KEDGE BUSINESS SCHOOL
ILS2016
Information Systems Logistics and Supply Chain
6th International Conference
université de BORDEAUX

The Risk-Aware Multi-Period Capacitated Plant Location Problem (CPLP-Risk)

Iris Heckmann [1], Stefan Nickel [1,2], Francisco Saldanha-da-Gama [3]

[1] Department of Logistics and Supply Chain Optimization, Research Center for Information Technology (FZI), Karlsruhe, Germany
[2] Institute for Operations Research, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[3] DEIO and CMAF-CIO, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
{heckmann@fzi.de, stefan.nickel@kit.edu, fsgama@ciencias.ulisboa.pt}

Abstract. Unexpected deviations and disruptions - subsumed under the notion of supply chain risk - increasingly aggravate the planning and optimization of supply chains. Over the last decade there has been a growing interest in including risk aspects for supply chain optimization models. This development has led to the adoption of risk concepts, terminologies and methods defined and applied in a broad variety of related research fields and methodologies. In [3] the core characteristics of supply chain risk have been identified. Based on contemporary research gaps identified in [3] for optimization approaches we introduce a mixed-integer two-stage stochastic programming model that extends the capacitated plant location problem and additionally offers the possibility to formalize and operationalize supply chain risk. The evaluation of the developed optimization model discloses its usefulness in terms of providing risk-aware solutions and of approaching risk by stochastic programming.

Keywords: analytics, risk definition, supply chain optimization, capacitated plant location problem

Introduction

The management of supply chains seeks to plan, monitor, and control a network of interdependent organizations that facilitates different types of flows between the original producer to the final customer. The major objectives of supply chain management are the maximization of profitability and the achievement of customers' satisfaction [5]. As the determination of the best supply chain configuration that supports supply chain's goal achievement is an important task of the strategic planning process, facility location problems are of particular interest for supply chain management [4]. One of the core problems of facility location is the capacitated plant location problem (*CPLP*) also known as the fixed-charge facility location problem (*FLP*) [1]. With regard to the strategic planning of supply chains, it is especially suitable, because it respects capacity restrictions that can be referred to production, inventory or handling capacities.

In the presence of the continuously increasing fierce competition for customers and their profitable satisfaction, supply chain management needs to respect numerous optimization criteria. Besides different aspects of network complexity, stochastic parameters need to be considered on different planning levels of supply chain management. Over the last decade supply chain risk became increasingly relevant, although the notion of risk or more precisely supply chain risk was not clearly defined. An extensive literature review on supply chain risk concluded that supply chain risk can be defined by three elementary characteristics, namely: risk objective, risk exposition, and risk attitude [3]. Figure 1 presents the *Core Characteristics of Supply Chain Risk (CCSCR) Hierarchy* embracing the main characteristics of this new supply chain risk definition. A joint consideration of those characteristics provides the possibility to accomplish formalization and operationalization of supply chain risk.

The purpose of this work is to adopt the aforementioned core characteristics of risk to strategic supply chain decision problems, i.e. to a *CPLP* problem, by the use of stochastic programming.

