Facility Location Planning and Network Design

7

Learning Objectives for This Chapter

- Understand the importance of selecting the right facility locations
- Describe the main phases of location-related decision-making processes
- Apply quantitative analysis techniques to solve SCD problems
- Compute solutions to different settings of the warehouse location problem
- Compute facility location with the help of Steiner-Weber model
- Use center-of-gravity methods and the Miehle algorithm
- Understand the role of multiple factor analysis in locating facilities
- Apply factor-ranking method to facility location decisions

7.1 Introductory Case Study Power Pong Sports, China

In 1856 Alexander Parks produced the first celluloid, a plastic material that can be easily melted and made into different shapes. Originally, Parks was looking for a material similar to ivory in order to make the production of billiard balls easier and cheaper. In the middle of the twentieth century celluloid was mainly used for film carriers and table tennis balls, but it has also been an important ingredient of several explosive materials as well as weapons. It is a very dangerous material since it is harmful and is spontaneously inflammable.

One of the most commonly used products based on celluloid and sold in high quantities all over the world are table tennis balls. The majority of the annual overall production quantity originates in factories in China and Japan. However, table tennis balls are needed all over the world, so significant quantities are exported. For example, in Germany, more than 20 million table tennis balls are sold annually.

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Transporting large quantities of products containing significant amounts of celluloid falls into the category of transporting dangerous goods. In 2001, a container loaded with 300,000 table tennis balls is reported to have exploded after being heated by the sun. Due to the aforementioned hazards, more and more countries have banned celluloid in all forms from production, trading, and handling. For these reasons, more and more products are being replaced by celluloid-free substitutes.

Referring to the ongoing worldwide ban on celluloid, Mr. Adham Sharara, chairman of the International Table Tennis Federation (ITTF), announced in 2011 that the ITTF was going to change the international table tennis rules in order to allow the use of table tennis balls made without any celluloid. After this announcement, some manufacturers of table tennis balls started to redesign their corresponding production processes in their SCs. It turns out that any waiver of celluloid requires a significant redesign of production processes, and investment in new production facilities and technologies becomes necessary.

One of the major table tennis ball manufacturers is Power Pong Sport (PPS) headquartered in China. The most important markets for PPS in Europe (measured in goods sold) are France (FRA), Germany (GER), and the United Kingdom (UK). All other European countries are grouped into the markets of South-Eastern Europe (SEE), South-Western Europe (SWE), and Northern Europe (NEU). Because of the importance of the first three markets, PPS has long-lasting exclusive import contracts with one retailer of sports equipment in France (TriColor Sportive), Germany (TT Profi), and the UK (Competitive Fitness).

PPS has decided to build a new factory in Shanghai exclusively for the new table tennis balls manufactured without any celluloid. Mr. Xu Chen is head of the logistics department at PPS and is in charge of new contracts with resellers in Europe in order to supply the European markets with the new celluloid-free table tennis balls. Mr. Chen has already made two significant decisions, subject to PPS's SC strategy:

- A contract made with a European retailer will extend for 1 year in order to ensure that significant quantities can be sold.
- Only the most important markets in Europe will receive deliveries directly from PPS. This contributes to the realization of significant economies of scale for the shipment of the table tennis balls from Shanghai to Marseille (TriColor Sportive), Bremerhaven (TT Profi), and Felixstowe (Competitive Fitness) by maritime container transportation in completely filled 20 foot containers.

Having monitored these settings, Mr. Chen is now going to identify reasonable ways to ensure that, besides the three major markets, all European countries will have access to the new PPS balls. The basic idea is that PPS will extend the contracts made with TriColor Sportive, TT Profi, and Competitive Fitness and distribute rights among these three resellers to deliver PPS balls in SEE, SWE, and NEU countries.

Mr. Chen proposes his idea to the board of managers of PPS and gets a "go ahead", since his idea keeps the SC simple. However, Mr. Chen is instructed to keep

Table 7.1 Annual transportation costs between European resellers and markets as well as fixed annual payments to the European resellers (1000 €)

Reseller	Fixed annual costs	All markets					
		j = 1 FRA	j = 2 GER	j = 3 UK	j = 4 SEE	j = 5 SWE	j = 6 NEU
TriColor Sportive (FRA)	95	4	24	12	23	16	19
TT Profi (GER)	90	24	1	19	11	14	13
Competitive fitness (UK)	70	30	16	3	24	21	17

the annual distribution costs as low as possible. At the same time, his distribution strategy has to ensure that the PPS balls are spread over the whole European market.

As a starting point for cost minimization, Mr. Chen contacts three resellers, invites their representatives to his office, and explains his proposal. All three representatives are quite excited. In a few days, they get the OK from their management. Contract negotiations are established.

Mr. Chen asks the local representatives of the three resellers to estimate their annual transportation costs from the corresponding warehouse to six markets. Since PPS wants to be the first to distribute celluloid-free table tennis balls in Europe, it will cover all transportation costs for the first-year contract. Table 7.1 contains aggregate costs per 1000 € for the first year. The forwarding costs from the selected European resellers to the rest of Europe are independently assessed.

In order to make cooperation attractive for the three resellers, PPS pays an annual fixed amount to a reseller used to redistribute balls into other European countries, as shown in Table 7.1. Furthermore, PPS does not allow conflicts of interest between the three indirect markets SEE, SEW, and NEU. It guarantees that each of the six aforementioned markets is exclusively assigned to exactly one reseller.

Mr. Chen has general agreement with the conditions from the three resellers. His next task is to decide about the way(s) in which the PPS balls can reach the six European markets.

Discussion

- Which resellers should PPS use to distribute the celluloid-free table tennis balls in Europe?
- Which reseller(s) respectively should be assigned to SEE, SWE, and NEU?
- Is it necessary to use more than one reseller to serve a market?
- What happens if one of the resellers is unable to handle expected demand from SEE, SWE, or NEU?
- Assume that a reseller has to open a new facility to handle the additional demand. Where should this facility be located?
- How can the annual costs be kept as low as possible?

7.2 Supply Chain Design Framework

The core decision to be made in the PPS case was the *selection of markets* (country) in which a base for the PPS operations should be installed. This decision was influenced by previous choices, but also influences subsequent decisions. Strategic decisions made by the PPS board regarding the strategy for serving European markets through only a few entry gates were an implication of the strategic position of the PPS SC—to keep distribution costs as low, and as simple, as possible. These board decisions had to be considered by Mr. Chen during the selection of the gateway country to be used to deliver PPS balls into the six European markets.

Mr. Chen has to consider these guidelines in order to ensure that the *strategic fit* of the PPS distribution system is achieved and preserved. On the other hand, as soon as the gateway markets have been determined, these decisions are binding and must be considered when making subsequent decisions. For example, if Germany were selected as the unique gateway country to serve the European markets, the planning of all transport operations must include consideration of the available infrastructure, regulations, and laws. Selection of the regions (countries) involved in SC operations is therefore an individual decision that is positioned in a sequence of other decision tasks which must be solved in order to set up and use the distribution network as part of the PPS SC.

In Fig. 7.1, a modified Chopra and Meindl (2012) SCD framework is presented to show the arrangement of all decision tasks required to setup and deploy the SC.

