Uncertainty in Logistics Network Design: A Review

Li Li, and Lothar Schulze

***Abstract*—Along the logistics network either horizontally or vertically, uncertainty can appear anywhere. At the beginning of the network, even the most reliable supplier could have a late delivery. At the end of the network, customer demand is always the most challenge problem. In the literature, uncertainty is from time to time considered in logistics network design problems and corresponding models in order to enhance the flexibility of the network. It is necessary to investigate the uncertainty especially modeled in logistics network design. The uncertainty sources, description methods, network measurements, and sovling methods are especially important for research and practice.**

***Index Terms*—Supply Chain management, Logistics Network Design, Uncertainty**

I. Introduction

The supply chain, which is also referred to as the logistics network, consists of suppliers, manufacturing centers, warehouses, distribution centers, and retail outlets, as well as raw materials, work-in-process inventory, and finished products that flow between the facilities. Logistics network involve wide range of problems, which affect the firm from long term to short term.

Designing logistics network means finding the answers for the decisions in the long term panning, such as - Where should the plants or warehouses be located? Should existing facilities be used or new ones built? Which products should be produced at which plants? How much of which products should be produced and by which? How much inventory should be kept in stock? How much as raw materials, semi-finished products, finished products? When is the best to move the goods? Which transport mode should be used?

In the operation research as well as management science, the attraction of the topic logistics network design or supply chain configuration has well proved by a huge number of studies and researches.

The surveys in logistics network design area in the time frame from 1960 until recent years are summarized (table I). These surveys don not cover all the articles published, but they provide a comprehensive view of trends, solutions and applications in specific industry.

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TABLE I
SUMMARY OF LOGISTICS NETWORK DESIGN MODELS SURVEYS

Papers	Stochastic/All Models	Timeframe
Vidal and Goetschalckx (1997) [1]	6 / 40	1974 - 1996
Beamon (1998) [2]	9 / 25	1961 - 1997
Owen and Daskin (1998) [3]	36 / 58	1968 - 1996
Mina and Zhou (2002) [4]	9 / 41	1960 - 2001
Snyder (2006) [5]	54 / 90	1974 -2005
Melo et al.(2009) [6]	20 / 120	1995 - 2008

The reviews of the supply chain literature reveal that most logistics network design models are deterministic, treating customer demand, production, and other parameters as known. This simplification has reduced the complexity of modeling the supply chain. However the adaptability of these models to real world context also reduced.

The globalization of economic activities together with fast development in technology has led to shorter product life cycles but larger variety of products and a very dynamic customer behavior in terms of preference. Managing logistics network effectively is therefore a complex and challenging task. The real problem with such a confusing network is the uncertainty that plagues it [7].

Uncertainty is defined by Ivanov and Sokolov [8] as a comprehensive term, consider situations that came both positive like chance and negative like threats deviations from an expected outcome.

Along the logistics network, uncertainty can appear anywhere. At the beginning of the network, even the most reliable supplier could have a late delivery. In the middle, a new machine could fail to work; even it's just been purchased. And at the end, customer demand is the most challenge problem. Uncertainty is also one of the most challenging problem and the main factor that can influence the effectiveness of the configuration and coordination of supply chains. In reality, critical parameters like demand, cost, time is quite uncertain and a precise forecast is hard to obtain. Moreover, as many cooperations move towards to global supply chains, many other kind of uncertainty will be exposed, such as exchange rates, reliability of transportation channels, transfer price, political stability.

A late delivery of supply could freeze the whole production process if the organization runs out of raw materials or force the organization to reschedule the regular production. An unexpected machine breakdown could disrupt the production line. Or an unaccurate forecast of customer demand could lead to over stock or under stock. All of these causes increase the cost that the organization has to pay, concurrently fail to satisfy the customer.

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In order to keep the long term competing ability corresponding satisfying customer requirements, the necessity of understanding and controlling the factors of supply chain uncertainty are required. One way to consider uncertainty can be realized when designing or configuring the logistics networks so as to build flexibility into the network. When the network or supply chain is flexible enough, undoubtedly the capability of confronting uncertainty is increased. Hence, in the literature of logistics network design, although from the paper amount viewpoint, the research of stochastic logistics networks is not dominant, uncertainty is from time to time and increasingly concerned. An interesting question is how uncertainty is dealt with in logistics network design in the literature. To comprehensively answer this question is the aim of this review paper.

II. Sources of Uncertainty

Davis [7] identified three distinct sources of uncertainty in supply chain - supply uncertainty, process uncertainty, and demand uncertainty. Fig. 1 summaries the three main sources of uncertainty, which are proposed in recent decades.

