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Disruptions in supply chains and recovery policies: state-of-the art review

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Abstract: Recent research underlines the crucial role of disruption events and recovery policies in supply chains. Despite a wealth of literature on supply chain design with disruption considerations, to the best of our knowledge there is no state-of-the art review on supply chain with disruptions and recovery considerations. We analyse state-of-the-art research streams on supply chain design and planning with both disruptions and recovery considerations with the aim to relate the existing quantitative methods to empirical research. The paper structures and classifies existing research streams and application areas of different quantitative methods subject to different disruption risks and recovery measures. We identify gaps in current research and delineate future research avenues. The results of this study are twofold. Operations and supply chain managers can observe which quantitative tools are available for different application areas. On other hand, limitations and future research needs for decision-support methods in supply chain risk management domains can be identified. Copyright © 2016 IFAC

Keywords: supply chain, design, planning, disruptions, recovery, ripple effect, dynamics, control, quantitative analysis

1. INTRODUCTION

Supply chain design (SCD) is a decision-making area that is involved with facility location planning, allocation of customers, and supplier selection (Melo et al. 2009, Chopra and Meindl 2012, Sawik 2013). In many cases, inventory, lead-time and demand fluctuations have been integrated into those models (Kumar and Tiwari 2013, Pan and Nagi, 2013, Askin et al. 2014). In SCD, 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).

D*isruptive risks* represent a new challenge for SC managers who face the *ripple effect* subject to *structural disruptions* in the SC, unlike *parametrical deviations* in the bullwhip effect (Ivanov et al. 2014a). The ripple effect describes the impact of a disruption on SC performance and the disruption-based scope of changes in the SC structures. Managing the ripple effect is closely related to designing and planning robust and resilient SCs. Recent studies extensively considered SCD and SCP taking into account disruption risks (e.g., Snyder and Daskin 2005, Cui et al. 2010, Ivanov et al. 2013, 2014a, Sawik 2013, Paul et al. 2014). A number of remarkable state-of-the-art reviews and conceptual frameworks have been published in this area (Klibi et al. 2010, Ambulkar et al. 2015).

It can be observed in the existing studies that two groups of problem statements are generally considered:

- Disruption consideration without recovery measures and
- Disruption consideration with recovery measures.

In many practical settings, companies need analysis tools to estimate the impacts of recovery measures subject to different disruptions and performance indicators. Ambulkar et al. (2015) provide the evidence that recovery policies belong to the most important drivers of SC resilience. Such recovery options comprise back-up suppliers, warehouses, depots and transportation channels, inventory and capacity expansion. Contingency plans or backup planning (e.g., alternative suppliers or shipping routes) need to be developed (Benyoucef et al. 2013).

The goal of this study is to structure and classify existing research streams and application areas of different methods for SCD and SCP with disruptions and recovery considerations as well as identifying gaps in current research and delineating future research avenues with the aim to relate the existing quantitative methods to empirical research.

The remainder of this paper is organized as follows. Section 2 provides a state-of-the-art overview of research on disruption risks with recovery considerations in SCD with the help of quantitative methods. In Section 3, analysis of the considered literature is performed regarding the reasons for different risks, pro-active and reactive measures for risk mitigation and recovery, and application areas of different quantitative methods. Section 4 identifies gaps in current research and delineates future research needs. The paper concludes by summarizing the most important insights from the research.

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2. STATE-OF-THE-ART

2.1. Literature selection

Reasons for disruptions in SCs have been extensively investigated. Numerous studies revealed basic reasons for the disruptions and their impact on SC execution and performance. In order to restrict ourselves to quantitative methods, we feel that the review of wealth of literature on SC risk management and collaboration strategies is out of scope of this paper. In quantitative analysis, two basic approaches to hedging SC against the negative impacts of different disruptions – *proactive* and *reactive* have been developed in recent years. The proactive approach creates certain protections and takes into account possible perturbations without recovery considerations while generating SCD (Klibi et al. 2010). The reactive approach aims at adjusting SC processes and structures in the presence of unexpected events (Ivanov et al. 2014). Literature on pro-active strategies to SC disruption management suggests different approaches to generate robust and resilient SC structures. Studies by Snyder and Daskin (2005), Cui et al. (2010), Peng et al. (2011), Benyoucef et al. (2013), belong to the recommendable references on pro-active approach. We focus on the reactive approach.

2.2 Mixed-integer programming

Mixed-integer programming (MIP) with application to reliable SCD has been a broad research avenue over the past ten years. The reliable location model was first introduced by Snyder and Daskin (2005). Losada et al. (2012) use a bilevel MIP for protecting an uncapacitated median type facility network against worst-case losses.

