Chapter 16
Location Logistics in Supply Chain Management

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Abstract Location decisions play a key role in strategic logistics and supply chain management. In this chapter, we place the emphasis on the interaction of logistics activities and long-term supply chain decision-making on location logistics models. We cover modeling formulations of logistics core activities related to different industrial supply chain settings. In particular, we relate current challenges in supply chain management and their implications on relevant logistics activities. Finally, new research directions and areas of interest are provided.

16.1 Introduction

Since the 1960s many models developed in the context of location theory incorporate logistics aspects. For this reason they are also applicable for logistics and supply chain problems (see for example Melo et al. 2008). However, these inclusions have not always been systematic. In this chapter, we approach location decisions by starting from a logistics point of view and problem description. In particular we discuss logistics settings and their suitability for location models.

It is worth-noting that the terminology and the definitions in logistics are not as consistent and unified as in operations research. Many terms are used in practice before they are introduced into the academic literature. Therefore, we sometimes give our own or refine existing definitions. Whenever a specific reference is useful, we provide it. Nevertheless, we can directly list some sources where definitions and terms in logistics can be found: CSCMP (2013), Zijm et al. (2019) and Web Finance Inc. (2019).

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Location decisions in an industrial context imply the opening, the closing or the positioning of facilities. While the first and the second type of decisions focus on whether or not to open or close facilities such as production sites, distribution centers, or warehouses, positioning decisions refer to the location of suppliers, customers or facilities of similar or successive functions among each other. Those decisions have to be made whenever companies need to expand their capacities because they enter new markets or grow into new product segments. The ultimate reason for making these decisions, however, arises from the fact that facilities are not autonomous entities, but they have to interact with each other as well as with their environment. Due to this interaction, facility location problems are often cast as network design problems.

The activities that take place within a set of facilities include, for example, the shipment of raw material or finished goods from suppliers to production sites or from production sites to storage facilities or end-customers. The manufacturing or production, the storage and the handling of raw material and finished goods, take place within one facility. Nevertheless, they have to be coordinated among several locations. Generally, these activities are referred to as *logistics* and more precisely described as procurement and distribution, production or manufacturing, transportation, storage and handling, respectively (CSCMP 2013; Zijm et al. 2019; Web Finance Inc. 2019). Logistics activities that take place at a single location such as materials handling, forklift transportation and inventory management are referred to as *site logistics* or *on-site-logistics* (Logistik-Lexikon 2019). We define logistics activities that interact with other locations or that have to be coordinated among several locations as *location logistics*.

Facility location and allocation represent a core link between supply chain and logistics management. In the supply chain management literature it is also often referred to as supply chain network design. When considering a single location instead of a set of interacting locations that have to be coordinated, location selection is often referred to as *plant location*.

In order to leverage the efficiency of the resulting set of facilities, e.g. respect capacities, costs and availabilities, activities are subject to an overall logistics management, which is part of modern supply chain management.

We follow the Council of Supply Chain Management Professionals (CSCMP 2013) that defines Logistics Management as

> that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverses flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements.

For a definition of supply chain management we refer to CSCMP (2013) and for an in-depth discussion on the topic we refer to the review papers by Lummus and Vokurka (1999) and Mentzer et al. (2001). It is important to note that supply chain management differs from logistics management by important aspects: In addition to the planning and management of logistics activities supply chain management includes coordination and collaboration of business partners as well as integration of major business functions and business processes.

Table 16.1 Common terms used in supply chain management

Geographic	Granularity	Modeling	Management
Site	Site logistics	Plant location	Site management
(Supply chain) Locations	Location logistics	Facility location and allocation/supply chain network design	Logistics management
Supply chain	Supply chain logistics		Supply chain management

Due to the increased complexity of today's businesses supply chains should be called supply networks. For the remainder of this chapter we use the term supply chain and supply network interchangeably.

The terms used to refer to geographical entities, type of logistics granularities, strategic location selection modeling frameworks, and management paradigms are summarized in Table 16.1.

In this chapter, we discuss the interaction of logistics activities and challenges for supply chain management as well as the consequences when building a facility location model. The focus is on modeling aspects rather than on solution methods. Therefore we only consider literature relevant for such aspects.

The remainder of the chapter is organized as follows. Section 16.2 introduces logistics activities and their inclusion in location models. Section 16.3 provides a first integrated location model capturing relevant logistics aspects. In Sect. 16.4, some challenges of modern supply chain management are discussed and a mapping between each such challenges and the corresponding logistics activity is presented. Section 16.5 discusses extensions of the first integrated location model with respect to logistics activities and relevant challenges for supply chain management. Finally, in Sect. 16.6 further research directions are discussed.

16.2 From Logistics to Location Models

An adequate model for a facility location problem emerging in the context of logistics systems calls for a clear understanding of the fact that logistics activities and processes affect location decisions. Consequently, we must answer to some major questions prior to modeling and analyzing a problem, namely:

- Which logistics activities are to be considered?
- Which logistics activities must be integrated in a model?
- Which modeling paradigm is the most adequate given the nature of the underlying data?

We start this section by briefly discussing the aforementioned questions. Next, we present logistics elements for a facility location model in the context of supply chain management. We offer models and discuss the importance of each element.The last Paragraph is dedicated to the presentation of a first integrated location logistics model.

16.2.1 Why Logistics Matters in Location Modeling

Historically, researchers have focused relatively early on the design of distribution systems (Geoffrion and Powers 1995), but missed to consider logistics processes as interacting functions over the whole supply chain (Melo et al. 2009) as well as to analyze the importance of logistics activities for location models.