In this framework, the SC strategy is understood as the first decision phase. We refer to Chap. 4, Supply Chain Strategy, regarding this phase. Phase I addresses the

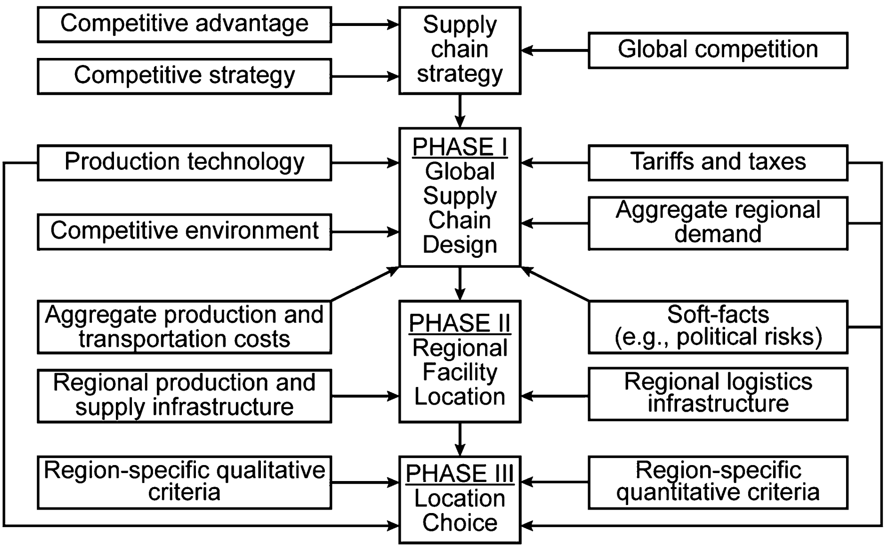


Fig. 7.1 Supply chain design framework (based on Chopra and Meindl 2012)

compilation of those sourcing or supply regions/markets which are considered subject to the long-term fulfilment of market demand. Such a region might cover a continent, a country, an area of cultivation, or a fishing ground. Also the segmentation of the total (global) market varies from local areas to continents. Phase I provides a list of geographic regions that could be promising for the set up of the SCD. In addition, suggestions for the installation of transportation links between supply and demand regions are provided by phase I.

In phase II, all regions are processed individually. In each region, specific locations (expressed by coordinates) are identified at which a facility can be installed or from which supply quantities can infiltrate the SC. The output of phase II is a short list of candidates for locations (with existing facilities or with prospective facilities) which have been selected for cost efficiency.

In phase III, final selection of the locations that will be considered in the SCD is carried out. Multiple criteria are considered at this stage and the analysis reaches far beyond cost minimization. Furthermore, capacities are allocated at all locations that are considered to contribute to the fulfilment of demand from the markets to be served.

Decisions associated with phases I-III fall into the category of strategic (long-term) SCD decisions. A revision of these decisions is hardly possible or implies significant costs. This chapter addresses these three decision phases of the location planning framework. We discuss and investigate tools to support SC managers in identifying the best decision alternatives. In Sect. 7.3, we introduce the *warehouse location problem* as a representative example of a core decision task in the selection of contributing regions (phase II). Tools for supporting the derivation of adequate location selection decisions are the focus of Sect. 7.4 (phase III). Decisions associated with phase III are considered in Sect. 7.5.

7.3 Global Supply Chain Design

Phase I of the location analysis framework addresses the selection of source regions that are incorporated into the overall SC. From the sourcing regions selected, markets are served such that the overall supply from the different sources covers the demand of each individual market. The PPS case is a typical representation of a phase I decision situation. By means of the PPS case presented in Sect. 7.1, we develop an appropriate mathematical optimization model (Sect. 7.3.1) as the starting point of rational decision making that incorporates computational resources to derive optimal location decisions.

For solving this so-called (uncapacitated) *warehouse location problem* (WLP), we explain the usage of a spreadsheet approach (Sect. 7.3.2) as well as the configuration of a general purpose decision support algorithm called *branch-&-bound* (Sect. 7.3.3). Finally, we investigate the consequences of scarceness, i.e. the limited availability of the quantities offered in source regions, leading to the definition of the *capacitated warehouse location problem* (CWLP). For the CWLP, we also propose an appropriate mathematical optimization model as well as a decision support technique (Sect. 7.3.4).

7.3.1 Warehouse Location Problem and Its Formalization

The case of PPS is a representative example for a frequent decision situation related to the SCD. First, a decision about regions (markets, countries) hosting a facility (factory, warehouse, partner) to be used as a network node is required ("location decision"). Second, a decision must also be made as to how those markets are supplied from a regional facility so that the demand of each market is covered ("supply decision"). Such a problem requiring both location and supply decisions is called a *warehouse location problem* or WLP (Daskin 1995; Drezner 1995; Melo et al. 2009; Askin et al. 2014). The overall goal to be achieved in solving a WLP is to keep the total costs of supplying all regions as low as possible. Therefore, for each region it has to be decided if it is more beneficial to open a facility (creating fixed costs for running the facility) or use transportation links to supply a region (creating transportation costs).

Let S denote the set of all regions in which a facility/warehouse can be installed or used (e.g. $S = \{GER; FRA; UK\}$) and let M be the set of all markets (e.g. $M = \{GER; FRA; UK; SEE; SWE; NEU\}$). The set $T := S \times M$ contains all possible transportation links between a warehouse region and a market. If a facility is opened in region $s \in S$ then the annual costs rise by the amount f_s. The decision to use the transportation link $(s, m) \in T$ between the facility in region $s \in S$ and the market $m \in M$ increases the annual costs by the additional amount c_{sm}. Using the aforementioned sets, we are able to formally present the WLP as follows.

First, the *objective function* (7.1) is formulated:

$$Z = \sum_{s \in S} f_s \cdot y_s + \sum_{s \in S} \sum_{m \in M} C_{sm} \cdot x_{sm} \tag{7.1}$$

The sum of (annual) costs expressed in Eq. (7.1) has to be minimized by varying the values of the *decision variables* y_s as well as x_{sm}. The family y_s of binary decision variables represents the facility opening decisions. All these decision variables are allowed to be set to either 1 ("use this facility") or 0 ("do not use this facility"). Similarly, x_{sm} code the decisions about whether to use the transportation links in T between warehouses and markets. Although the two decision categories introduced address different managerial decisions, they fall into the same type of decisions: exactly one of two options must be selected (binary decisions). Therefore, the WLP turns out to be a collection of interdependent binary decisions about the opening of the locations.

Each market has to be served from exactly one facility as is the case in the PPS example. In order to ensure this condition when fixing the values for the x-decision variables, it is necessary to ensure that constraint (7.2) is respected.

$$\sum_{s \in S} x_{sm} = 1, \forall m \in M \tag{7.2}$$

In a case where (7.2) remains unfilled, then at least one market in M remains unserved. Since the overall sum of costs for supplying all markets must be minimized: every solution in which a market m ∈ M is connected with two or more facilities implies higher costs and selecting one of these facilities for serving the markets may reduce costs. In summary, in a cost optimal solution of the WLP each market is supplied from exactly one facility s ∈ S.

Obviously, it is useless to install a transport link between market *m* and facility *s* if *s* is not opened, e.g., if we set $x_{sm} = 1$ if, and at the same time, $y_s = 0$ then we would end up with a useless and unrealizable solution for the WLP. In order to avoid such a failure, we introduce the constraints (7.3) and (7.4) that couple facility installation with transport link installation decisions and ensure that we install a transport link only if it has been decided that the origin facility should also be installed.

$$x_{sm} \leq y_s, \forall s \in S, \forall m \in M \tag{7.3}$$

$$y_s \in \{0; 1\} \forall s \in S, x_{sm} \in \{0; 1\} \forall (s, m) \in T \tag{7.4}$$

Using the mathematical model (7.1)–(7.4), we are now ready to state precisely the WLP problem as follows:

It is necessary to minimize the total costs for the installation of facilities and transportation links subject to Eq. (7.1), so that each market is served by exactly one facility (7.2). If we use a facility for supplying a market, then this facility must be open (7.3). Each available facility is either opened or closed and each available transportation link is either used or not (7.4).

