}$$

$$\mathbf{x}(T_0) \in \mathbf{X}_0(\boldsymbol{\beta}),\ \ \mathbf{x}(T_f) \in \mathbf{X}_f(\boldsymbol{\beta}). \tag{6}$$

where B is an area of allowable parameter values (e.g. an inventory level) and $\mathbf{X}(\boldsymbol{\xi}(t), t)$ is an area of allowable states.

Vectors (1) and (2) should meet space–time limitations that belong to given sets (3)–(5). Equation (6) determines the end conditions for the SC state vector $\mathbf{x}(t)$ at time $t = T_0$ and $t = T_f$ (T_0 is the initial time of the time interval in which the SC is being investigated, and T_f is the final time of the interval).

Table 5. Quantitative methods for the Ripple effect analysis in the SC.

Stage	Methods	Advantages	Limitations	Application
Mitigating	Mathematical optimization	Optimal solution Easy to implement in practice	No state-space representation for dynamic analysis	SC design SC strategic-tactical planning
	Simulation	Analysis of disruption impacts on performance in dynamics	Quality of solution	Resilience analysis
	System dynamics and control theory	Understanding dynamics of execution Dynamic performance analysis	Mathematics of differential equation; Orientation at automatic control	Stability, attainability, and robustness analysis
Recovery	Mathematical optimization	Optimal solution	Difficulties in changing parameter values in order to estimate impact on performance Data accuracy and volume Long organizational process Plan stability is affected (full re-planning)	Sensible in the case of full SC redesign or replanning
	Simulation	Impact on performance in dynamics Data volume is moderate Plan stability can be maintained since only partial re-planning can be implemented	Quality of solution	Quick analysis at stabilization stage Recovery strategies
	System dynamics and control theory	The basic theory for feedback control Optimal solution Adaptation can be integrated with planning (if described in terms of continuous optimization)	Difficult to implement at detailed level Only aggregate flow view Orientation at automatic regulation	Applicable as analysis tool for recovery stage, not as solver with real data volumes

The above features are represented in the framework shown in Figure 7.

From Figure 7, it can be observed that four basic execution control scenarios (corresponding to arrows outgoing from the F-block) are possible:

- a perturbation does not affect the SC execution, SC continues execution according to the planned $\dot{\mathbf{x}} = \mathbf{f}(t, \mathbf{x}, \mathbf{u})$;
- a perturbation does not affect the SC execution, since the master plan robustness $\boldsymbol{\alpha}(t)$ allows continued execution according to the planned $\dot{\mathbf{x}} = \mathbf{f}(t, \mathbf{x}, \mathbf{u})$;
- a perturbation affect the SC execution subject to β-parameters, then components of $\mathbf{J}_{\boldsymbol{\Theta}}{}^{\mathrm{T}}$ deviate from the plan, but the $\dot{\mathbf{x}} = \mathbf{f}(t, \mathbf{x}, \mathbf{u})$ can be recovered with the help of a correcting programme $\mathbf{v}(t)$ through the construction of $\dot{\mathbf{x}}_\sigma = \mathbf{f}(t, \mathbf{x}, v)$, and the desired output performance can be achieved; and
- a perturbation affects the SC execution subject to β-parameters, then components of $\mathbf{J}_{\boldsymbol{\Theta}}{}^{\mathrm{T}}$ deviate from the plan. No correcting programme $\mathbf{v}(t)$ can be found to offer an updated $\dot{\mathbf{x}}_\sigma = \mathbf{f}(t, \mathbf{x}, v)$ in order to achieve the planned $\mathbf{J}_{\boldsymbol{\Theta}}{}^{\mathrm{T}}$. In this case, a change in master plan, in SC design or in the planned performance $\mathbf{J}_{\boldsymbol{\Theta}}{}^{\mathrm{T}}$ or influencing D or S are needed in order to calculate a feasible $\mathbf{u}^*(t)$.

These four control scenarios can be brought to correspondence with some analysis domains for the Ripple effect and with the control business processes (see Figure 8).

An SC manager plans execution programmes subject to the ‘normal’ conditions ($\mathbf{u}_{pl}(t)$) and disasters ($\mathbf{u}_d(t)$). Monitoring results (subject to error measurement e) through an SC visibility system guides the SC manager to one of the control business processes on the basis of an integrated analysis of execution and economic performance. A stabilisation plan ($\mathbf{u}_\xi(t)$) and a recovery plan are then developed in collaboration with other parts in the SC.