Benyoucef et al. (2013) considers SCD with unreliable suppliers. Rafiei et al. (2013) developed a comprehensive model for a problem statement with multiple products and many periods. The solution to the model is based on a priority-based genetic algorithm. The study by Lim et al. (2013) turned away from probability estimation issues and faced the trade-off of under- vs. overestimation of disruption probabilities. Gedik et al. (2014) model disruptions and train rerouting actions in a coal supply chain network and assess impacts of disruptions in terms of transportation and delay costs using a two-stage MIP model.

2.3. Stochastic programming

Stochastic programming models are scenario-based and parameters are represented by a set of discrete scenarios with a given probability of occurrence. In robust stochastic programming models (Azaron et al. 2008), facility disruptions and capacity expansion costs are also considered to be uncertain. Sawik (2013) developed a stochastic programming model to integrated supplier selection, order quantity allocation and customer order scheduling in the presence of SC disruption risks.

2.4 Inventory management and contracting

Hishamuddin et al. (2013) presented a recovery model for a two-echelon serial SC with consideration of transportation disruption. Hou et al. (2011) analyse the coordination with a backup supplier through buy-back contract under supply disruption. Iakovou et al. (2010) analyse a single period stochastic inventory model for capturing the trade-off between inventory policies and disruption. Shao and Dong (2012) analyse an assemble-to-order system with a backup source to offer on-time delivery and compensation policy to compensate customers for waiting in each period during the disruption. Hu et al. (2013) analyse the incentive mechanisms to motivate a supplier's investment in capacity restoration. The study by Kim and Tomlin (2013) indicates that if recovery capacity investment is the only option, the firms in a decentralized setting overinvest in capacity. Paul et al. (2014) analysed series of disruptions over time and presented an inventory control-based model to develop optimal recovery policies.

2.5 Simulation, system science and control theory

Simulation approaches have been proved to be a suitable tool for analysis of SCD in terms of the ripple effect. Schmitt and Singh (2012) presented a quantitative estimation of the disruption risk at production and supply capacities in a multi-echelon SC using discrete-event simulation. Carvalho et al. (2012) analysed impacts of transportation disruptions on lead-time and overall costs in an automotive SC using ARENA-based simulation model. Unnikrishnan and Figliozzi (2011) developed a scenario-based model with an adaptive routing policy. Vahdani et al. (2011) applied fuzzy program evaluation and review technique to calculate the completion time of SC operations in the case of a severe disruption. Xu et al. (2014) used AnyLogic software and modelled SC as an agent system to study the disruption at suppliers and recovery policies on the SC service level. Ivanov et al. (2013) included transportation reconfiguration in the case of SC disruptions into the SCD. Ivanov et al. (2014b) developed a model for multi-period and multi-commodity SCD with structure dynamics considerations. Xu et al. (2014) developed an approach to predict SC resilience by including recovery measures that use the analogy to biological cells with the abilities to self-adaptation and self-recovery. Ivanov et al. (2016a) studied disruption-driven SC (re)-planning and performance impact assessment with consideration of pro-active and recovery policies. Ivanov et al. (2016b) applied simulation to analysis of dynamic recovery policies for time-critical SCs under conditions of ripple effect.

3. ANALYIS AND OBSERVATIONS

3.1. Literature analysis

Based on the multi-disciplinary literature analysis, our next objective is to derive some classifications regarding the following issues:

- What types of disruptive risks should be considered by SC managers
- How to protect the SC against disruptions
- How to react in the case of disruptions
- Which methods are mostly suitable for certain problems in SC risk management and control

Table 1 depicts the matrix “risks-recovery”. In Table 2, the matrix “methods-contingency plans” is presented.

Table 1 Matrix "risks-recovery"

	Inventory	**Capacity**	**Dual/multiple vendors Back-up suppliers**
Production disruptions	Vahdani et al. (2011), Rafiei et al. (2013), Paul et al. (2014)	Azaron et al. (2008), Ivanov et al. (2013), Ivanov et al. (2014b)	Lim et al. (2010), Schmitt and Singh (2012), Ivanov et al. (2013), Ivanov et al. (2014b)
Supply disruptions	Vahdani et al. (2011), Hu et al. (2013), Iakovou et al. (2010), Shao and Dong (2012), Paul et al. (2014)	Azaron et al. (2008), Ivanov et al. (2013), Kim and Tomlin (2013), Ivanov et al. (2014b)	Hou et al. (2010), Sawik (2013), Schmitt and Singh (2012), Shao and Dong (2012), Ivanov et al. (2013), Ivanov et al. (2014b)
Transportation disruptions	Carvalho et al. (2012), Hishamuddin et al. (2013), Lewis et al. (2013), Paul et al. (2014)	Azaron et al. (2008), Ivanov et al. (2013), Lewis et al. (2013), Ivanov et al. (2014b), Gedik et al. (2014)	Unnikrishnan and Figliozzi (2011), Ivanov et al. (2013), Lewis et al. (2013), Ivanov et al. (2014b), Gedik et al. (2014)