A pure, formalized problem formulation is as follows: "minimize (7.1) while taking into account (7.2)–(7.4). The collection of mathematical expressions (7.1)–(7.4) is a mathematical model for the WLP. This model represents the underlying decision problem in a formal way. A solution to this model is comprised of a selection of values for each of the *y*-decision variables as well as each of the *x*-decision variables. Such a solution is called *feasible*, if and only if, all constraints (7.2)–(7.4) are fulfilled, e.g., if the implementation of the selected values for the decision variables leads to logically true statements. Every feasible solution of the proposed WLP-model that leads to a non-dominated objective function value is called an optimal solution of the WLP-model. Such an optimal solution can be used to derive an optimal solution to the underlying real world WLP.

If we want to use the WLP model to represent Mr. Chen's problem in the PPS case, we first have to collect all relevant planning data. The set *S* of potential regions hosting a facility is compiled as S = {GER; FRA; UK} and the set of markets *M* equals {GER; FRA; UK; SEE; SWE; NEU}. Consequently, the set of transportation links is formed as *T* = {(GER;GER); (GER;FRA); (GER;UK); (GER;SEE); (GER;SWE); (GER; NEU);(FRA;GER); (FRA;FRA); (FRA;UK); (FRA;SEE); (FRA;SWE); (FRA; NEU); (UK;GER); (UK;FRA); (UK;UK); (UK;SEE); (UK;SWE); (UK;NEU)}. The cost coefficients representing the annual running costs for an opened facility are $f_{GER} = 95$, $f_{FRA} = 90$ and $f_{UK} = 70$. Finally, the cost coefficients for the annual distribution costs in Europe are $c_{GER;GER} = 1$; $c_{GER;FRA} = 24$; $c_{GER;UK} = 19$; $c_{GER;SEE} = 11$; $c_{GER;}$

$_{SWE} = 14$; $c_{GER;NEU} = 13$;$c_{FRA;GER} = 24$; $c_{FRA;FRA} = 4$; $c_{FRA;UK} = 12$; $c_{FRA;SEE} = 23$; $c_{FRA;SWE} = 16$; $c_{FRA;NEU} = 19$; $c_{UK;GER} = 16$; $c_{UK;FRA} = 30$; $c_{UK;UK} = 3$; $c_{UK;SEE} = 24$; $c_{UK;SWE} = 21$; $c_{UK;NEU} = 17$.

Mr. Chen puts all the aforementioned data into the general WLP model and obtains the following mathematical optimization model that represents his SCD problem in Europe as mixed integer linear programing (MILP) model by (7.5)–(7.13):

$$\begin{aligned}\text{Minimize } Z = \; & 90y_{GER} + 95y_{FRA} + 70y_{UK} + 1x_{GER;GER} \\ & +24x_{GER;FRA} + 19x_{GER;UK} + 11x_{GER;SEE} + 14x_{GER;SWE} \\ & +13x_{GER;NEU} + 24x_{FRA;GER} + 4x_{FRA;FRA} + 12x_{FRA;UK} \\ & +23x_{FRA;SEE} + 16x_{FRA;SWE} + 19x_{FRA;NEU} + 16x_{UK;GER} \\ & +30x_{UK;FRA} + 3x_{UK;UK} + 24x_{UK;SEE} + 21x_{UK;SWE} + 17x_{UK;NEU}\end{aligned} \tag{7.5}$$

So that

$$x_{GER;GER} + x_{FRA;GER} + X_{UK;GER} = 1 \tag{7.6}$$

$$x_{GER;FRA} + x_{FRA;FRA} + X_{UK;FRA} = 1 \tag{7.7}$$

$$x_{GER;UK} + x_{FRA;UK} + X_{UK;UK} = 1 \tag{7.8}$$

$$x_{GER;SEE} + x_{FRA;SEE} + X_{UK;SEE} = 1 \tag{7.9}$$

$$x_{GER;SWE} + x_{FRA;SWE} + X_{UK;SWE} = 1 \tag{7.10}$$

$$x_{GER;NEU} + x_{FRA;NEU} + X_{UK;NEU} = 1 \tag{7.11}$$

$$\begin{aligned} & x_{GER;GER} \le y_{GER}, \; x_{GER;FRA} \le y_{GER}, \; x_{GER;FRA} \le y_{GER}, \\ & x_{GER;UK} \le y_{GER}, \; x_{GER;SEE} \le y_{GER}, x_{GER;SWE} \le y_{GER}, \\ & x_{GER;NEU} \le y_{GER}, x_{FRA;GER} \le y_{FRA}, x_{FRA;FRA} \le y_{FRA}, \\ & x_{FRA;UK} \le y_{FRA}, x_{FRA;SEE} \le y_{FRA}, \; x_{FRA;SWE} \le y_{FRA}, \\ & x_{FRA;NEU} \le y_{FRA}, \; x_{UK;GER} \le y_{UK}, \; x_{UK;FRA} \le y_{UK}, x_{UK;UK} \le y_{UK}, \\ & x_{UK;SEE} \le y_{UK}, \; x_{UK;SWE} \le y_{UK}, \; x_{UK;NEU} \le \; y_{UK}\end{aligned} \tag{7.12}$$

$$\begin{aligned} & y_{GER} \in \{0;1\}, y_{FRA} \in \{0;1\}, y_{UK} \in \{0;1\}, x_{GER;GER} \in \{0;1\}, \\ & x_{GER;FRA} \in \{0;1\}, x_{GER;UK} \in \{0;1\}, x_{GER;SEE} \in \{0;1\}, \\ & x_{GER;SWE} \in \{0;1\}, x_{GER;NEU} \in \{0;1\}, x_{FRA;GER} \in \{0;1\}, \\ & x_{FRA;FRA} \in \{0;1\}, x_{FRA;UK} \in \{0;1\}, x_{FRA;SEE} \in \{0;1\}, x_{FRA;SWE} \in \{0;1\}, \\ & x_{FRA;NEU} \in \{0;1\}, x_{UK;GER} \in \{0;1\}, x_{UK;FRA} \in \{0;1\}, x_{UK;UK} \in \{0;1\}, x_{UK;SEE} \in \{0;1\}, \\ & x_{UK;SWE} \in \{0;1\}, x_{UK;NEU} \in \{0;1\}\end{aligned} \tag{7.13}$$

The fairly small SCD problem in the PPS case is represented by the mathematical model (7.5)–(7.13). Although only three potential facility sites and six markets are involved in the problem, the PPS case is quite a complex decision situation and the proposed model is so complex that it is impossible to solve it manually. We need to utilize the support of a computer system.

7.3.2 A Spreadsheet Approach to the WLP

Even for a rather small WLP case such as the PPS scenario, it is hardly possible to identify a minimal cost instantiation of the y_i- and the x_{ij}-values. A spreadsheet calculation schema as shown in Fig. 7.2 is a first step to managing the problem's inherent complexity and determining the costs of different decisions.

	A	B	C	D	E	F	G	H	I
1									
2									
3	PowerPong Sports - Distribution Costs								
4									
5	i	re-sellers	annual fixed costs	All markets					
6				j=1	j=2	j=3	j=4	j=5	j=6
7				FRA	GER	UK	SEE	SWE	NEU
8	1 (FRA)	TriColor Sportive (FRA)	95	4	24	12	23	16	19
9	2 (GER)	TT Profi (GER)	90	24	1	19	11	14	13
10	3 (UK)	Competitive Fitness (UK)	70	30	16	3	24	21	17
11									
12	Decisions about incorporated re-sellers and established delivery links from re-sellers into markets								
13									
14	i	re-sellers	y_i	delivery links (x_{ij})					
15				j=1	j=2	j=3	j=4	j=5	j=6
16				FRA	GER	UK	SEE	SWE	NEU
17	1 (FRA)	TriColor Sportive (FRA)							
18	2 (GER)	TT Profi (GER)							
19	3 (UK)	Competitive Fitness (UK)							
20	number of used sources			0	0	0	0	0	0
21									
22	Cost calculation (all values in thousand EUR)								
23									
24	annual fixed costs from selected re-sellers					0			
25	re-distribution costs					0			
26	total costs					0			

Fig. 7.2 Cost calculation sheet for the PPS-case

Table 7.2 Payments to the European resellers (1000 €)

Cell	Formulas	
F24	=SUMPRODUCT(C17:C19;C8:C10)	Sum of annual fixed costs
F25	=SUMPRODUCT(D17:I19;D8:I10)	Annual link costs
F26	=F24 + F25	Total annual costs

The upper part of this spreadsheet (rows 5–10) contains all relevant problem data, which are the annual fixed costs for each reseller (column C) and the costs for installing a transportation link from a reseller into a market (columns D–I).