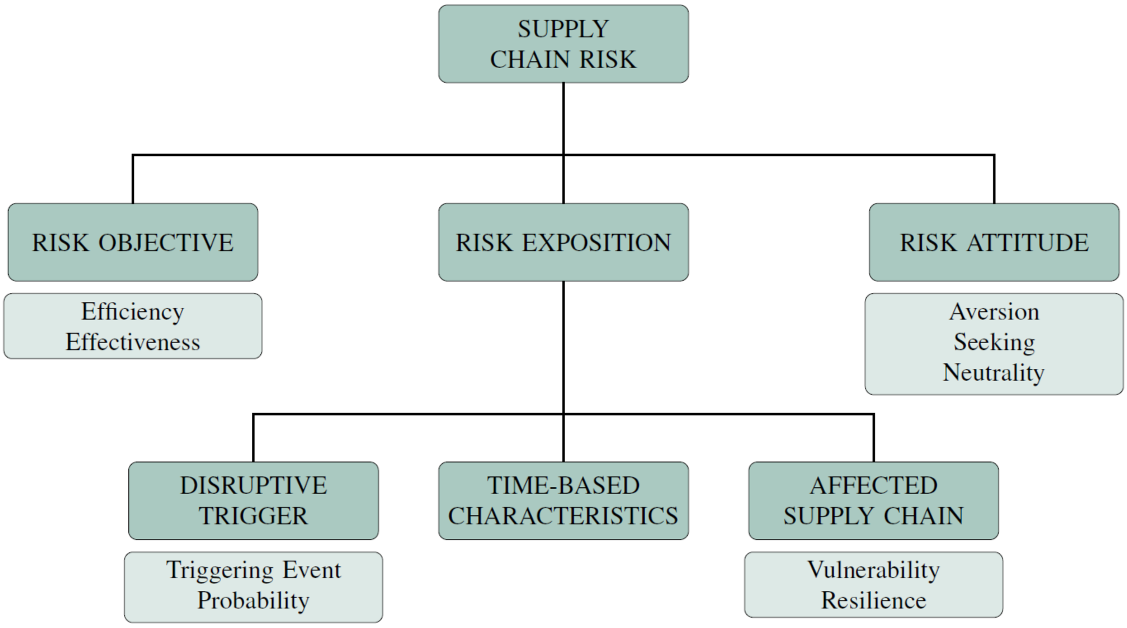

Figure 1: Core Characteristics of Supply Chain Risk (CCSCR)

Operationalization of Supply Chain Risk: CPLP-Risk

In this section we propose a mixed-integer two-stage linear programming model for a risk-aware supply chain design problem. We therefore extend the capacitated plant location problem (*CPLP*) to the risk-aware capacitated plant location problem ($CPLP^{Risk}$).

Notations

First we give an overview of the sets, parameters and decision variables needed.

Table 1: Sets and Indices applied for the $CPLP^{Risk}$ Model

Index Symbols	Set Symbol	Description
i	I	Facilities
j	J	Customers
t	T	Time periods
h	H	Expansion levels
s	S	Scenarios

Table 2: Deterministic and Stochastic Parameters for the *CPLP*^{Risk} Model

Model Identifier	Name	Description
f_i	Opening costs	Amount of costs related to the opening of each facility i
K_i	Capacity	Amount of capacity related to facility i
c_{ij}	Transportation costs	Amount of costs related to the transport between facility i and customer j
b_i	Extra-capacity costs	Amount of extra-capacity related to facility i
r_j	Reward	Amount of reward related to demand fulfillment for customer j
u	Value of service level adherence	Amount of costs related to each unit of unreached target service level
v_h	Expansion costs	Amount of costs related to each unit of extra-capacity of expansion level h
o_h	Expansion capacity	Amount of capacity related to each unit of extra-capacity of expansion level h
β^o	Target service level	Level of targeted service level
π_s	Scenario probability	Probability related to scenario s
d_{jts}	Customer demand	Amount of demand related to customer j in time period t and scenario s
γ_{its}	Capacity reduction	Amount of relative capacity reduction within facility i in time period t and scenario s

Table 3: Decision Variables for the *CPLP*^{Risk} Model

Model Identifier	Name	Description
y_i	Opening decision	Binary variable equals 1 iff facility i is opened
z_i	Installation decision	Binary variable equals 1 iff expansion options are installed at facility i
x_{ijts}	Transportation decision	Amount transported from facility i to customer j in time period t and scenario s
φ_{jts}	Unsatisfied demand decision	Amount of unsatisfied demand related to customer j in time period t and scenario s
ω_{iths}	Expansion-level decision	Binary variable equals 1 iff in scenario s expansion level h is installed at facility i at time period t
β_s	Service level	Level of service level in scenario s
Δ_s	Service level deterioration	Amount of level reduction in scenario s