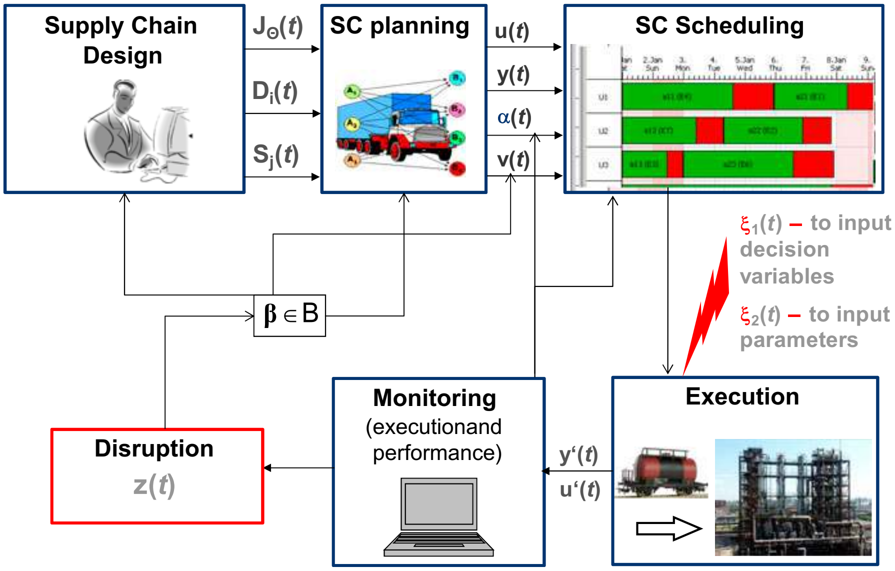

Figure 7. Dynamic Framework for the SC Execution Control.

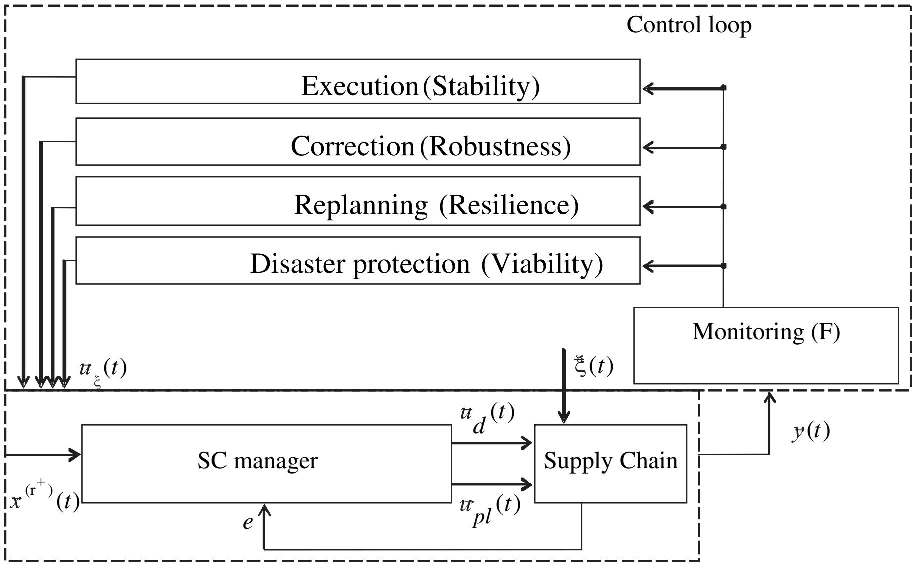

Figure 8. Control business process organisation.

4. Future research needs

As identified in Figure 4, recent research considered issues related to the Ripple effect from different perspectives. They include SC resilience with pre- and post-disruption views, SC flexibility, business processes, mathematical models and IT. The literature review and above-mentioned observations allow us to define some crucial gaps in current research.

Lack of clear business process description for SC control / lack of connection 'IT-process-model'

The efficient application of model-based support for any quantitative analysis implies clear description of control processes in the case of different deviations and disturbances. Such processes (i.e. control loops) have also to include different control objectives and strategies (e.g. recovering planned execution, maintaining plan stability, minimising future impacts, etc.). In addition, impacts of control actions on economic performance and related *costs of control* have not so far found sufficient consideration in the literature.

Lack of problem and model taxonomy

Unlike the SC planning domain, the SC recovery domain has so far only been addressed episodically. In the SC planning domain, a clear terminology, problem class systematisation (i.e. at the SC design, planning and execution levels) and a taxonomy of quantitative methods exist. Such a taxonomy does not exist for SC control domain. Recent studies indicated different approaches to analysing the impact of uncertainty on SC performance, based on categories of stability, robustness, flexibility, resilience, etc. Nevertheless, there is considerable variation in the definitions of terms related to SC dynamics, uncertainty, and performance (Klibi, Martel, and Guitouni 2010).