In the middle part of the calculation scheme (rows 14–19) setup decisions can be typed into the grey shaded cells. The area covering cells C17–C19 is used to code the decisions associated with the incorporation of a reseller. When "1" is inserted, then the corresponding reseller is considered, but if a "0" is typed in then this reseller remains unconsidered. For example, if TriColor Sportive is considered in the PPS European distribution system, then cell C17 is filled with "1". Similarly, "1" and "0" are typed into the cell area D17–I19 in order to code the decisions on the installed transportation links from the resellers into the six markets. For each market, the number of selected resellers is calculated in row 20.

The costs for a coded collection of decisions are calculated in the lower part of the spreadsheet (rows 24–26). The corresponding formulas are given in Table 7.2.

Theoretically, one might use the spreadsheet to test every possible combination of "0" and "1" values in the grey shaded cells. Unfortunately, there are $2^{21} = 2{,}097{,}152$ different combinations. First, each combination has to be checked for feasibility with respect to the constraints (7.6)–(7.13). Second, for each feasible combination, the associated costs have to be calculated using Eq. (7.5). If we assume that these two steps can be executed within 1 second, then it takes 2.5 days to find the best feasible solution for the PPS-WLP setting. Therefore, testing all combinations manually is impractical. Fortunately, spreadsheet calculation tools (e.g. Microsoft Excel, Open Office) provide special add-ins that assist us in testing different combinations. One add-in is called "*Solver*".

The concept of the solver tool is as follows. The user specifies those cells that are variable (here: the grey shaded cells) and the cell in which the objective function value is contained (here: cell F26) and then the solver proposes a first set of values and inserts these values tentatively into the variable cells. After this, the solver reads the value in the objective function cell. Using optimization algorithms, the solver is now able to decide if the proposed values form an optimal solution or not. In the first case, the solver returns the current solution proposal by definitively inserting the current values into the variable cells. In the latter case, the solver iterates the recent proposal and re-evaluates this new proposal by reading the updated objective function cell. This iteration is repeated by the solver until an optimal combination of values for the decision variables is found or if it decides that there is no better solution available.

Note: An Excel file pre-configured with the PPS data and a suitable solver configuration can be found in the E-Supplement. The Excel solver is an add-in

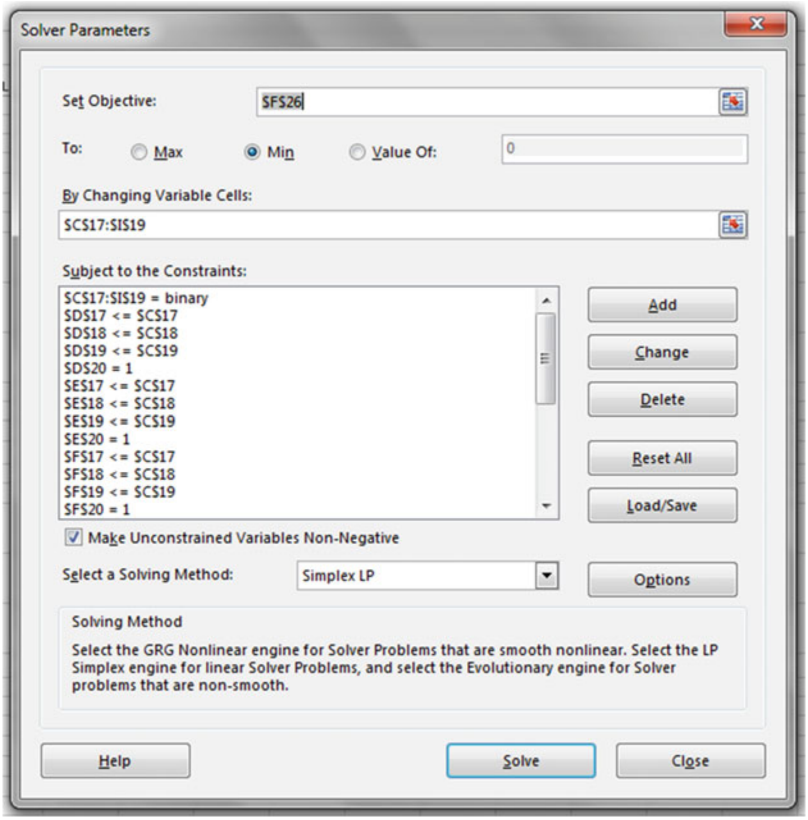


Fig. 7.3 Parameter settings for the solver

that comes with each Excel installation. In order to use this add-in, it is necessary to activate it before first use. Open Office also includes a solver tool.

Before you can apply the solver add-in to the PPS case, it is necessary to execute a careful configuration in order to provide the solver with comprehensive problem information, e.g. to input the model parameter and decision variables. Figure 7.3 exhibits the necessary parameter settings.

First, the cell that contains the objective function value (or in which the objective function value is calculated) is inserted into the “set objective” input box. Here, cell $F$26 contains the target value that is the subject of optimization.

Second, the optimization goal is specified, e.g. whether the objective function value is going to be minimized or maximized, or if a certain target value must be achieved is established. In the PPS case, the totals calculated in cell $F$26 are minimized.

Third, those fields that should be modified by the solver (“variable cells”) must be specified. Here, all cells in the area $C$17:$I$19 can be varied by the solver. The

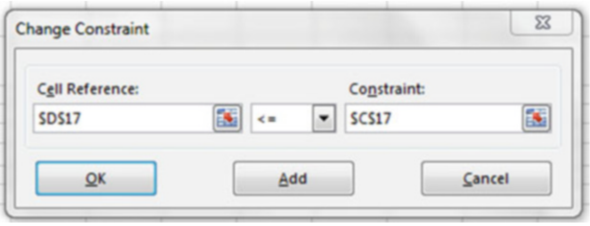


Fig. 7.4 Specification of constraints

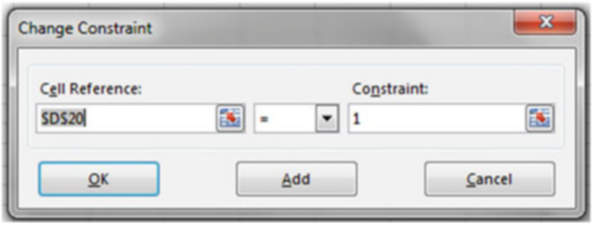


Fig. 7.5 Compilation of constraints

area \$C\$17:\$C\$19 represents the decision variable vector (y_{FRA}, y_{GER}, y_{UJ}) whereas the area \$D\$17 to \$I\$19 corresponds to the matrix of the x_{ij}-decision variables.

Fourth, you need to specify the constraints that must be considered/that belong to the model. Constraints are typed in one after another by clicking the add button in the solver parameter window. Figure 7.4 shows an example of how the constraint $x_{GER; NEU} \leq y_{GER}$ from Eq. (7.12) is specified.

For the input of the constraints (7.2), the solver refers to cells D20–I20 where the sum in the left side of Eq. (7.2) is calculated (Fig. 7.5).