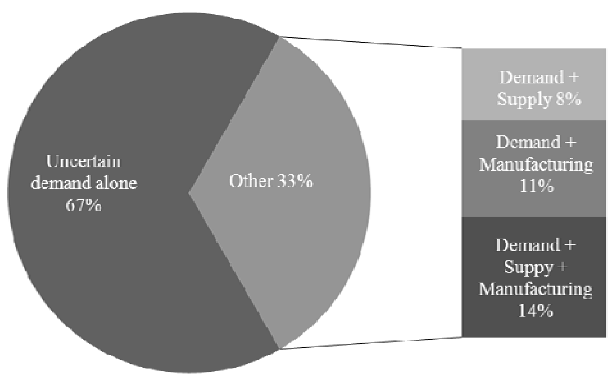

Fig. 1. Sources of Uncertainty

Supply uncertainty is caused by the variability of supplier performance. Poor performance in material quality or delivery often disrupts the production process; a high fluctuation in selling price of material may reduce the profit of company and adds to difficulty of managing material procurement. Frequently replacing of critical material suppliers lead to uncertainty, because the organization must adjust its related business processes or examine the reliability of the supplier's performance.

Problems with the manufacturing process are the second source of supply chain uncertainty. The impacts which are caused by this source of uncertainty depend on the degree of process interaction, degree of process, components interaction or decomposition; process stability; manufacturing lead time or changes in production technology. When the sub-processes are dependent to each other, the different process steps cannot be separated without affecting overall process performance. Multi interactions among product components or ability of separating the product into simple components also affect the manufacturing performance. These factors are mostly unpredictable as well as hard to measure directly.

The final major source of uncertainty lies in customer demand. Forecasting demand is the most valuable source for the organization in production scheduling. However, there are always a gap between forecasting and reality. How big the gap is highly depends on the accuracy level of forecasting data. Without a sales history, the demand for a new product is frequently difficult to predict. A wide range of products also adds to the difficulty of managing product demand.

It's easy to realize that the researchers pay the most attention in demand uncertainty. Shortening products life cycle, irregularity of customer orders in terms of time and quantity, changing in customer's preference are the reasons of errors in forecasting the customer's demand. Either overproduction or underproduction leads to unexpected cost for transportation and stocking. With the products with limited shelf life, it could be more complicated when the products are expired. Moreover, stock out means the organization fails to satisfy their customer, and often with that, the organization loses their customers to other rivals. The articles with uncertainty in customer demand will be next discussed in details.

It is also reveallled that over half of the models include only one source of uncertainty (fig. 1). Not many authors included the discussed articles addressed more than one uncertain parameter in their model. But only besides some models with fuzzy supplier's performance, the demand uncertainty always appears.

Ahmedi [9] and Snyder et al. [10] described demand and cost parameters as uncertain and scenario depended. Chen et al. [11] considered not only the variability in demand but also the incompatible preference of product price for all participants in the supply chain. Santoso et al. [12] presented the sample average approximation scheme, with an accelerated Benders decomposition algorithm with the ability of computing a huge number of scenarios. Taking that advantage, in their model any parameters like processing cost, demand, supplies or capacities can be uncertain and be described via scenarios.

III. Describing the Uncertainty

Considering stochastic parameters in an analytical supply chain model, most research can be distinguished as two primary approaches, referred as the probabilistic approach and the scenario approach [3].

One of the traditional ways to address uncertainty is to solve a deterministic problem using the mean values of the parameters. The probabilistic approach is suitable when the values of random parameters are controlled by a probability distribution known by the decision maker, for instances through historical data or forecasting data.

The type of distribution includes continuous distribution and discrete distribution. Continuous distribution can be Gaussian distribution or triangular distribution. Discrete distribution can be Poisson distribution, Boltzman distribution, or Joint distribution.

If no probability information is known, e.g. for new products, or new segment of market, the uncertain parameters could be more easily to be described as possible scenarios. Scenario approach is a method, in which uncertainty is characterized through a set of realization or instances, which

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describe the set of admissible situations and a probability distribution over the set. Each complete realization of all uncertain parameters forms a scenario. Once the scenarios are defined, each of scenarios needs to be assigned a probability of occurrence.

Depending on the problem or the situations, the probability of each scenario will be different. By introducing discrete scenarios, the difficulty of continuous distribution is avoided. In some situations, scenario planning does the work of forecasting as evaluating trends and potential changes. However the scenario approach has two main disadvantages. The first one is that identifying scenarios is a difficult task, as well as determining the probabilities to them. The second drawback is the limitation of realizations, which the decision makers could evaluate.