Somehow, it seems to be an unwritten rule that strategic decision making only considers those activities and processes that are either associated with high investments or not flexible enough to change when new circumstances demand for modifications. In the context of logistics, Daskin et al. (2005) among others, discussed how decisions on transportation and inventory may change within a short-to mid-term time frame, when relevant characteristics of the underlying supply chain indicate the necessity of such modifications. Production quantities can be modified in a mid-term time horizon, when material shortages or customers demands make it necessary. However, decisions on production capacities are typically fixed for longer time periods and they are less flexible. Consequently, they are considered in strategic decision making. The investments associated with the installation of new production plants are usually high compared to those of transportation or inventory. It seems natural, though, that investments on production facilities are included in strategic location models. In fact, the relocation of a production plant due to changes in customer demands, transportation costs, or component prices is hardly acceptable (Daskin et al. 2005). Moreover, the relocation of production facilities is often expensive and nearly impossible except in the long-term. Finally, modern distribution centers containing highly technologized–thus expensive–material handling equipment or transportation hubs such as airports are difficult or even impossible to relocate (Daskin et al. 2005). General aspects of logistics planning with time dependent decisions are discussed in Dunke et al. (2018).

The main conclusion to be derived from this discussion is that making location decisions ignoring primary logistics activities like production or distribution, may result in excessive costs incurred throughout the lifetime of the facilities supporting the logistics system. Inefficiencies and excessive costs, however, may be a consequence of other aspects. For instance, transportation costs may raise or labor costs may evolve differently from what was expected. Additionally, inventory holding costs may increase due to unexpected changes of interest or exchange rates. Overall, a logistics planning ignoring relevant logistics activities may lead to bad location decisions. In fact, apart from production, the location decisions made for a logistics network carry out all logistics activities in one way or another. Decisive for facility location modeling, however, is the way logistics activities are taken into account.

The logistics tasks of a facility in a supply chain can be manifold. It can be a raw material plant, a production plant, a warehouse, a transshipment center, a hub, or even a retailer. Despite its major logistics function each location often fulfills a number of additional logistics activities, which need to be respected and sometimes integrated in location models (Cordeau et al. 2006). Before formulating a location decision model, it is necessary to analyze the industrial setting in which the underlying supply chain is or will be operated as well as the business objectives the supply chain is exposed to. Sometimes it is not necessary to integrate all existing logistics activities—at least not in every detail.

Consider as an example a set of production sites engaged in the chemical industry. In this case, raw material and finished products are often stored in silos, whose capacities can vary over time since whenever a silo becomes empty it can be used for another product. However, when a silo is not empty it can only be used for the product it is already filled with. It is very complex to model this type of inventory management. Nevertheless, this may not be relevant if decision makers conclude, that silo capacities are not determinant for an opening, closing or positioning decision. Silos may be assumed to be at any production site with the necessary capacity. In other words, a decision maker might decide to leave the inventory management aspects out of the location model.

This motivates another important aspect when modeling location logistics for supply chain management: the appropriate way for modeling logistics activities. Facilities as elements of the supply chain are often globally dispersed with separated data bases and different logistics operation modes. This complicates the availability, accuracy, and thus the reliability of information and data needed for building a facility location model. Additionally, globally spread facilities are exposed to numerous environmental, cultural and infrastructural uncertainties that provoke changes in information that often is assumed to be deterministic. In order to avoid that a set of efficient sites suddenly becomes inefficient, uncertainty influencing logistics activities should be taken into account in advance. The nature and type of data uncertainty is however in itself uncertain and decisively affects the modeling paradigm that should be considered. Uncertainty in data can be tackled using different tools such as stochastic programming, chance-constrained programming, or robust optimization (see Chap. 8). The paradigm to consider strongly depends on the nature of the uncertainty.

16.2.2 Building Blocks of Logistics

From the discussion presented so far we conclude that the traditional hierarchical planning sequence starting with the strategic decisions, then tactical and finally operational may lead to low quality, conflicting or even infeasible decisions. The challenge lies in the integration of the three planning levels in order to find feasible and good decisions for logistics execution.

Integrated facility location problems may turn into large-scale complex optimization problems that call for sophisticated solution methods. In the light of location problems, a common approach to overcome such difficulties is to split larger problems into smaller sub-problems (Stadtler 2008). Unfortunately, such approaches may lead to sub-optimal solutions. However, while technology is further developing and new solution techniques for nonlinear and large-scale linear mathematical models evolve, increasingly larger integrated planning problems become more tractable (Zanjirani Farahani et al. 2015).

Next we take a close look on prominent logistics activities, namely: procurement (or inbound logistics), production (or assembly or manufacturing), inventory (and handling), routing and distribution (or transport), as well as layout.

In what follows we assume that we have a finite planning horizon divided into several time periods. Additionally, we consider a set of customers whose demand (known for all periods) is to be supplied throughout the planning horizon. We consider the possibility of having a service level below 100%. This may be due to high costs associated to some demand satisfaction, shortage of production capacity or service times impossible to fulfill. In an optimization model, unsatisfied demand is often accounted for by introducing a penalty in the objective function. Finally, we note the multi-commodity nature of many logistics systems. Hence, production capacity and resource availability must be balanced across the different products or commodities.

16.2.2.1 Procurement

Procurement or inbound logistics, is an activity that focuses on the acquisition of goods needed for production, assembly or manufacturing. Typically the amount acquired from suppliers as well as related variable costs and fixed costs describe the procurement activity. Nevertheless, before procurement activities can even begin, strategic decisions such as the selection of suppliers based on their solvency as well as quality and availability of goods have to be made.

Supplier selection represents often, by itself, a decision to make. However, some qualitative aspects should also be integrated in models tailored for location logistics in supply chain management. Solvency and product quality can be integrated by including supplier-dependent penalty costs or reward terms in the objective function. Nevertheless, the availability of goods is often captured via a capacity constraint that limits the amount that a location can purchase from a specific supplier.

From a supply chain management perspective, the type of product and the company-specific logistics requirements are important aspects to analyze up-front, because they can have an impact when modeling the aforementioned aspects. For instance, if the products involved in a supply chain require a sparse bill-of-materials (BOM), or if only a few suppliers exist, it becomes relevant to consider supplier shortages in a model. Accordingly, attention should be given to product type, technology knowledge, available capacity, initial investment required, and specific logistics requirements before integrating procurement relevant formulations in the location model (Simchi-Levi et al. 2007).

Although capturing procurement is recognized as a vital element in supply chain management (Kraljic 1983), it is rarely present in the facility location literature (see Melo et al. 2009; Zijm et al. 2019).