If necessary, the decision variable domains must be restricted as shown in Fig. 7.6 to limit the values of y_i and x_{ij} to either 0 or 1.

Finally, it is necessary to specify the optimization algorithm that the solver invokes to solve the specified mathematical model. For the PPS model, we select the option simplex algorithm since the model (7.1)–(7.4) consists of a linear objective function and of linear constraints. The solver detects that the decision variables may only be instantiated with the values 0 or 1.

When the five steps mentioned above have been executed, the solving process is initiated by clicking on the "Solve" button. Now the optimization routines start the optimization process and write the final solution proposal into the variable cells.

In Fig. 7.7 the values returned for the PPS case have been written into the variable cells.

The optimal design of the PPS-network in Europe is to agree to the contract with the reseller in Germany ($y_2 = 1$) and to forward balls from Germany to the five remaining markets ($x_{2j} = 1$ for all $j = 1, \ldots, 6$). The annual costs for this design account to 172 TEUR (thousand Euro) p.a. and this sum includes the amount of 80 TEUR paid to TT Profi as a fixed annual amount to cover all the reseller's expenses for handling the intra-European orders, as well as the costs for the transportation links, which account for 92 TEUR p.a. This proposal reduces the

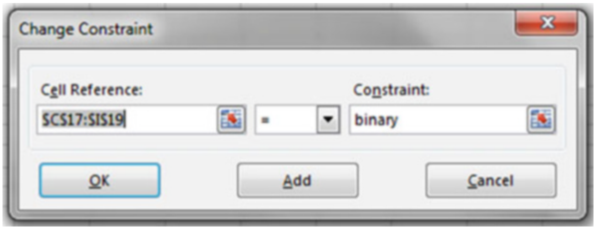


Fig. 7.6 Specification of the decision variable's domains

PowerPong Sports - Distribution Costs

i	re-sellers	annual fixed costs	All markets j=1 FRA	j=2 GER	j=3 UK	j=4 SEE	j=5 SWE	j=6 NEU
1 (FRA)	TriColor Sportive (FRA)	95	4	24	12	23	16	19
2 (GER)	TT Profi (GER)	90	24	1	19	11	14	13
3 (UK)	Competitive Fitness (UK)	70	30	16	3	24	21	17

Decisions about incorporated re-sellers and established delivery links from re-sellers into markets

i	re-sellers	y_i	delivery links (x_{ij}) j=1 FRA	j=2 GER	j=3 UK	j=4 SEE	j=5 SWE	j=6 NEU
1 (FRA)	TriColor Sportive (FRA)	0	0	0	0	0	0	0
2 (GER)	TT Profi (GER)	1	1	1	1	1	1	1
3 (UK)	Competitive Fitness (UK)	0	0	0	0	0	0	0
number of used sources			1	1	1	1	1	1

Cost calculation (all values in thousand EUR)

annual fixed costs from selected re-sellers	90
re-distribution costs	82
total costs	172

Fig. 7.7 Returned optimal solution for the PPS case

total annual costs so that Mr. Chen will go on to sign the contract with TT Profi, but not the contracts with TriColor Sportive in France. In addition, no contract with Competitive Fitness in the UK will be signed.

From the methodological perspective, we conducted three steps consecutively to solve the real world decision situation:

- The real world decision situation is coded into a mathematical decision model ("modelling step").
- The formalized decision representation (the mathematical decision model) is processed by an optimization algorithm which returns an optimal solution of the model ("model solving step").
- The model solution is interpreted as a decision proposal for the real world problem ("model solution implementation step").

The problem solving approach reported here is a typical example of a *model-based decision approach*. The major challenge was to represent the WLP using a mathematical model. Due to the *linear* structure of the objective function as well as of the constraints, we were able to apply a black-box model solving tool to derive the model solution.

Exercise

The management board of directors of PPS has decided to redesign the market segmentation in Europe. The former market region SWE has been split into South-Western Europe I (SWE-I) and South-Western Europe II (SWE-II). SWE-I now demands one third of the former SWE-market. The annual costs for installing a transportation link are correspondingly split between SWE-I and SEW-II. Is it necessary to redesign the network in Europe?

Assume that SWE remains complete. However, due to the recent success of the Portuguese national table tennis teams, the Portuguese market has grown rapidly. Situated in this emergent market, an additional potential reseller offers PPS the following conditions for cooperation: Annual costs are fixed at 60,000 € and for each of the six markets equal forwarding costs of 20 € per packaging unit are possible. Is there a benefit for PPS to consider this fourth reseller candidate for its European distribution network?

7.3.3 Branch-&-Bound: How the Solver Add-In Works

So far we have learned how to code a WLP into a mathematical optimization model. Furthermore, we have learned how we can deploy a black-box tool such as Excel Solver to derive a high quality (optimal) solution for the model.

Obviously, the knowledge of an appropriate decision model type is sufficient to solve the real world challenge of the WLP. However, so far, we do not have any knowledge about the way the black-box model solver processes the specified model nor do we have a chance to judge the optimality of the proposed model solution. In this section, we will learn the basic principles of a model solving algorithm that serves as the base for many decision model solvers. This technique is called *branch-&-bound* (b&b).

As the name b&b suggests, there are two interdependent activities for processing the model. One activity is to split the problem into smaller problems (*branching*) and the second activity is to estimate the best objective function value that may be achieved by solving a model of such a specific "branch" of the overall problem (*bounding*).

In this section, we explain an efficient branching strategy for a WLP model as well as an efficient bounding scheme to determine the lower bound of the objective function associated with a model for each splitting up of a WLP sub-problem. Although the idea of b&b is applied to a fairly comprehensive collection of decision models for a large entirety of decision problems, both the branching strategy as well as the bounding scheme has to be adjusted for any specific model.

Let us begin the motivation and explanation of b&b algorithms with a simple observation that is valid for the WLP model of PPS. Independently from the decisions on the reseller selection we can determine the least required transportation linkage costs in the following way. First, select a minimal value in each column associated with a target market in Table 7.1. Second, calculate the sum Z(---) of the six selected values, e.g. Z(---) = 4 + 1 + 3 + 11 + 14 + 13 = 46 TEUR. This value is needed to maintain the distribution network independently from the incorporated resellers. The fact that no reseller is selected is expressed by the three dashes "---" where the first dash represents the selection to incorporate the first reseller ("1") or the decision to refrain from cooperating with the first reseller ("0").

We start the configuration of a b&b algorithm for the WLP with the derivation of an adequate branching strategy. This strategy recursively splits the model M(---) of the given WLP model into two sub-models M(1--) and M(0--).

- In the model M(1--) we add the constraint that the first supplier must be incorporated ($y_1 = 1$).
- In the model M(0--) we postulate the constraint that the first supplier may not be considered ($y_1 = 0$).

Note that no solution of the WLP model remains unconsidered if we handle M(1--) and M(0--) instead of the initial WLP model, since y_1 equals either 1 or 0. However, one might now ask what the benefit of dealing with two models instead of one is. In order to justify this model split, we analyze the consequences of the model replacement.

The recently generated models M(1--) and M(0--) are "smaller" than the original model M(---), since one of three requested decisions has already been made and only two decisions (about the second as well as the third reseller) must be solved.

The cost estimation value Z(1--) associated with M(1--) as well as the cost estimation value Z(0--) associated with M(0--) can be refined compared to the cost estimation Z(---) associated with M(---).

In the sub-problem represented by M(1--), the first reseller is incorporated and therefore the annual fixed cost of $f_1 = 95$ TEUR definitely has to be paid in addition to the least transportation costs Z(---) = 46 TEUR so that we get Z(1--) = 46 TEUR

+ 95 TEUR = 141 TEUR: each decision alternative in which the first reseller is incorporated ($y_1 = y_{FRA} = 1$) creates annual costs of at least 141 TEUR.