According to Zimmermann [13], the choice of an appropriate uncertainty calculation may depend on: the cause of uncertainty, the availability of both quantity and quality of information, type of required information and the language required by the final observer. An overview on how these two approaches have been used in the literature (fig. 2). From the statistics, it can be seen that scenario approach is dominant. This phenomenon indicates that it is indeed difficult to obtain adequate information to apply any type of distribution.

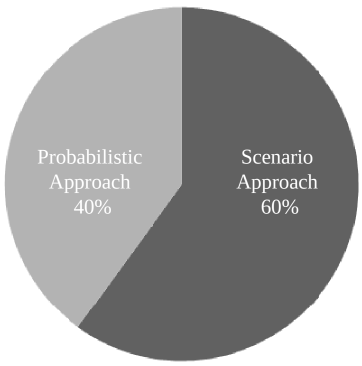

Fig. 2. Describing the Uncertainty

IV. Performance Measures of Logistics Network Model

The primary task of logistics network is moving the products from point of origin to point of consumption effectively and efficiently. But the question is what the right definition of "effectively and efficiently" is. Although each logistics network is unique, and there are no configurations suitable for all contexts, there are some key performance measures that are applicable in most settings. Performance measures indicate the work performed and the results achieved in an activity, process, or organizational unit.

Performance measures should be both nonfinancial and financial. Performance measures enable periodic comparisons and benchmarking. Performance measures are an important component in logistics design for the logistics managers. Depending on the strategy of the organization, the objective of the logistics network model will be different.

Fisher [14] classified two types of products: functional products and innovative products in which the supply chain with functional products aims to reduce the cost as low as possible while the latter supply chain need to respond quickly to deal with unpredictable demand. The strategy of the organization could define by their customer. In different circumstances, for different industries, with different products, the customer can demand differently. For instance, in parcel delivery service, some providers measure their performance by an efficient network regardless the cost, or the cost play minimal role while the others configure their network to be efficient by minimizing total cost, but no doubt that time will always be their major concern.

Before designing a logistic network, the logistics managers have to set the goals of the model, whether it is high customer satisfaction or low cost, flexible, etc. These measures may be categorized as either qualitative or quantitative.

A. *Qualitative Performance Measures*

Qualitative performances are the measures which cannot or are hard to model direct by numerical measurement. The qualitative performance measures can be categorized into:

- Customer satisfaction: satisfaction of customers with the products or the service received. The customer satisfaction could associate with the service before or after purchasing products or service as well as with service elements directly involved in the physical distribution of products.
- Flexibility: ability of the company to respond to diversity or change of environment. Flexibilities include labor flexibility, machine flexibility, and volume flexibility or mix flexibility.
- Visibility: measuring time and accuracy of information transfer. The transfer of information between operational levels could be delayed or inaccurate, therefore affect the efficiency of the whole network.
- Trust: reliability and consistency between different levels of the supply chain. Importance is the supplier performance, how consistent suppliers deliver raw materials on time in good condition.

However, where the decisions are mostly in strategic level considered, it is no need to discuss deeply in qualitative models. Next comes the discussion about the quantitative models with the objectives of monetary factors and/or customer responsiveness.

B. *Quantitative Performance Measures*

Quantitative performance measures, in contrast are those measures that may be directly described numerically. They can be divided into objectives that are based on cost or profit and objectives that are based on some measure of customer responsiveness [2].

More than half of the literature considers cost or profit as the major objective (fig. 3). However, in details, profit maximization has received less attention in comparison to minimization costs. This is strange because most business activities are profit oriented. However, it could be understood, when minimizing cost somehow also means maximizing profit. Alonso [15] defined the benefit as the product net profit over the time horizon minus the investment depreciation and operations costs. The goal of the model is to minimize the expected benefit, in which the product net price and demand are uncertain. Tactical planning is devoted to

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better utilization of available resources and strategic planning is devoted to better acquisition of resources so that the tactical planning profit minus the resources depreciation cost is maximized subject to given strategic constraints.