16.2.2.2 Production

Production activities transform one or several materials or components into one or several products. They include the production from raw materials as well as the assembly of several products to one final product. Note that we consider production as part of logistics without the special aspects of production technology. Similarly to procurement, production activities are described by an amount produced as well as related variable and fixed costs. Often specific limits for the production capacities are given. In addition, the production process itself can be further described by consumption factors provided by the BOM. They represent the amount of materials needed for the production of one unit of a product. Resource capacities such as those induced by production lines in a discrete production setting or capacities of converters in a continuous setting and occasionally surplus capacity provide a more detailed description of the necessary production infrastructure. Typically, a capacity constraint has to be considered limiting the production. For further reading we refer to Esmaeilian et al. (2016).

16.2.2.3 Inventory

The main functionality of storing materials, components, semi-finished or finished products is the decoupling of precedent or successive logistics activities such as sourcing, production and distribution facilitating the planning of such activities. During the decoupling period, material, goods and products have to be stored at production sites, warehouses, or distribution centers resulting in inventory costs. The consumption of stored products is generally formulated as inventory balancing constraints. In the light of industrial (and even civil or public) supply chain management, inventory models have to include decisions on safety stocks, re-order points, turnovers, and service levels. A relevant issue when developing a model for supporting decision making, is to describe centralized and decentralized inventory systems, to capture lead times or safety stocks, and to integrate multi-layer supply chains in a multi-period setting.

For a deeper discussion of logistics activities related to inventory as well as model formulations tailored for location-inventory problems, we refer to Melo et al. (2009) and Zanjirani Farahani et al. (2015).

16.2.2.4 Routing and Distribution

Routing and distribution—transportation in general—can take place between all entities within a supply chain. Material and products are transported from one location to another in distinct time periods and at certain costs. Besides distance, the level of transportation costs depend on the type of product and on the transportation mode. In the facility location literature, most often trucks or airplanes are considered. In the particular case of road transportation, two possibilities exist: full-truck-load (FTL) and less-than-full-truck-load (LTL). Decision-makers often favor FTL. However, when delivery becomes urgent (production may stop or customer service level is at risk) LTL may be necessary. At an operational level (e.g. short-term decisions) discounts for larger volumes play an important role. In this case, the cost curve is often non-linear (concave). However, in a strategic setting, a linear approximation is in most cases sufficient. The shipping from and the entrance of transported products at a facility is generally formulated using balancing constraints.

While transportation is a concept describing the movement of goods in general, distribution refers to the allocation of material or goods to the end user of material or goods and routing refers to the determination of the optimal path to serve a group of customers. Routing and distribution decisions have been extensively discussed in location theory because they integrate two major decisions: location and routing. For more details we refer to Nagy and Salhi (2007) as well as to Chap. 15.

16.3 A Basic Integrated Logistics Location Model

Following the aforementioned logistics activities we introduce a basic integrated logistics location model, $BILL$, as a mixed-integer linear program. The $BILL$ model considers capacities of different logistics activities as well as multiple products. It assumes that there is an underlying planning horizon divided into several time periods. Additionally, several general non-hierarchical levels are considered. The model includes decisions about location, procurement and production, inventory and distribution as well as customer demand fulfillment. It takes into account costs for procurement and production, inventory (stock-level and stock-turnover), installation and closing of facilities, transportation and non-fulfillment of customer demand. The overall objective of the model is to minimize the total cost. All entities of a supply chain—whether they belong to the same organization or not—can be divided into so-called *selectable* and *non-selectable* facilities (see e.g. Melo et al. 2006). Selectable facilities are those that may have their status changed. Non-selectable facilities cannot have their status changed.

The mathematical formulation is presented in Sect. 16.3.2 and captures the aforementioned features. The required notation is first introduced in Sect. 16.3.1.

16.3.1 Notation

Table 16.2 presents the sets used in the $BILL$ model.

Table 16.3 introduces the parameters related to both tactical logistics activities and strategic location decisions. Besides the demand requirements, we need input for capacity resources. Each product consumes a certain share of the overall resource capacities. Similarly, handling capacities are taken into account. we assume that resource capacities can be expanded at additional costs. Extra handling capacity

Table 16.2 Sets used for the *BILL* model

Set	Description
L	Locations
S	Selectable locations
S^o	Selectable facilities that can be opened
S^c	Existing selectable facilities that can be closed
T	Time periods
P	Products
R^p	Production resources
R^h	Handling resources

Table 16.3 General parameters for the *BILL* model

Symbol	Description
d_{ipt}	Demand of location $i \in L$ for product $p \in P$ in period $t \in T$
a_{iqp}	Number of units of product $q \in P$ required to produce one unit of product $p \in P$ ($q \neq p$) at facility $i \in L$
μ_{irp}	Amount of resource $r \in R^p$ required to produce one unit of product $p \in P$ in facility $i \in L$
$\lambda_{irp}^{in}, \lambda_{irp}^{out}$	Amount of resource $r \in R^h$ required to handle one unit of product $p \in P$ upon its entrance at and its shipment from facility $i \in L$, respectively
K_{rt}	Initial capacity of resource $r \in R^p \cup R^h$ in period $t \in T$
K_{rt}^e	Maximum capacity expansion of resource $r \in R^p \cup R^h$ in period $t \in T$

can be made available through overtime work or outsourcing (e.g. via external service providers). Additional storage or production capacities can be acquired by purchasing or leasing additional space or production lines.

There are three different ways of modeling the relationship between facilities and resources. In a *one-to-many* relationship, the same resource is used at several facilities. This is the case, for instance when a production manager is responsible for several production lines in different facilities. A *one-to-one* relationship represents the situation where the same resource is used by all the products of a facility. Typical examples include a foiling machine or a storage place. In a *many-to-one* relationship, several resources are used at the same facility. A set of resources can be product-specific and a different set of resources can be used for multiple products. The former is the case, for instance when a machine is dedicated to a particular product; the latter refers for example to a production manager or a picking system.

In Table 16.4 cost parameters are introduced. Finally, Table 16.5 presents the decision variables of the problem.