In the sub-problem represented by M(0--), the first reseller is not incorporated. Therefore, no transportation link can originate from this reseller ($x_{ij} = x_{FRAj} = 1, \forall j \in \{FRA; GER; UK; SEE; SWE; NEU\}$). In particular, the link FRA to FRA cannot be used. The market FRA must be served from another reseller. Because of this, we cannot consider these transportation links for calculation of the least transport costs among the resellers and the markets. From the remaining links that can be used to serve FRA, we select the cheapest link, which is (GER;FRA). Since the linkage costs $c_{FRA;FRA} = 4$ but $c_{GER;FRA} = 24$, the least transportation cost sum increases by 20 TEUR p.a. so that we have Z(0--) = 46 − 4 + 24 = 46 + 20 = 66 TEUR p.a.

Having generated the two models M(1--) and M(0--) by deciding about the incorporation of reseller 1, we continue with the decision about consideration of reseller 2. Both sub-problems represented by M(1--) as well as M(0--) are therefore split into two smaller problems M(11-) and M(10-), respectively M(01-) and M(00-). Each of these four sub-problems is then split again in order to incorporate reseller 3 into the cost evaluation (Fig. 7.8).

The tree structure of all possible sub-problems in the PPS case is shown in Fig. 7.8. Each node in the tree represents one sub-problem determined by combinations of involved/rejected/so far undecided resellers. A node represents an incomplete solution of the WLP where at least one reseller remains undecided. A node represents a solution of the WLP if there is a decision made for each reseller. The nodes in the first three upper levels of the tree in Fig. 7.8 represent incomplete solutions, but the nodes in the lower level represent the different solutions of the WLP. The solution of the model M(000) is infeasible because no reseller is used and this is impossible. The remaining seven solutions are feasible and the solution of M (010) with total costs of 172 is the cheapest solution available. Excel Solver has returned the same solution.

Overall, it was necessary to set up and evaluate 15 sub-problems to solve the PPS case. In general, WLPs come along with a significantly larger number of potential

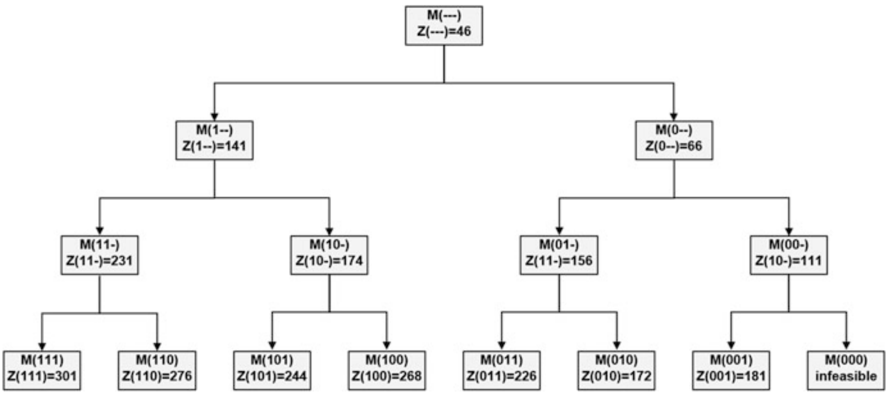


Fig. 7.8 Tree of sub-problems and cost estimations as well as solutions for the PPS case

locations corresponding to resellers (or suppliers). Let N be the number of supply sources so that the number of sub-problems equals $1 + 2 + 2^2 + 2^3 + \ldots + 2^N$. For example, let N = 5 which requires the specification and evaluation (cost estimation) of 1 + 2 + 4 + 8 + 16 + 32 = 63 sub-problems and if N = 10 then the number of sub-problems climbs up to 1 + 2 + 4 + 8 + 16 + 32 + 64 + 128 + 256 + 512 + 1024 = 2047. The time needed to solve all these sub-problems is prohibitively high. However, we can use the objective function value of the first solution found during a b&b execution to reduce the number of sub-problems that must be set up and evaluated. For this reason, we analyze the sequence in which the sub-problems are generated (Figs. 7.9, 7.10, 7.11, 7.12, and 7.13).

After the first branching step on the decision about the incorporation of reseller 1, we have two sub-problems. We now select the sub-problem with the lower cost estimation and assume that the first reseller remains unconsidered (Fig. 7.10).

The right-hand sub-problem represented by M(0--) has a lower cost estimation value and will be split up next. For this reason, we generate the sub-problems 01- and 00- and determine the lower bound of the costs (Fig. 7.11).

Figure 7.11 contains the current stage of the decision tree. The right-hand sub-problem represented by M(000) is infeasible, but the left-hand sub-problem corresponds to the first complete and feasible solution with costs of 181. We set the current least cost to Z^{least}:=181 TEUR. Since both sub-problems 001 and 000 cannot be split up further, it is necessary to go back to the previous level and to investigate