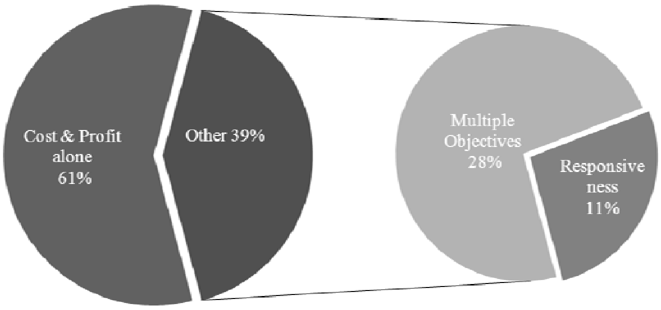

Fig. 3. Quantitative Performance Measures

Applequist [16] considered two objective functions in their model: maximization the expected value of the net present value and maximization of the risk premium. The risk premium provides the basis for a rational balance between expected value of investment performance and variance. Guillen et al. [17] investigated the effect of the uncertainty in the production scenario through designing a multi-objective supply chain. The three objectives: the net present value, the demand satisfaction and the financial risk are considered.

V. Stochastic Programming

In strategic logistic network design problem with random parameters, there are two main optimization approaches are appropriate to find a good solution: stochastic optimization and robust optimization. Both stochastic and robust optimizations aim to well performance of the network under any possible realization of the uncertain parameters. The main difference between these two optimizations is the objectives of each model. Many of the stochastic location models have the objective of minimizing the expected cost or maximizing the expected profit.

In robust location models, the objective is to find a solution, which is feasible for all data and optimal in some sense. Considering instances a logistics network model with uncertain demand, stochastic optimization will design the model with least expected cost. However, extra costs can appear with the probability of stock out. The robust optimization model, in the other hand, will design the model with adjustment that can cope with any possible scenarios of demand. In exchange, the total cost for the network will be higher than with stochastic optimization. Next the discussion will focus on robust optimization and their appearance in the research literature; then on stochastic optimization.

A. Robust Optimization

The robust optimization is often used to tackle with problems, where no probability information is known, but the data are within certain bounds, or only known to belong to some uncertainty set; for example “-15 % average”, “average” and “+15 % average”. The robust optimization concern of measuring the robustness, the stability of the model, concretely, the common goals are mini-max cost or mini-max regret. Instead of seeking to immunize the solution in some probabilistic sense to stochastic uncertainty, here the decision maker constructs a solution that is close or almost optimal for any realization of the uncertainty in a given set.

The robust optimization can also be understood as optimizing the worst case performance of the system. In robust optimization, the uncertainty data are often described as scenario approach, a set of realization of uncertain parameters, which defined as a set of scenarios, each with related probability. The objective function of robust optimization contains two parts, the first part measures optimality robustness; the second part contains a feasibility penalty function measuring the model robustness. It is used to penalize violations of the control constraints in some scenarios. The use of penalty function is situation dependent.

Ferretti et al. [18] designed a distribution network that has the lowest total cost under the whole set of possible demand scenarios. Two possible strategies are defined: the robust distribution network and the stable distribution network while the former minimizes the total expected costs over the scenarios and the latter minimizes the variability of the different cost components over the different scenarios.

Romauch et al. [19] formulated a stochastic dynamic facility location problem with random demands. The aim of the model is to find the optimal decisions for production, inventory and transportation in multi period. The periods are linked by current level of inventory and demand forecast.

Butler et al. [20] presented a robust optimization model for strategic production and distribution planning for a new product. Only robust optimization is suitable for this problem, because of the lack of information in customer demand and cost. Their models are divided into two categories: the regret model and variability model. The regret model measures the difference between the chosen solution and the optimal solution. The variability model control the spread of the costs by adding standard deviation, variance, or other measures to the objective function.

Yu et al. [21] reformulated a stochastic management problem as a high efficient robust optimization model capable of generating solutions that are progressively to the data in the scenario set. The authors also use a feasibility function, which used to penalized violations of the control constraints, capable of adjusting the model in response to the change in data under different scenarios. However, the model can be applied with linear functions.

B. Stochastic Optimization

Stochastic optimization is another method, which incorporates random data. Both stochastic and robust optimizations aim to well performance of the network under any possible realization of the uncertain parameters. In stochastic optimization, the most common objective is to optimize the expectation of some function of the decisions data and the random parameters.

In contrast to robust optimization, here some information is known before hand, or can be estimated. The data, say in other way, are governed by probabilistic distribution with mean and variance value. In the logistics network model, the objective can be maximizing the expected cost or maximizing expected profit. In the literature, the most widely applied and studied stochastic programming models for

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supporting making decision under uncertainty are two stage linear programs. With stochastic programming, the decision maker is allowed to analyze uncertainty explicitly. Before the uncertain data are realized, some prior decisions must be made. The set of decisions is then divided into two groups.