16.3.2 The BILL Model

The objective function to be minimized includes the total cost for procurement and production, distribution, inventory, penalty for unsatisfied demand, opening for new

Table 16.4 Cost parameters for the $BILL$ model

Symbol	Description
OC_{it}	Fixed cost for opening a facility in location $i \in S^o$ at the beginning of period $t \in T$. This parameter includes the operation costs until the end of the planning horizon
CC_{it}	Fixed costs for closing a facility in location $i \in S^c$ at the end of period $t \in T$. This parameter includes the operation costs until the end of t
XC_{ipt}	Unit penalty cost for not serving demand of facility $i \in L$ for product $p \in P$ in period $t \in T$
BC_{ipt}	Unit cost for buying/procuring product $p \in P$ at facility $i \in L$ from an external source in period $t \in T$
PC_{ipt}	Unit cost for producing product $p \in P$ at facility $i \in L$ in period $t \in T$
HC_{ipt}	Unit cost for holding/storing product $p \in P$ at facility $i \in L$ in period $t \in T$
TC_{ijpt}	Unit cost for shipping product $p \in P$ from facility $i \in L$ to facility $j \in L$ in period $t \in T$
EC_{rt}	Unit cost of expanding resource $r \in R^p$ or handling resource $r \in R^p \cup R^h$ in period $t \in T$

Table 16.5 Decision variables for the $BILL$ model

Symbol	Description
y_{it}	Binary variable equal to 1 if facility $i \in S^o$ is opened at the beginning of period $t \in T$ and 0 otherwise
y_{it}	Binary variable equal to 1 if facility $i \in S^c$ is closed at the end of period $t \in T \setminus \vert T\vert$ and 0 otherwise
$y_{i\vert T\vert}$	Binary variable equal to 1 if facility $i \in S^c$ is kept open during the entire planning horizon, 0 otherwise
φ_{ipt}	Quantity of unsatisfied demand of location $i \in L$ for product $p \in P$ in period $t \in T$
b_{ipt}	Quantity of product $p \in P$ procured from facility $i \in L$ from an external source in period $t \in T$
X_{ipt}	Quantity of product $p \in P$ produced at facility $i \in L$ in period $t \in T$
h_{ipt}	Quantity of product $p \in P$ stored at facility $i \in L$ in period $t \in T$
x_{ijpt}	Quantity of product $p \in P$ shipped from facility $i \in L$ to facility $j \in L$ in period $t \in T$
w_{rt}	Extra capacity to acquire of production resource $r \in R^p$ or handling resource $r \in R^h$ in period $t \in T$

facilities and removal of existing ones.

$$
\begin{aligned}
\min \; & \sum_{t\in T}\sum_{i\in L}\sum_{p\in P}(BC_{ipt}b_{ipt} + PC_{ipt}X_{ipt}) + \\
& \sum_{t\in T}\sum_{i,j\in L, i\neq j}\sum_{p\in P} TC_{ijpt}x_{ijpt} + \\
& \sum_{t\in T}\sum_{r\in R^h\cup R^p} EC_{rt}w_{rt} +
\end{aligned}
$$

$$\sum_{t\in T}\sum_{i\in L}\sum_{p\in P} HC_{ipt}h_{ipt} + \tag{16.1}$$

$$\sum_{t\in T}\sum_{i\in L}\sum_{p\in P} XC_{ipt}\varphi_{ipt} +$$

$$\sum_{t\in T}\sum_{i\in S^o} OC_{it}y_{it} + \sum_{t\in T}\sum_{i\in S^c} CC_{it}y_{it}$$

The flow conservation constraints balance incoming amounts with the outgoing amounts of each logistics activity, production and procurement, transportation, inventory and demand. They can be written as follows:

$$b_{ipt} + \sum_{j\in L, i\neq j} x_{jipt} + X_{ipt} + h_{ipt-1} =$$

$$\sum_{j\in L, i\neq j} x_{ijpt} + \sum_{q\in P} a_{iqp}X_{iqt} + h_{ipt} + d_{ipt} - \varphi_{ipt} \quad i \in L, p \in P, t \in T \tag{16.2}$$

Capacity constraints are necessary for limiting the resources consumption of different logistics activities, namely for production and handling as well as their expansions. Mathematically we can write:

$$\sum_{i\in L}\sum_{p\in P} \mu_{irp}X_{ipt} \leq K_{rt} + w_{rt} \quad r \in R^p, t \in T \tag{16.3}$$

$$\sum_{p\in P}\left(\sum_{i,j\in L, i\neq j} (\lambda^{in}_{jrp} + \lambda^{out}_{jrp})x_{ijpt} + \sum_{i\in L} \lambda^{in}_{irp}b_{ipt}\right) \leq K_{rt} + w_{rt} \quad r \in R^h, t \in T \tag{16.4}$$

$$0 \leq w_{rt} \leq K^e_{rt} \quad r \in R^p \cup R^h, t \in T \tag{16.5}$$

The selectable facilities can have their status changed at most once during the planning horizon. Formally we have:

$$\sum_{t\in T} y_{it} \leq 1 \quad i \in S^o \tag{16.6}$$

$$\sum_{t\in T} y_{it} = 1 \quad i \in S^c \tag{16.7}$$

Furthermore, for $i \in S$ and $t \in T$ we define:

$$T_i^t = \begin{cases} \{1, \ldots, t\}, & \text{if } i \in S^o. \\ \{t, \ldots, T\}, & \text{if } i \in S^c. \end{cases} \tag{16.8}$$

This helps writing constraints ensuring that the logistics activities are limited by their capacities but in those facilities that are operating:

$$b_{ipt} \leq M \sum_{\tau \in T_i^t} y_{i\tau} \quad i \in L, p \in P, t \in T \tag{16.9}$$

$$X_{ipt} \leq M \sum_{\tau \in T_i^t} y_{i\tau} \quad i \in L, p \in P, t \in T \tag{16.10}$$

$$h_{ipt} \leq M \sum_{\tau \in T_i^t} y_{i\tau} \quad i \in L, p \in P, t \in T \tag{16.11}$$

$$x_{ijpt} \leq M \sum_{\tau \in T_i^t} y_{i\tau} \quad i, j \in L, p \in P, t \in T \tag{16.12}$$

$$x_{jipt} \leq M \sum_{\tau \in T_i^t} y_{i\tau} \quad i \in L, j \in L \setminus \{S\}, p \in P, t \in T \tag{16.13}$$