The Risk-aware Capacitated Plant Location Problem (CPLP-Risk)

$$\min \sum_{i\in I}(f_i y_i + b_i z_i) + \sum_{s\in S}\pi_s\left(u\Delta_s + \sum_{i\in I}\sum_{h\in H} v_h o_h \sum_{t\in T}\omega_{iths} + \sum_{t\in T}\sum_{i\in I}\sum_{j\in J}(c_{ij}-r_j)\,d_{jts}x_{ijts}\right) \tag{1}$$

$$(CPLP^{Risk}) \qquad \begin{array}{rlll}
\sum_{i\in I} d_{jts}x_{ijts} + \varphi_{jts} = d_{jts} & \forall & j,t,s & (2)\\
\sum_{j\in J} d_{jts}x_{ijts} \le \gamma_{its}K_i y_i + \sum_{h} o_h\omega_{iths} & \forall & i,t,s & (3)\\
\sum_{h\in H}\omega_{iths} \le z_i & \forall & i,t,s & (4)\\
z_i \le y_i & \forall & i & (5)\\
\beta_s = 1 - \frac{\sum_j\sum_t \varphi_{jts}}{\sum_j\sum_t d_{jts}} & \forall & i,s & (6)\\
\Delta_s = \beta^o - \beta_s & \forall & s & (7)\\
0 \le \Delta_s \le 1 & \forall & s & (8)\\
x_{ijts} \ge 0 & \forall & i,j,t,s & (9)\\
\varphi_{its} \ge 0 & \forall & i,t,s & (10)\\
z_i \in \{0,1\} & \forall & i & (11)\\
y_i \in \{0,1\} & \forall & i & (12)\\
\omega_{iths} \in \{0,1\} & \forall & i,t,h,s & (13)
\end{array}$$

The model decisions consist of first stage and recourse decisions. Initially, the opening and capacity extension decisions are made for each facility, while minimizing the expected costs of the consequences of these decisions. Opening and capacity extension decisions are declared as first stage decisions. When uncertain parameters are disclosed, the recourse or second stage decisions lean on, improve or correct the decisions made at the first stage. The selection of the type of expansion level for every period depicts the second stage decision. It follows that the overall objective function minimizes the costs of the first and the expected costs of the second stage decision. Costs related to the opening of a facility and installing capacity options belong to the costs of the first stage decision. Costs related to the execution of available capacity options as well as the value of unsatisfied demand refer to costs of the second stage decision.

Demand constraint 2 equalizes demand fulfillment, $\sum_i d_{jts}x_{ijts}$, and unsatisfied demand, φ_{its}, with customer demand, d_{jts}. The capacity constraint 3 restricts the ratio of demand fulfillment of each facility to the available capacity at the facility considered. Facility-related capacity sums to the reduced capacity, $\gamma_{its}K_i y_i$, and the capacity extension units, $\sum_h o_h\omega_{iths}$. For each time period and facility only one extension level, h is allowed to be executed, constraint 4, if and only if a capacity extension option has been alloted to the facility, constraint 5. The amount of service level deterioration is calculated by constraints 6 to 8. Additionally, variables are limited to appropriately accomplish the aforementioned requirements by constraints 9 to 13.

In the following we briefly describe how the supply chain risk core characteristics from Figure 1 have been operationalized. (For more details see [2].)

Risk Objective

For the $CPLP^{Risk}$ model we add the consideration of effectiveness by introducing the evaluation of deviation of service level, β_s, from a targeted value, β^o, within the objective function, $u(\beta^o - \beta_s)$. In order to calculate the service level we allow the non-fulfillment of customers' demand, φ_{jts}. The service level is then calculated by $\beta_s = 1 - \frac{\sum_j \varphi_{jts}}{\sum_j d_{js}}$.

Risk Exposition

The risk exposition of the underlying supply chain is a core characteristic, which is further specified by time-based characteristics having tremendous impact on the severity, disruptive triggers occurring within or exterior to the supply chain and the constitution of the affected supply chain itself.

Disruptive Triggers A triggering event can impose the root cause of the non-achievement of targeted service level or increase of overall costs. A triggering event or a sequence of consecutive events is denoted as a disruptive event, when it results in the non-achievement of supply chain objectives. A disruptive trigger negatively affects one or several supply chain processes and its consequences propagate through the entire supply network. The initial impact of a disruptive trigger on the supply chain can be uncovered by its capability to influence supply chain processes. A disruptive trigger, for example, can result in a capacity reduction, γ_{its}, and/or simultaneously in increased customers' demand, d_{jts}. We consider the effects of a disruptive trigger on the capacities of facilities by introducing a capacity reduction parameter, γ_{its}.