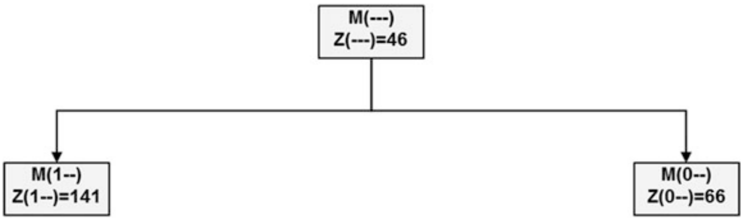


Fig. 7.9 Tree after first branching step

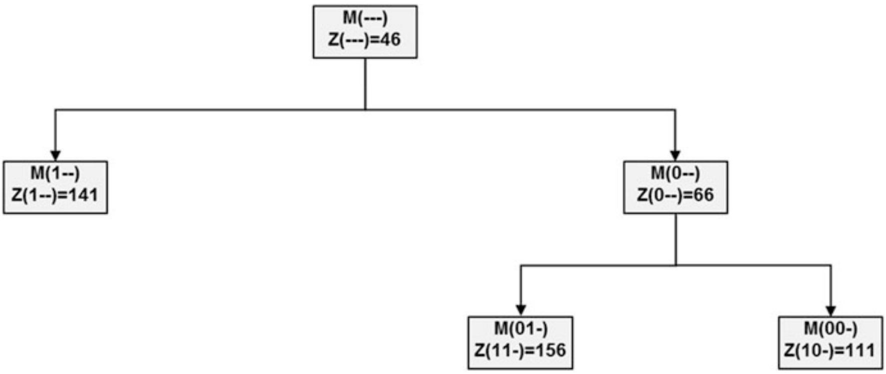


Fig. 7.10 Tree after second branching step

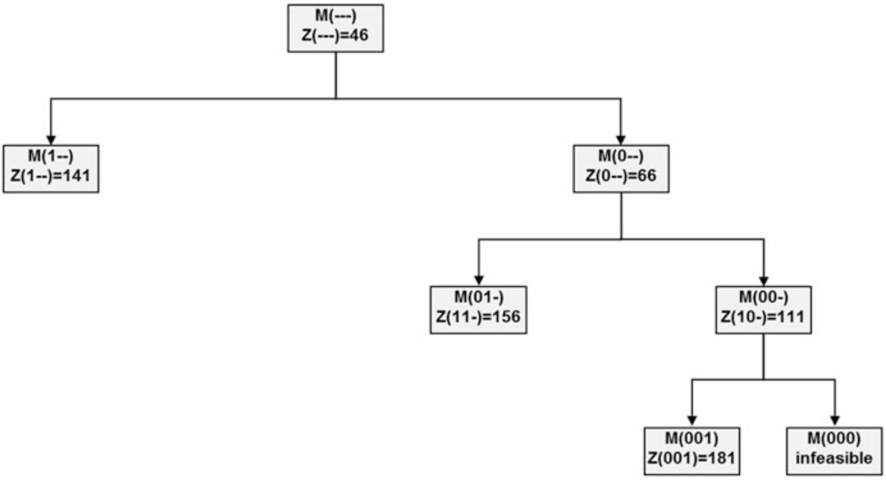


Fig. 7.11 Tree after third branching step

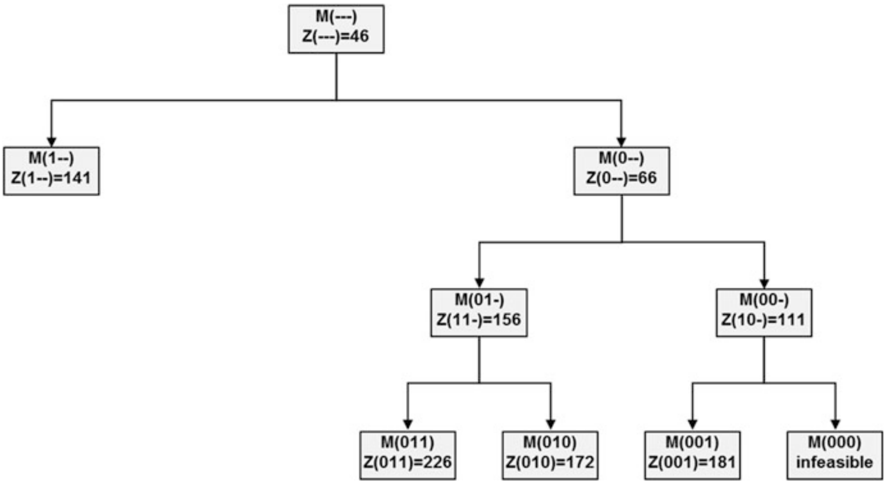


Fig. 7.12 Tree after backtracking and fourth branching step

the open sub-problem represented by M(01-). Such a step back into a higher level is called a backtracking step (Fig. 7.12).

After backtracking has been done, we expand the sub-problem 01- and obtain two new solutions for the WLP. The costs from solution 011 are 226 TEUR and do not improve the least cost Z^{least} of the best solution found so far. Solution 010 creates costs of 172 TEUR which improves Z^{least} so that we may update Z^{least} and set Z^{least} :=172 TEUR, tracking back to level three. Since there are no open sub-problems left in level three which have not been processed we track back into level 2 and process the open sub-problem 1-- (Fig. 7.13).

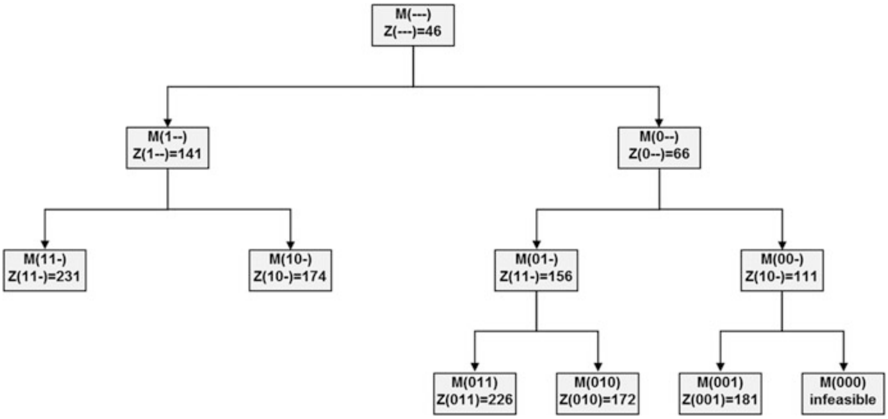


Fig. 7.13 Tree after double backtracking and fifth branching step

We generate sub-problem 11- as well as sub-problem 10- and determine the lower bound of the costs (Fig. 7.13). For both sub-problems, the lower bounds 231 and 174 exceed the costs 172 of the least cost solution found so far. Therefore, it is not necessary to analyze these two sub-problems any further since it is impossible to find an improved solution for the WLP model.

As we see from the final tree in Fig. 7.13 it is not necessary to generate all possible sub-problems if we save the best found solution so far.

▶ **Practical Insights** For small instances, b&b is a suitable method. However, the solution of real-life problems involves a higher complexity. This makes it necessary to solve the WLP by different heuristic methods (offering no guarantee of finding the best available solution) rather than exact algorithms. The reason for this is the high number of integer variables. However, heuristic procedures offer no guarantee of finding an optimal solution.

7.3.4 Capacitated WLP

We now investigate the impacts of limited capacities on SCD. Therefore, it is necessary that we know the quantities q_s ($s \in S$) that can be handled by each reseller per year. Furthermore, in order to assign a sufficient quantity to each reseller we need to have the demand quantity d_m of each market ($m \in M$). For the PPS case, the maximal quantities that can be handled by a reseller are summarized in Table 7.3. Table 7.4 shows the expected annual demand from the six markets. All values are expressed in number of packing units (parcels).

Table 7.3 Annual handling quantities (packing units) of the reseller/market

s	q_s
TriColor Sportive (FRA)	20,000
TT Profi (GER)	20,000
Competitive Fitness (UK)	15,000

Table 7.4 Annual demand of six markets packing units

m	d_m
FRA	5000
GER	8500
UK	3200
SEE	2800
SWE	2100
NEU	1700

Of course, there is no reseller solely able to serve the total demand of 23,300 packing units. Therefore, it is necessary that at least two resellers are incorporated. Consequently, at least a second annual fixed handling amount has to be paid. In contrast to the uncapacitated WLP, an optimal solution to the case investigated here, called the CWLP or Capacitated Plant Location Model (CPLM) differs from a WLP solution, because more than one reseller is considered in an optimal solution.

Again, we have to make a decision about the incorporation of resellers, so the corresponding decision is coded again by the binary decision variables y_s ($s \in S$). In the WLP we use the binary decision variable family x_{sm} to represent decisions about the installation of a transportation link connection supplier (reseller) *s* with market *m*. In the context of the CWLP, it is also necessary to determine the quantity shipped along a transportation link. Therefore, we use the family of non-negative decision variables z_{sm} to represent decisions about the installation and usage of transportation links. If z_{sm} equals 0, then there is no link installed to connect supplier s with market m. If z_{sm} is larger than 0, then the value z_{sm} is interpreted as the quantity shipped along the transportation link originating from supplier *s* and terminating in market *m*.

We have used the annual fixed cost value c_{sm} to determine the annual costs for the incorporation of the transportation link between supply location *s* and market *m*. This parameter determines the annual costs for moving the whole demand of the target market *m* from the supply source *s*. In the CWLP, we aim to distribute the total demand of a market among different transportation links; it is necessary to know the costs c'_{sm} for moving one package unit along the transportation link, connecting supply source *s* with market *m*. We can calculate the values for c'_{sm} from the values contained in Table 7.1. We explain this as an example of the transportation link between the UK reseller and the market SEE. Here, the total costs for delivering the market's demand of 2800 package units are 24,000 € per year, so that each package unit shipped between the supplier in the UK and the market SEE has a cost of 24,000

Table 7.5 Shipment costs c'_{sm} between European resellers and markets per package unit

Reseller	All markets					
i = 1, . . ., 3	j = 1 FRA	j = 2 GER	j = 3 UK	j = 4 SEE	j = 5 SWE	j = 6 NEU
TriColor Sportive (FRA)	0.80	2.82	3.75	8.21	7.62	11.18
TT Profi (GER)	4.80	0.12	5.94	3.93	6.67	7.65
Competitive Fitness (UK)	6.00	1.88	0.94	8.57	10.00	10.00

€/2800 package units ≈ 8.57 €. Table 7.5 summarizes the shipment costs c'_{sm} per package unit.