Table 2 Matrix "methods-contingency plans"

		Mixed-integer programming	Stochastic programming	Simulation and control theory	Inventory management and contracting
Disruption risks	Production disruptions	Lim et al. (2010), Li et al. (2013)	Azaron et al. 2008,	Paul et al. (2014), Schmitt and Singh (2012), Vahdani et al. (2011), Ivanov et al. (2013,2014)	
	Supply disruptions	Lim et al. (2010)	Azaron et al. 2008),	Carvalho et al. (2012), Vahdani et al. (2011), Ivanov et al. (2013,2014)	Hishamuddin et al. (2013)
	Transportation disruptions	Gedik et al. (2014)	Azaron et al. (2008),	Schmitt and Singh (2012), Vahdani et al. (2011), Ivanov et al. (2013,2014)	Hou et al. (2010), Hu et al. (2013), Iakovou et al. (2010), Shao and Dong (2012), Lewis et al. (2013)
Contingency plans / recovery measures	Alternative suppliers			Schmitt and Singh (2012), Ivanov et al. (2013,2014),	Iakovou et al. (2010), Lewis et al. (2013)
	Inventory			Carvalho et al. (2012), Schmitt and Singh (2012), Vahdani et al. (2011)	Hishamuddin et al. (2013), Hsu and Li (2011), Hu et al. (2013), Shao and Dong (2012)
	Capacity		Azaron et al. (2008),	Schmitt and Singh (2012), Ivanov et al. (2013,2014),	Hsu and Li (2011)
	Backup suppliers	Lim et al. (2010), Li et al. (2013)		Schmitt and Singh (2012), Vahdani et al. (2011)	Hou et al. (2010), Shao and Dong (2012)
Performance measures	Fixed costs	Lim et al. (2010), Li et al. (2013)	Azaron et al. 2008	Ivanov et al. (2013,2014)	Hsu and Li (2011)
	Variable costs	Lim et al. (2010), Li et al. (2013)		Carvalho et al. (2012), Schmitt and Singh (2012), Vahdani et al. (2011), Ivanov et al. (2013,2014)	Hishamuddin et al. (2013), Hsu and Li (2011), Hou et al. (2010), Hu et al. (2013), Iakovou et al. (2010), Shao and Dong (2012)
	Disruption costs	Li et al. (2013)		Ivanov et al. (2013,2014)	Hishamuddin et al. (2013), Hu et al. (2013),
	Recovery costs		Azaron et al. (2008)	Schmitt and Singh (2012), Vahdani et al. (2011)	Hishamuddin et al. (2013), Hsu and Li (2011), Hou et al. (2010), Hu et al. (2013), Iakovou et al. (2010)
	Service level / profit			Schmitt and Singh (2012), Vahdani et al. (2011), Ivanov et al. (2013,2014)	Hsu and Li (2011), Hu et al. (2013), Shao and Dong (2012)

The analysed literature considers three basic types of disruptive risks that should be considered by SC managers:

- Production
- Supply and
- Transportation disruptions

Next, recent literature discussed different recovery strategies:

- Back-up suppliers,
- Back-up depots and transportation channels/modes
- Inventory and capacity buffers
- Capacity expansion

Reaction to disruptive events can be performed depending on the severity of disruptions:

- Parametrical adaptation
- Structure adaptation

Parametrical adaptation represents the simplest case where stabilization and recovery are possible through tuning of some critical parameters like lead-time or inventory. Structure adaptation considers back-up supplier on contingency transportation plans. MIP formulations consider product shift to back-up suppliers if primary suppliers are disrupted. Inventory control models also suggest policies for recovery. Simulation techniques consider "what-if" scenarios which can be used by SC managers in the case of disruption occurrence to quickly estimate the recovery policies and impacts on performance.

3.2. Critical analysis

MIP models provide interesting managerial insights and can be successfully used in cases where disruption probabilities can be fairly estimated. Second, most of the MIP solutions suggest opening new facilities. That increases total costs even if transportation costs are not increased.

However, as pointed out in recent articles by Chopra and Sodhi (2014) and Simchi-Levi et al. (2014) it is almost impossible to determine probability of factory fires, natural disasters, or piracy in certain regions. That is why one has to concentrate mostly on mitigation strategies and identification of the impact of disruption on financial and operational performance regardless of what caused the disruption.