Affected Supply Chain To endow supply chains with the ability to absorb or to flexibly adjust to consequences of disruptive triggers, two different types of decisions need to be done. First, it is necessary to assess the need to increase the supply chain resilience. We integrate these thoughts by introducing additional terms in the $CPLP^{Risk}$ model. Therein each facility can be endowed with additional capacity extensions, z_i, that can be used whenever facilities are disrupted or demand volume is increasing, ω_{iths}, such that the overall capacity cannot fulfill overall customer demand. The $CPLP^{Risk}$ model allows to execute only one type of capacity expansion, h, at each facility, i, in each period t, see $CPLP^{Risk}$ 4. Capacity expansions come along with costs that depend on the expansion level selected, therefore the cost amount in the objective function is increased by $\sum_{i\in I}\sum_{h\in H} v_h o_h \sum_{t\in T} \omega_{iths}$.

Time-based Characteristics Within the $CPLP^{Risk}$ model the capacity reduction and the demand modifications are multi-period parameters whose dependent developments are depicted in different scenarios. A common approach to pro-actively manage unpredictably occurring disruptive triggers is to install additional time or capacity buffers before a disruption has even occurred. However, so called robust approaches omit the dynamic nature of disruptive triggers and forestall the possibility to design the supply chain cost-efficiently for the times, when no disruptive triggers occur. Therefore, the $CPLP^{Risk}$ model is endowed with the first-stage decision of preparation for disruptive triggers, z_i, and the second-stage decision of executing a capacity extension of an appropriate level and duration, ω_{iths}.

Risk Attitude
The risk attitude of the decision maker is a core characteristic of supply chain risk as it reflects the level of risk the decision maker is willing to accept. When a decision maker is, for example, risk-seeking, he accepts higher degrees of value deterioration of a specific goal in exchange for the adherence or increase of an opposite one. The $CPLP^{Risk}$ model has to consider two main objectives: customer satisfaction (an effectiveness-based objective) and cost minimization (an efficiency-based objective). The decision maker has to balance both objectives by evaluating how much he is willing to invest for capacity extensions with respect to the value of customer satisfaction. The input parameter u expresses the value of customer satisfaction with respect to the costs spent for capacity establishment and potential expansions.

Computational Results and Conlusions

First computational results show that a deterministic approach is not completely misleading, but that a stochastic formulation is still better even though the range of uncertainty is rather small. The computational results will be presented in detail in the talk. In particular we present results for the value of the stochastic solution and for the expected value of perfect information.
The $CPLP^{Risk}$ model introduced in this talk proves that it is possible to operationalize supply chain risk. The approach incorporates the core characteristics of supply chain risk derived for the *CCSCR Hierarchy* and thus provides risk-aware solutions for strategic facility location problems.

References

[1] Elena Fernández and Mercedes Landete. Fixed-charge facility location problems. In G. Laporte, S. Nickel, and F. Saldanha-da-Gama, editors, *Location Science*, pages 47–77. Springer, Berlin-Heidelberg-New York, 2015.

[2] Iris Heckmann. *Towards Supply Chain Risk Analytics : Fundamentals- Simulation - Optimization*. PhD thesis, Karlsruhe Institute of Technology, 2015.

[3] Iris Heckmann, Tina Comes, and Stefan Nickel. A critical review on supply chain risk – definition, measure and modeling. *Omega*, 52(0):119 – 132, 2015.

[4] M.T. Melo, S. Nickel, and F. Saldanha-da-Gama. Facility location and supply chain management: A review. *European Journal of Operational Research*, 196:401–412, 2009.

[5] J. Stock and S. Boyer. Developing a consensus definition of supply chain management: A qualitative study. *International Journal of Physical Distribution & Logistics Management*, 39(8):690–711, 2009.