The first group is that a number of decisions have to be taken before the experiment. All these decisions are called first stage decisions and the period when these decisions are taken is called the first stage.

The second group means that a number of decisions can be taken after the experiment. They are called second stage decisions. The corresponding period is called the second stage.

Here the decision makers take some action in the first stage, after which a random event occurs affecting the outcome of the first stage decision. The first stage variables correspond to those decisions that need to be made "here and now", prior to the realization of the uncertainty. In two stages stochastic facility location models, the location of facilities have to be made, before the uncertainty exposes, in capacity expansion models. The first decision stage establishes the capacity expansion schedule for the planning horizon, while the second stage decision constitutes taking recourse actions in order to correct the failure.

The second stage therefore called "wait and see" recourse decision. A recourse decision can then be made in the second stage that compensates for any bad effects that might have been experienced as a result of the first stage decision. The optimal policy from such a model is a single first stage policy and a collection of recourse decisions, a decision rule defining which second stage action should be taken in response to each random outcome.

VI. Application in Supply Chain Context

For illustrating the applicability of the mathematical formulations presented, many studies represented numerical experience. The data of the proposed examples could be generated from specific industry or already applied in real life scenario. The applications of stochastic model in a supply chain context are summarized (table II).

According to Melo et al. [6], the contexts are classified into: the Case study refers to a real life scenario, even if it was not implemented in practice, while the category industrial context stands for a study using randomly generated data for a specific industry.

Tsiakis et al. [22] considered a European wide supply chain with three manufacturing plants in three different countries, producing 14 different types of products and sharing production resources.

Santoso et al. [12] took two realistic supply chain problems as example. One is designing a domestic supply chain network for a US cardboard packages company; the other is designing a global supply chain network included United States and seven Latin American countries.

In cooperation with the Norwegian Meat Cooperative, Schuetz et al. [24] provided the model for the slaughter location case of Norwegian industry. The purpose of the work has been to reduce the number of slaughterhouses for cattle from an original number of 25 to utilize economies of scale.

TABLE II
APPLICATIONS IN SUPPLY CHAIN CONTEXT

Industry	Context	Solver	Implementation	Article
Generic Application	Case study	CPLEX 6.5	ILOG	[22]
Chemical	Case study	BARON and SBB	GAMS	[23]
Food	Case study	XPRESS-MP	Dash Optimization	[18]
Paper	Case study	CPLEX 7.0	C++	[12]
Food	Case study	XPRESS 2006	C++	[24]
Food	Case study	XPRESS-MP	Dash Optimization	[25]
Chemical	Industrial context	CPLEX	Virtecs of APC, CSIM18	[26]
Petro-chemical	Industrial context	XA or BDMLP LINDO for industrial size	GAMS	[27]
Energy	Industrial context	CPLEX 7.0	GAMS	[28]

Jung et al. [26] conducted the research with a case study based on an application provided by a major US polyethylene producer has been developed to examine the performance of the framework.

The chemical industry seems receiving much attention in supply chain management. Lababidi et al. [27] developed an optimization model for the supply chain of a petrochemical company under uncertain operating and economic conditions. A number of case studies were conducted to test the performance of the optimization model.

In the energy industry context, Kim et al. [28] considered modeling a hydrogen supply chain of Korea in the near future. Hydrogen is potential to become the major energy carrier in the future, thus designing logistics network for hydrogen is necessary.

In the category of industrial context, Yu and Grossman [23] presented two examples for the design of polystyrene supply chains. Two examples, one medium size, one large-scale in ten years planning horizon divided into three periods.

In food industry, Ferretti et al. [18] applied their model to a producer and distributor of milk products in Italy. Milk products have limited shelf life of product so it needs to be delivered within 24 hours in special vehicles for maintaining the right temperature.

VII. Concluding Remarks

It has been suggested that competition is no longer between companies but supply chains, which is being driven by cost pressures, increased consumer choice and shortening product life cycles. The conclusion is supported by the above reviewed researches: the number of researches in this area, of which with cost measurement. In the last ten year, because of the increasing of diversity in customer preference, the saturation of market, the subject of uncertainty in customer demand get more attention.

The need to change the way of regarding demand as deterministic to uncertainty is a good way for the modern organization to survive in today's environment. Such requirement is especially unvoidable in some situations like late product individulization proposed in [29] when customer requirements are more difficult to catch. That is why Li and

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Schulze [30] mentioned with emphasis of considering uncertainty in their further research of logistics network design for late auto individualization.

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