In addition, a general shortcoming of existing studies, as pointed out by Cui et al. (2010) and Li et al. (2013) is that the dynamics of SC execution is not considered. The disruptions are mostly considered as static events, without taking into account their duration, stabilization/ recovery policies. As a general shortcoming of robust optimization, the tendency for quite pessimistic solutions has to be pointed out. In practice, it is hard to assume that managers will accept SCDs with low efficiency and high fixed-costs just in anticipation of the worst-case.

Different methods are suited to different problems. No single technique is likely to prove a panacea in this field. While mathematical and stochastic optimization has its place at the SC design and planning stages without recovery considerations, they fail to throw much light on the dynamic behaviour of the SC. The implications of SCD on SC performance at the execution and recovery stage can be enhanced by using models based on the dynamics of the execution processes.

3.3. Managerial implications

Disruption risks may result into ripple effect and structure dynamics in the SC. It is to notice that the scope of the rippling and its performance impact depend both on robustness reserves (e.g., redundancies like inventory or capacity buffers) and speed and scale of recovery actions (Ivanov and Sokolov 2013, Hu et al. 2013, Kim and Tomlin, 2013, Pettit et al. 2013). In many practical settings, companies need analysis tools to estimate both the SC robustness and SC resilience. For SC resilience, the impacts of recovery actions subject to different disruptions and performance indicators need to be estimated. The results of the literature as analysed can contribute to support decisions in these practical problems (Table 3).

Table 3. Matrix of managerial implications

	Sourcing	**Production**	**Distribution**	**Integrated SCM**	
Strategic	Segment suppliers according to disruption risks; Optimize inventory management	Segment production cites according to disruption risks; Increase manufacturing process and capacity flexibility	Increase transportation process and capacity flexibility Optimize inventory management	Create SC visibility Prioritize and allocate resources according to risk considerations	**Risk mitigation**
Tactical	Collaborative emergency trainings in the SC: Tracking changes, SC monitoring, and alerting the executives				**Preparedness**
Operative	Re-direct material flows using back-up suppliers and inventory	Re-allocate resources and change manufacturing plans	Re-allocate resources and change transportation plans	Re-configure the SC by re-matching demand and supply points	**Stabilization and recovery**

4. FUTURE RESEARCH AGENDA

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) should also include different control objectives and strategies (e.g., recovering planned execution, maintaining plan stability, minimizing 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.

4.1 Performance and resilience measurement in SC design and planning models

Understanding and finding SCD with effective and efficient constellations of complexity, robustness, flexibility, adaptability and resilience are areas of promising research. It is vital to extend existing SCD models by integrating objectives like flexibility, robustness, stability and resilience into multi-criteria SCD selection procedures. Redundancy and responsiveness elements of SC flexibility may increase both service level and costs. The optimal resilient state of an SC means that the SC achieves maximal service level at minimal costs in the presence of the considered scope of disruptions.

4.2 Developing the recovery policies

From a practical point of view, the expected results of the research in this domain are to provide operations and 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

(iii) suggest efficient and effective stabilization and recovery measures.

First, different control strategies regarding construction of the optimal recovery programs can be analysed. Here, basic cybernetic principles (critical events, final deviations, free trajectories and interim solutions) can be investigated. For example, an immediate adaptation program (i.e., immediate recovery and return on the planned execution) and smooth adaptation program (i.e., constructing an alternative execution in anticipation of new perturbations) can be compared. Second, different control objectives may be considered (e.g., maintaining planned economic performance, extremizing this performance through control, maintaining plan stability rather than recovering the planned economic performance, etc.).

4.3 Costs analysis and performance measurement for recovery stage

This is a very promising research area. So far, cost analysis has rarely been included within SC control models. 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 only be anticipated.

5. CONCLUSIONS

Frameworks for tackling the bullwhip effect and ripple effect so far exist in literature regarding operational and disruption risks respectively. Most of them include:

- mitigating uncertainty at the SCD stage
- continuous preparedness and risk control
- response and stabilization of process execution in the case of deviations or disruptions
- recovery and minimizing middle-term and long-term impacts of deviations and disruptions.

The performed analysis has revealed application areas of different quantitative methods from SC risk analysis in SCD. We could observe that the majority of quantitative research pertains to demand and lead-time fluctuations at the operational risks side and structural disruptions at the disruption risks side. Proactive and recovery measures, different redundancies (e.g., inventory, capacity buffers, back-up suppliers) and flexibility strategies (e.g., dual or multiple sourcing, product and process flexibility, and coordination concepts) are typically considered with a clear domination of the redundancy area.

In future, elements of recovery should be considered integrated with proactive models. Such integration requires simultaneous consideration of both the static structural properties of SCD and execution dynamics subject to uncertainty and disruptions. In investigating the dynamic behaviour of the SC, an interesting research avenue would be to apply dynamic systems theory in combination with mathematical programming methods.

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