The model is concluded by the domain constraints:

$$h_{ip0} = 0 \quad i \in L, p \in P \tag{16.14}$$

$$b_{ipt}, h_{ipt}, h_{ipt} \geq 0 \quad i \in L, p \in P, t \in T \tag{16.15}$$

$$0 \leq \varphi_{ipt} \leq d_{it} \quad i \in L, p \in P, t \in T \tag{16.16}$$

$$x_{ijpt} \geq 0 \quad i, j \in L, p \in P, t \in T \tag{16.17}$$

$$y_{it} \in \{0, 1\} \quad i \in L, t \in T \tag{16.18}$$

Computationally, the above problem is NP-hard since it generalizes the capacitated plant location problem (see Chap. 4). Nevertheless, the existing literature shows that it can be tackled within an acceptable CPU time using a general purpose solver for small- and medium-sized instances. For larger instance we may have to resort to heuristic algorithms (see Melo et al. 2008, 2012, 2014).

16.4 Challenges in Industrial Logistics

The management of logistics activities operates in an environment that is usually set by corporate supply chain strategies. The latter follow business strategies that nowadays are influenced by upcoming new information and production technologies, new business opportunities, and new political as well as environmental changes. Consequently, supply chain management has become a major strategic issue for every company involved in the efficient processing of value creation—be it through products or services. Trends in the economy and society resulting from computerization, increased complexity and uncertainty of trade flows, increased competition. These facts together with the need for sustainable developments, has resulted in major big structural as well as organizational effects on supply chain designs (Eskandarpour et al. 2015).

It turns out that currently the major challenges in supply chain management are sustainability, uncertainty and the digital transformation of the supply chain (Garcia and You 2015; Kache and Seuring 2017). The aim of this section is to discuss these major research streams. It is not the goal in this chapter to discuss in detail every obstacle that hinders efficient supply chain management in general and location logistics in specific.

16.4.1 Sustainability

One of the current trends and challenges in supply chain management is the design and operation of sustainable supply chains. In this context, three dimensions can be considered: economic aspects, environmental (green) performance and social responsibility (Eskandarpour et al. 2015). The increasing interest in sustainable development has pushed supply chains to be sustainable as well: Nowadays, they have to be socio-political aware, ecologically sensitive, and green.

Until some time ago, repair and container logistics stood in the foreground when it came to plan and manage a supply chain. More recently, reverse logistics and reusable logistics have started playing a greater role due to the increase in customer expectations.

We do not go further into that topic since there is a complete chapter in this book devoted to green logistics (see Chap. 20). Nevertheless, in the following sections we provide another model related to sustainability.

16.4.2 Uncertainty, Risk and Disaster Events

Decision-making in industrial supply chain management calls for information about future developments (e.g. demand and lead-time forecast, spot prices for transportation and inventory). A major concern for the achievement of any business goal, including that of a supply chain system or a logistics task, is the treatment of uncertainty. Usually a decision maker has a certain amount of information about future developments. Customers demands for example most often slightly deviate from the initial outlook. In an industrial context, modern supply chains have evolved into transnational systems and since then they are often caught in a crossfire of influences (e.g., political, environmental) that are hardly predictable. Additionally, in the presence of the continuously increasing fierce competition for customers and their profitable satisfaction, supply chain management needs to account for numerous optimization criteria and different information sources that are all subject to uncertainty. This evolution has led to a wider range of uncertainty to be dealt with. The lack of a good uncertainty management becomes visible when unexpected incidents interfere with the normal operation of the supply chain. For instance, natural disasters such as earthquakes, can destroy production facilities or roads, and impede the possibility to satisfy customer’s needs as promised. Similarly, effects are triggered by socio-economic or socio-political turmoils. Unpredictable and slightly aggravating deviations, e.g. lead time increase, exchange rate fluctuations or oil price variability, may also affect supply chain's goal achievement.

Unknown deviations, supply chain disruptions and disasters as well as the supply chain risk impede the availability of resources, the realization of the plan, and ultimately, the satisfaction of demand. For an in depth discussion of the different concepts we refer to Heckmann et al. (2015) and Heckmann (2016). In order to anticipate these perils, supply chain models need to be endowed with the information about uncertain developments. Different types of models, capturing both different types of decisions and uncertainty, exist (Melo et al. 2009).

The consideration of uncertainty, risk, or disasters that have the potential to impede a supply chain goal achievement is carried out within different research streams. One such stream emerges in the context of facility location and focuses on disaster prevention and management (see Chap. 22). For general uncertainty extensions the reader is referred to Chap. 8. Instead of going into detail concerning these extensions we concentrate in Sect. 16.5.2 on capturing and quantifying supply chain risk in facility location models.

16.4.3 Digital Supply Chain Transformation and Supply Chain Integration

Contemporary supply chains evolved into highly stretched and interdependent systems (Christopher 2016). The variety of products, suppliers and customers, who constantly emerge with new and demanding expectations, has increased tremendously. The possibility to integrate logistics as well as other supply chain related activities has reached its limits—as stated at the annual meeting of the World Economic Forum (WEF) by global chief executives WEF (2017). Influences of Industry 4.0 and IoT on supply chain planning are starting to be considered in scientific papers. See for example Manavalan and Jayakrishna (2019), Müller et al. (2019) and references therein. The new aspects emerging increase immensely the complexity of the systems and limit most of the originally laid-out infrastructures. Accordingly, the WEF asks for new forms of structural and organizational agility that offers better supply chain visibility. Instruments for automated data identification (Auto-ID/RFID) and the intelligent integration of systems, assemblies, and sensors into higher-level value networks, allow to continuously acquire and process data. In turn, this provides data and information for the decision making process on different scales: online, operational, tactical and strategic. Note, however, that these technologies could not yet be leveraged to the fullest possible extent. Once this is accomplished, supply chain integration will also change.