Lack of special tools for SC control

In some cases, it is possible to use planning tools for SC control. However, new multi-disciplinary investigations in this direction are needed. In addition, some useful tools for quantitative analysis (e.g. attainable sets) from control and systems theory still remain undiscovered for a wide SCM research community.

SCs as technical-organisational systems

Although control techniques have high practical relevance, they cannot be applied to SCM in the same form as they to automatic control systems. In technical systems, the controller is a technical device (e.g. a sensor) that adapts system behaviour within milliseconds based on error identification. The controller in the SC is a manager, or more precisely, a number of managers with possible conflicts of interests. Even if a deviation in SC execution has been identified, the control action will not be taken within seconds or minutes. Finally, control and recovery in SCs have to consider control costs. In SCs, economic performance can be more important than operative execution performance. The conditions of equilibrium in SCs differ from those in mechanical or automatic systems. SCs evolve not through automatic signals or mechanical laws, but by managerial decisions. SCs do not need 100% robustness, because of the individual risk perceptions of decision makers, who are taking risks and can adapt their decisions accordingly. That is why, additional research is needed in the applicability of control to human-driven SC adaptation.

In summary, recent years have shown explicitly that SCs become vulnerable and uncontrollable without integrating operability objectives (e.g. stability and robustness) into planning decisions, developing execution control policies and adaptation processes and algorithms. As such, to enhance decision-making, new research is needed in SC dynamics and control dynamics with the help of quantitative analysis tools, control process organisation, and IT.

We regard these shortcomings in light of the Ripple effect as an opportunity for research, which could contribute to the theory and practice of SCM and the application of optimisation methods in combination with systems and control theoretic approaches to the SCM domain. In particular, the following future research directions can be stated.

4.1 *Measuring the Ripple effect and incorporation of operability objectives into SC design and planning models*

Understanding and finding SC designs and plans with effective and efficient constellations of complexity, robustness, flexibility, adaptability and resilience are areas of promising research. In this respect, advanced graph theory can help in analysing such network properties as density, diversity, linkage, homogeneity and criticality, which in recent literature are argued to be highly related to the severity of SC disruptions. This research can provide professionals with tools to specify new performance indicators for SC resilience as well as improve both design and execution control policies.

Alternative SC strategies could be investigated with regard to different robustness and flexibility content. These could be a strategy of maximum reliability maintenance, a strategy of maximum flexibility maintenance and/or a strategy of risk financing (insurance contracts to cover possible losses caused by disruptions).

In addition, inverse analysis models are needed. For example, in the case of a disruption, the bottle-necks should be identified and their prevention strengthened by investment in new facilities or capacity expansions. Similarly, such models can be applied to the analysis of planning future investments in new facilities/capacities or revealing excessive (unnecessary) structural elements (e.g. machines or facilities).

4.2 *Response/Stabilisation analysis*

From a practical point of view, the expected results of the research in this domain are to provide operations and SC planners with the processes, models and algorithms for the following two issues:

- What is the impact of a disturbance or plan deviation on economic performance?
- Is a change in the schedules and/or master plans needed? If yes, when, where and what changes are needed?

In this setting, research is needed that will provide SC planners with new tools in order to support them in decisions on how to (i) estimate the impact of possible perturbations on economic performance at the planning stage, (ii) quickly estimate the impact of real plan deviations on economic performance at the execution stage and (iii) suggest efficient and effective stabilisation and recovery measures.

A crucial practical problem is to determine where exactly changes are needed: in the schedule, in the master plan or in the business plan. Such an analysis should incorporate multiple control loops including corresponding business process models, quantitative models and IT for gathering and processing real-time data. Decentralised interests of SC enterprises also have to be included in such analyses.

4.3 *Control policies and algorithms*

First, different control strategies regarding construction of the optimal recovery programmes can be analysed. Here, basic cybernetic principles (critical events, final deviations, free trajectories and not final solutions) can be investigated. For example, an immediate adaptation programme (i.e. immediate recovery and return on the planned execution) and smooth adaptation programme (i.e. constructing an alternative execution in anticipating new perturbations) can be compared. Second, different control objectives may be considered (e.g. maintaining planned economic performance, extremising this performance through the control, maintaining plan stability rather than recovering the planned economic performance, etc.).