The best way for integrating a network is still an ongoing discussion. For instance, it can be done by acquiring new supply chain entities, activities or products (e.g. through direct acquisitions or joint ventures). Alternatively, in the case of many enterprises, outsourcing emerges as a possibility to consider. Since this discussion is still evolving many concepts and methodological approaches are still to be adequately framed.

Network integration approaches including outsourcing and joint ventures are very specific and depend on the circumstances as well as the current environment. Nevertheless, we can find several authors discussing these aspects such as Babazadeh et al. (2013), Johansson and Olhager (2018), Wilhelm et al. (2013) and Dou and Sarkis (2010).

16.5 Modeling Formulations for Industrial Location Decisions

There is no one-to-one solution, in terms of modeling formulation capturing the emerging challenges faced by supply chain management. However, there are facility location models available that address some well-framed sub-problems in this context. In Table 16.6 we present some of these challenges and some related aspects.

In the following we give two examples for location models addressing each one of the challenges in sustainability and uncertainty. Of course we are not able to provide in a book chapter all the details, but we decided to state always a complete model, which can be used in courses or for learning by the example. For a deeper understanding we cite the respective references.

16.5.1 Reverse Logistics

Reverse logistics and closed-loop supply chain have become a major area of supply chain management. Contrary to forward or traditional logistics which considers material flows from upstream to downstream of a value chain, reverse logistics refers to all operations related to the reuse of products.

According to Srivastava (2007) most often the model formulation relies on single economic objectives and miss to explicitly address environmental and social dimensions. The resolution of this mismatch can lead to sustainable supply chains. In this section we revisit a general facility location logistics model for reverse

Table 16.6 Some challenges faced by supply chain management and related topics

Sustainability	Uncertainty	Digital transformation
Reverse logistics	Interdiction and fortification	Collaboration
Supply sourcing	Supply chain risk	Network integration
Carbon footprint	Multi-period decision making	“Infinite” labor
Green supply chain	Multiple-criteria decision making	Organizational agility

logistics. This is a model fist introduced by Alumur et al. (2012) (see also Alumur et al. 2015).

Reverse logistics focuses on one of the first and still important objectives of sustainable supply chains: waste disposal. Additionally, it also includes what we can call return logistics and repair logistics as well as container and returnable container logistics (pallets, lattice boxes, small load carriers and reusable containers).

Following the Council of Supply Chain Management Professionals, reverse logistics is the process of moving goods from their typical final destination for the purpose of capturing value, or proper disposal (CSCMP 2013).

Before discussing an optimization model for reverse logistics ($RLND$) we introduce some notation. We make use of notation introduced in the context of the $BILL$ model presented in Sect. 16.3.1. Note, that the latter is introduced as a multi-period model and the $RLND$ model presented below as a single-period one.

We consider multiple products which include used, inspected, repaired or refurbished products, components, or raw materials. In order to take different states into account (inspected, repaired, refurbished, etc.), different product states need to be defined.

A recovery option describes an activity that transfers a product from one state to another. It includes all options related to real-life reverse logistics networks such as returns, recalls, repair, refurbishment, and recycle as well as non-recovery alternatives such as inspection, disassembly, repackaging for restock or resale, selling to suppliers, to the secondary market or to external (re)manufacturing facilities, and disposal. The latter alternative is operated by third-party logistics providers, which are external and therefore represent non-selectable facilities (see Alumur et al. 2015). Table 16.7 introduces the sets underlying the $RLND$ model.

Table 16.8 describes the parameters underlying the model. We highlight, in particular, parameters that represent the reverse BOM structure. For example, a damaged product can be converted into a repaired product through the recovery option repair. Another possibility is to have a used product disassembled into its components at a disassembly facility. Each recovery option has a given capacity which can be expanded at selectable facilities. Revenues may be obtained through some recovery options, e.g., by selling products or components to recycling facilities, to the secondary market, or to external (re)manufacturing facilities. Some

Table 16.7 Sets considered for the $RLND$ model is addition to those already presented for the *BILL* model

Set	Description
R	Recovery options
I_r	Selectable facilities with recovery option $r \in R$
E_r	Existing facilities with recovery option $r \in R$
N_r	Potential locations for installing recovery option $r \in R$
J_r	Non-selectable location with recovery option $r \in R$ (secondary market, disposal)
L	All locations, $L = \cup_{r \in R} (I_r \cup J_r)$

Table 16.8 New general parameters used for the $RLND$ model

Symbols	Description
g_{ip}	Amount of product $p \in P$ generated at location $i \in L$
a_{rqp}	Number of units of product $q \in P$ required to produce one unit of product $p \in P$ $(q \neq p)$ using recovery option $r \in R$
K_{ri}	Capacity of recovery option $r \in R$ at location $i \in L$
K_{ri}^e	Maximum increase in capacity for recovery option $r \in R$ at location $i \in I_r$
RT_{rp}	Target amount of products $p \in P$ with recovery option $r \in R$

Table 16.9 New cost parameters used for the $RLND$ model

Symbols	Description
RE_{rip}	Revenue from recovering one unit of product $p \in P$ with recovery option $r \in R$ at location $i \in L$
RC_{rip}	Cost of recovering one unit of product $p \in P$ with recovery option $r \in R$ at location $i \in L$
FC_{ri}	Fixed setup cost of establishing recovery option $r \in R$ at location $i \in N_r$
CC_{ri}	Fixed cost of closing recovery option $r \in R$ at existing facility $i \in E_r$
OC_{ri}	Fixed cost of operating recovery option $r \in R$ at location $i \in L$
EC_{ri}	Unit cost of expanding capacity of recovery option $r \in R$ at location $i \in I_r$

Table 16.10 New decision variables used for the reverse logistics model

	Description
y_{ri}	Binary variable equal to 1 if recovery option $r \in R$ is operated at the selectable facility $i \in I_r$ and 0 otherwise
v_{rip}	Amount of product $p \in P$ recovered with recovery option $r \in R$ or collected at location $i \in L$
w_{ri}	Extra capacity established for recovery option $r \in R$ at location $i \in I_r$

recovery options may also incur costs as in the case of product disposal (see Alumur et al. 2015).

Table 16.9 introduces the cost parameters for the $RLND$ Model.

In Table 16.10 we present the decision variables. While in the $BILL$ model the decision variable y refers to the opening or closing of a location, in the $RLND$ model it refers to the selection of a recovery option. Similarly, decision variable w defines extra capacity for a production resource in the $BILL$ model and it defines extra capacity for the recovery option in the $RLND$ model.

The $RLND$ model can be formulated as a MILP. Its objective function (16.20) maximizes the total profit, which sums up the revenues of various recovery options and subtracts the costs involved in the system.

$$
\begin{aligned}
\max \quad & \sum_{r\in R}\sum_{i\in L}\sum_{p\in P} RE_{rip}v_{rip} \\
& - \sum_{r\in R}\sum_{i\in L}\sum_{p\in P} RC_{rip}v_{rip} - \sum_{r\in R}\sum_{i\in N_r} FC_{ri}y_{ri} \\
& - \sum_{r\in R}\sum_{i\in E_r} CC_{ri}(1-y_{ri}) - \sum_{r\in R}\sum_{i\in I_r} OC_{ri}y_{ri} \qquad (16.19) \\
& - \sum_{r\in R}\sum_{j\in J_r} OC_{rj} \\
& - \sum_{i\in L}\sum_{j\in L\setminus\{i\}}\sum_{p\in P} TC_{ijp}x_{jip} - \sum_{r\in R}\sum_{i\in I_r} EC_{ri}w_{ri}
\end{aligned}
$$

The flow balance equalities (16.20) relate incoming flows like products shipped to a location and the amount of product obtained after processing at a location with outgoing flows like products recovered at a location and products shipped to other locations. The recovery target for each product category and recovery option should be achieved due to constraint (16.21). Inequalities (16.22)–(16.24) restrict capacities. The former guarantees that the amount of recovered products at selectable facilities does not exceed the available capacity. Inequality (16.23) formulates a similar conditions for non-selectable facilities. Constraints (16.24) limit the level of capacity expansions at selectable facilities. Constraints (16.25) and (16.26) ensure that products can only be shipped from operating facilities. Conditions (16.27)–(16.29) set the domains of the decision variables.

$$
\text{s.t.} \quad g_{ip} + \sum_{r\in R}\sum_{q\in P} a_{rqp}v_{riq} + \sum_{j\in L\setminus\{i\}} x_{jip} = \sum_{r\in R} v_{rip} + \sum_{j\in L\setminus\{i\}} x_{ijp} \quad i\in L, p\in P \qquad (16.20)
$$

$$
\sum_{i\in L} v_{rip} \geq RT_{rp} \quad r\in R, p\in P \qquad (16.21)
$$

$$
\sum_{p\in P} v_{rip} \leq K_{ri}y_{ri} + w_{ri} \quad r\in R, i\in I_r \qquad (16.22)
$$

$$
\sum_{p\in P} v_{rjp} \leq K_{ri} \quad r\in R, i\in J_r \qquad (16.23)
$$

$$
0 \leq w_{ri} \leq K^e_{ri}y_{ri} \quad r\in R, i\in I_r \qquad (16.24)
$$

$$0 \leq x_{ijp} \leq \mathscr{M} \sum_{r \in R} y_{ri} \quad i \cup_{r \in R} I_r,\ j \in L \setminus \{i\},\ p \in P \tag{16.25}$$

$$0 \leq x_{jip} \leq \mathscr{M} \sum_{r \in R} y_{ri} \quad j \in L \setminus \{i\}, i \cup_{r \in R} I_r,\ p \in P \tag{16.26}$$

$$x_{ijp} \geq 0 \quad i, j \in \cup_{r \in R} J_r (i \neq j),\ p \in P \tag{16.27}$$

$$v_{rip} \geq 0 \quad r \in R, i \in L, p \in P \tag{16.28}$$

$$y_{ri} \in 0, 1 \quad r \in R, i \in I_r \tag{16.29}$$

Again, this problem contains as a special case the CFLP. For more details and solution approaches concerning this and related problems we refer the reader to Alumur et al. (2012), Alshamsi and Diabat (2015), Chen et al. (2015), Govindan et al (2015), Khatami et al. (2015).

16.5.2 Supply Chain Risk

While uncertainty definitely is an important topic also in reverse logistics, we show in this section how to explicitly model uncertainty in a location model by addressing the notion of supply chain risk.

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 the topic concluded that supply chain risk can be defined by three elementary characteristics, namely: risk objective, risk exposition, and risk attitude (Heckmann et al. 2015). A risk-aware capacitated plant location model ($CPLP^{Risk}$) aims at overcoming systematic definitional inconsistencies and offers a risk-aware location formulation founded on the general capacitated plant location problem ($CPLP$) (Heckmann 2016).

If uncertainty can be captured by a joint CDF, a model incorporating uncertainty and risk can often be formulated as a two-stage stochastic program (see Chap. 8). The 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. 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 plus the expected costs of the second stage decision. In what follows we assume that uncertainty can be captured by a finite number of scenarios each of which occurring with some probability that we also assume to be known in advance.

Table 16.11 introduces the sets underlying the $CPLP^{Risk}$ model.

Table 16.12 contains the deterministic and stochastic parameters underlying the model.

Table 16.13 presents the cost parameters.

In Table 16.14 we present the decision variables, which are similar to those introduced in the context of the *BILL* model.