A special point of investigation can be the comparison of different options for SC adaptation, e.g.:

(1) applying master planning models (e.g. linear programming) for replanning;
(2) applying simulation (e.g. system dynamics) models for plan correction;
(3) applying optimal control models in combination with a simulation model for adaptation based on memorising control policies with feedback-oriented memorisation of state variables directly in the calculation procedure;
(4) applying MPC as a control strategy to predict control variables and process output over a period of time; and
(5) applying positional control in combination with MPC.

Comparison of the control models and algorithms can be performed subject to:

- different scale and scope of disturbances;
- different points in time of disturbances (e.g. beginning of the month, middle of the month and end of the month);
- different process control loops; and
- different IT and available data.

Another investigation may be to compare two adaptation policies: to recover immediately after a perturbation in order to return to the planned execution as soon as possible; or to recover slowly (i.e. to develop a new execution plan). In the first case, recovery may be costly and there is no guarantee that new perturbation will not occur during the execution of the stabilisation programme. So the slower recovery in anticipation of new perturbations may be more effective and efficient.

The results of research in this domain may include new models and algorithms, and recommendations for the applicability of different control algorithms and strategies within different control loops.

4.4 *Costs analysis and performance measurement for control and adaptation*

This is a very promising research area. So far, cost analysis has rarely been included within SC control models. First, costs of adaptation require a detailed analysis in interconnection with robustness costs. In this case, different trade-offs can be considered, e.g. robustness vs. adaptability. Consideration can be given to the fact that robustness costs are real but the protection effects and adaptation costs can be only anticipated.

Second, cost analysis can be extended by analysing deviation costs both as operative losses and long-term future impacts of deviations and recovery. Third, forecasting elements for predicting schedule execution in the period from deviation identification to the possible time of correction implementation may be incorporated in the positional optimisation algorithm. Finally, analysis of long-term impacts of control actions and creation of a performance measurement system for the SC dynamics and control domain may be an interesting research avenue.

4.5 *SC as an organisational system*

Special focus should be directed onto subjective human decisions on adaptation and multi-criteria decision-making. Comparing human behaviour with the SC execution, a human reference model maybe identified for interrelating basic classes of disturbances and corresponding adaptation actions. As a result, contingency plans can be provided for the dependable design of interfaces between the human operators in the SC on a *collaborative* basis.

5. Conclusions

In this study, we summarised recent developments in the field of SC dynamics, control and disruption management from a multi-disciplinary perspective that includes management frameworks, quantitative methods and IT. In analysing numerous studies conducted in this field over the last two decades, we came to the conclusion that details of empirical or quantitative methodologies across the works on SC disruption management differ, but most share a basic set of attributes: a disruption (or a set of disruptions), impact of the disruption on the operational and strategic economic performance, and stabilisation and recovery policies.

Within this set of attributes, most of the studies on SC disruptions consider impacts of how changes to some variables are rippling through the rest of the SC and influencing its performance. We suggested naming this situation *the Ripple effect in the SC*, in an analogy to computer science.

We found that frameworks for tackling the Ripple effect so far exist implicitly. Most of them include the following stages:

- quantification of the Ripple effect;
- mitigating uncertainty at the planning stage (i.e. creation of a robustness protection);
- monitoring process execution (i.e. continuous preparedness and risk control);
- response and stabilisation of process execution in the case of deviations or disruptions; and
- recovery and minimising middle-term and long-term impacts of deviations and disruptions.

At all of these stages, quantitative analysis tools and IT exist but are still rarely applied in praxis. This can be explained on one hand by the lack of business models and processes for SC control, and on the other hand by the lack of education and research activities in this field.

As for research, the following crucial avenues for the future can be stated:

- incorporation of operability objectives into SC design and planning models;
- response/stabilisation analysis;
- control policies and algorithms;
- cost analysis and performance measurement for control and adaptation; and
- SC as an organisational system.

In future, an interdisciplinary collaboration between SCM, OR, control and IT researchers is needed. Often, researchers in logistics and SCM apply CT techniques to solve existing problems, but are not in close contact with the progress of research in CT. Similarly, CT researchers are often unaware of the possibilities of connecting their work to state-of-the art in SCM and IT. Multidisciplinary research can potentially enrich the possibilities developing useful solutions to many practical problems. We conclude that the Ripple effect can be the phenomenon that can consolidate research in the SC disruption management and recovery similarly to the bullwhip effect regarding demand and lead-time fluctuations. This may build the agenda for future research on SC dynamics, control, continuity and disruption management to make SCs more robust, adaptable and profitable.

Abbreviations

CT	control theory
IT	information technology
MPC	model predictive control
OPC	optimal programme control
SC	supply chain
SCEM	supply chain event management
SCM	supply chain management

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