Table 16.11 Sets used for the $CPLP^{Risk}$ model

Set symbol	Description
I	Facilities
J	Customers
T	Time periods
H	Expansion levels
S	Scenarios

Table 16.12 General deterministic and stochastic parameters for the $CPLP^{Risk}$ model

Symbol	Description
d_{jts}	Demand of customer j in period t under scenario s
β^o	Level of targeted service level
K_i	Capacity of facility i
K_h^e	Extra capacity of expansion level h
γ_{its}	Relative capacity reduction within facility i in time period t and scenario s
π_s	Probability associated with scenario s

Table 16.13 Cost parameters for the $CPLP^{Risk}$ model

Symbol	Description
OC_i	Fixed cost of opening a facility in location $i \in I$
EC_i^o	Fixed cost of installing optional extra-capacity at facility i
TC_{ij}	Unit transportation cost between facility i and customer j
R_j	Unit revenue provided by customer j
XC	Unit penalty cost for not reaching target service level
EC_h	Unit cost of extra-capacity of expansion level h

Table 16.14 Decision variables for the $CPLP^{Risk}$ model

Symbol	Description
y_i	Binary variable equal to 1 iff facility i is opened
z_i	Binary variable equal to 1 iff expansion options are installed at facility i
x_{ijts}	Amount transported from facility i to customer j in time period t under scenario s
φ_{jts}	Unsatisfied demand of customer j in time period t under scenario s
ω_{iths}	Binary variable equal to 1 iff in scenario s expansion level h is installed at facility i at time period t
β_s	Service level in scenario s
Δ_s	Service level reduction in scenario s

The $CPLP^{Risk}$ model can be formulated as a MILP. Its objective function (16.30) minimizes the total costs, which sums up the costs related to the first-stage decision and costs associated to the recourse decision which are offset or decreased by the revenue.

$$\min \sum_{i\in I}\left(OC_i y_i + EC_i^o z_i\right) + \tag{16.30}$$

$$\sum_{s\in S}\pi_s\left(XC\Delta_s + \sum_{i\in I}\sum_{h\in H} EC_h K_h^e \sum_{t\in T}\omega_{iths} + \sum_{t\in T}\sum_{i\in I}\sum_{j\in J}\left(TC_{ij} - R_j\right) d_{jts} x_{ijts}\right)$$

$$\text{s.t.} \quad \sum_{i\in I} d_{jts} x_{ijts} + \varphi_{jts} = d_{jts} \quad j \in J, t \in T, s \in S \tag{16.31}$$

$$\sum_{j\in J} d_{jts} x_{ijts} \le \gamma_{its} K_i y_i + \sum_{h\in H} K_h^e \omega_{iths} \quad i \in I, t \in T, s \in S \tag{16.32}$$

$$\sum_{h\in H}\omega_{iths} \le z_i \quad i \in I, t \in T, s \in S \tag{16.33}$$

$$z_i \le y_i \quad i \in I \tag{16.34}$$

$$\beta_s = 1 - \frac{\sum_j \sum_t \varphi_{jts}}{\sum_j \sum_t d_{jts}} \quad s \in S \tag{16.35}$$

$$\Delta_s = \beta^o - \beta_s \quad s \in S \tag{16.36}$$

$$0 \le \Delta_s \le 1 \quad s \in S \tag{16.37}$$

$$x_{ijts} \ge 0 \quad i \in I, j \in J, t \in T, s \in S \tag{16.38}$$

$$\varphi_{its} \ge 0 \quad i \in I, t \in T, s \in S \tag{16.39}$$

$$z_i \in \{0, 1\} \quad i \in I \tag{16.40}$$

$$y_i \in \{0, 1\} \quad i \in I \tag{16.41}$$

$$\omega_{iths} \in \{0, 1\} \quad i \in I, t \in T, h \in H, s \in S \tag{16.42}$$

Demand constraint (16.31) equalizes demand fulfillment and unsatisfied demand with customer demand. Capacity constraints (16.32) restrict the ratio of demand fulfillment of each facility to the available capacity at the facility considered. Facility-related capacity sums to the reduced capacity and the capacity extension units. For each time period and facility only one extension level is allowed to be executed, constraint (16.33), if and only if a capacity extension option has been allotted to the facility, constraint (16.34). The amount of service level deterioration is calculated by constraints (16.35)–(16.37). Additionally, variables are limited to appropriately accomplish the aforementioned requirements by constraints (16.38)–(16.42).

Equivalent to the $RLND$ model this problem contains as a special case the CFLP. For more details and solution approaches concerning the $CPLP^{Risk}$ model we refer the reader to Heckmann (2016) and Heckmann et al. (2016).

16.6 Conclusions

In this chapter we have put an emphasis on the importance of logistics activities, their strong presence in supply chain management and their necessary integration into location modeling. Although several models and approaches have been published addressing logistics activities in location problems, the focus is mostly on some technical details missing the holistic point of view of logistics. Summing up the insights of this chapter, a location modeler has three main tasks to accomplish in order to adequately address these hurdles:

- to identify logistics activities that are relevant to the underlying industrial supply chain problem,
- to integrate relevant logistics activities in location decision models,
- to frame industrial challenges to smaller and well-defined problems of location modeling.

We presented a basic integrated logistics location ($BILL$) model that captures logistics activities for location decision making. In addition to a good integration of relevant logistics activities into location models, location modelers are confronted with several emerging challenges in the context of supply chain management which nowadays especially demand for effective location decisions. Three main challenges were discussed. We introduced two location models that address some well-framed sub-problems of the aforementioned supply chain challenges. In accordance to the discussion presented, we offered some further well-framed sub-problems to specific supply chain challenges in Table 16.15.

The need for future research directions emerges from the discussion within this chapter. In addition to new modeling approaches that integrate logistics activities and align to current challenges in supply chain management, we want to put an emphasis on dovetailing location decision with production structure. Operational production decisions are modeled through the inclusion of the BOM in the *BILL* model. Structural production decisions are modeled through facility layout decisions and should also be included in a holistic location logistics point of view. However,

Table 16.15 Supply chain challenges, corresponding location models and related chapters in this book

Challenge	Location Model	Reference
Uncertainty in supply chains	Facility location under uncertainty	See Chap. 8
	Location models with multiple-criteria	See Chap. 9
Transformation of supply chains	Multi-period facility location	See Chap. 11
Disaster events	Location problems under disaster events	See Chap. 22

we could not find models integrating strategic in-house decisions (layout) and inter-facility decisions (Supply Chain Design). Nevertheless, this might be an interesting research direction. We therefore recommend the interested reader to have a look at current reviews on facility layout, such as those by Briskorn and Dienstknecht (2017) and Anjos and Vieira (2017). However, the current view of facility layout problems is rather limited and models miss to include the general logistics perspective. Industrial supply chains continue to evolve demanding decision makers to adopt and to apply sophisticated decision support systems. This implies that locators as well have to follow closely the developments in industrial supply chains.

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