Using the transportation cost coefficients per package unit as well as the decision variables z_{sm} for the shipped quantities, we can determine the overall distribution costs Z^{CWLP} per year according to Eq. (7.14).

$$Z^{CWLP} = \sum_{s \in S} f_s \cdot y_s + \sum_{s \in S} \sum_{m \in M} c'_{sm} \cdot z_{sm} \tag{7.14}$$

Using the flow quantity variables z_{sm}, we can re-formulate the demand covering constraint (7.2), so that a supply of a market from more than one supplier (reseller) also becomes possible [Eq. (7.15)].

$$\sum_{s \in S} z_{sm} \geq d_m, \forall m \in M \tag{7.15}$$

Similarly, we have to ensure that no supplier (reseller) intends to deliver more quantities than available to all markets together. Such a constraint is not contained in the model of the uncapacitated WLP. The left side of constraint (7.16) calculates the actual supply quantities delivered from supplier *s* to all other markets and this quantity must not exceed the available quantity q_s.

$$\sum_{m \in M} z_{sm} \leq q_s, \forall s \in S \tag{7.16}$$

Again, it is necessary to ensure that a supplier (reseller) *s* sends out quantities only if this reseller *s* is not considered, i.e. it is necessary to code the implication $z_{sm} \geq 0 \Rightarrow y_s = 1$ in a linear constraint. We can adjust the corresponding constraint (7.3) and obtain constraint (7.17). In this constraint, K represents a “sufficiently large” number, e.g. K can be set to 1000.000 in the PSS-case scenario. If $z_{sm} > 0$ for a certain market *m* and if Eq. (7.17) should be valid, then it is necessary that $K \cdot y_s > 0$, which is equivalent to the fact that $y_s > 0$ and this means that supplier *s* is considered. This technique to model logical implications between non-binary and binary decision variables is called the “big-K-method” or “big-M-method”. It is necessary to select an appropriate value for K for each scenario that is modeled.

$$\sum_{s \in S} z_{sm} \leq K \cdot y_s, \forall s \in S, \forall m \in M \tag{7.17}$$

Finally, the domains of the incorporated decision variables are declared by constraint (7.18).

$$y_s \in \{0; 1\} \forall s \in S, z_{sm} \geq 0 \forall (s, m) \in T \tag{7.18}$$

Using the aforementioned mathematical expressions, we are now ready to state the CWLP challenge precisely:

It is necessary to minimize the total costs for the installation of facilities and the shipment of packages as expressed in (7.14), so that the each market's demand is covered (7.15), but no supplier distributes more than its local stock quantity (7.16). If we use a facility for supplying a market, then this facility must be open (7.17). Each available facility is either opened or closed and the number of packages to be shipped between each pair of suppliers and markets must be determined (7.18).

A pure formalized problem formulation of the CWLP is the following: minimize (7.14) while the constraints (7.15)–(7.18) are respected. Figure 7.14 represents the

	A	B	C	D	E	F	G	H	I	J	K	L
2												
3	PowerPong Sports - Distribution Costs, Demand and Availability											
4												
5	Distribution costs per loading unit in EUR											
6	i	re-sellers	max.	annual fixed costs	All markets							
7			handling		j=1	j=2	j=3	j=4	j=5	j=6		
8			quantities S_i		FRA	GER	UK	SEE	SVE	NEU		
9	1 (FRA)	TriColor Sportive (FRA)	20000	95000	0,80	2,82	3,75	8,21	7,62	11,18		
10	2 (GER)	TT Profi (GER)	20000	90000	4,80	0,12	5,94	3,93	6,67	7,65		
11	3 (UK)	Competitive Fitness (UK)	15000	70000	6,00	1,88	0,94	8,57	10,00	10,00		
12	demanded packages D_j		55000		5000	8500	3200	2800	2100	1700	23300	
13												
14	Decisions about incorporated re-sellers and established delivery links from re-sellers into markets											
15												
16	i	re-sellers		y_i	delivery quantities (z_{ij})							
17					j=1	j=2	j=3	j=4	j=5	j=6	deliverred	excess
18					FRA	GER	UK	SEE	SVE	NEU	quantities	quantities
19	1 (FRA)	TriColor Sportive (FRA)									0	-20000
20	2 (GER)	TT Profi (GER)									0	-20000
21	3 (UK)	Competitive Fitness (UK)									0	-15000
22	fulfilled demand				0	0	0	0	0	0		
23	uncovered deman				5000	8500	3200	2800	2100	1700		
24												
25	Cost calculation (all values in EUR)											
26												
27	annual fixed costs from selected re-sellers						0					
28	re-distribution costs						0					
29	total costs						0					

Fig. 7.14 A spreadsheet model of the CWLP

CWLP problem in the form of an Excel spreadsheet. The necessity of considering the limited availabilities of supply quantities at the different suppliers (resellers) makes the CWLP solving process more challenging compared to the solving of the WLP. In particular, it becomes necessary to redefine the components of the b&b algorithm used for the WLP. A major difficulty is to decide whether a sub-problem has a feasible solution, i.e., to find out if suppliers already considered and still untreated can provide enough capacity to cover the demand from all markets. The evaluation of a single sub-problem becomes quite complicated and requires huge computational effort. Therefore, we refer the reader to the scientific literature (Daskin 1995; Drezner 1995; Melo et al. 2009; Benyoucef et al. 2013; Askin et al. 2014) and report only a spreadsheet approach for the CWLP.

Figure 7.14 depicts a spreadsheet model that is used to provide all problem data to the Excel Solver. Special attention is paid to the preparation of the handling of the quantity constraints on the maximal supply quantities (7.15) as well as of the least provided quantities to cover the demand of the individual markets (7.16).

The upper part of the spreadsheet from row 1 to row 12 contains the problem parameter now including the locally available stock (column C) as well as the demand expressed from the individual markets (row 12). The cost matrix (E9:J11) contains the costs for shipping a single package unit instead of the annual costs for serving a complete market (the annual costs for the installation of a transportation link in the WLP).

The middle part of the spreadsheet from row 14 to row 23 contains the variable cells (D19:J21). In addition, we calculate the fulfilled demand (row 22) as well as the open (uncovered) demand for each market (row 23). The last mentioned values are used later in the formulation of the constraints propagated to the solver. Furthermore, we can calculate the total sum of deliveries from each supplier (column K) as well as the excess of local stock (column L). We are going to incorporate the stock excess values into the constraints. The lower part of the spreadsheet contains the costs calculated from the parameters as well as from the variable cells (rows 27–29).

In Figs. 7.15, 7.16, 7.17, and 7.18, we describe the building of the constraint system [Eqs. (7.15)–(7.18)] for CWLP.

According to the constraint shown in Fig. 7.15, we enforce the solver add-in to avoid uncovered demand. According to the constraint shown in Fig. 7.16, the solver add-in is instructed to prevent any excess of stock at the suppliers. The Big-K-method to represent the logical dependencies between the usage of a supplier and the delivery quantities coded in constraint (7.17) is shown in Fig. 7.17, where K = 1,000,000,000. Finally, Fig. 7.18 shows the domain specification for the shipped quantities represented by the decision variable family z_{sm}. In Fig. 7.19, the solution to CWLP is presented.

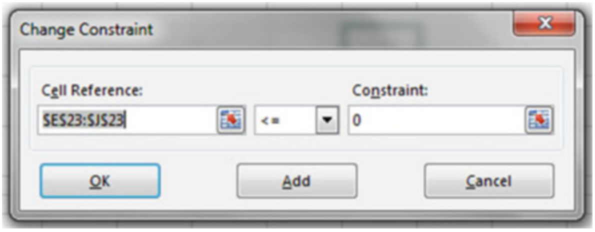


Fig. 7.15 Representation of the demand covering constraint (7.15) in the Excel Solver add-in

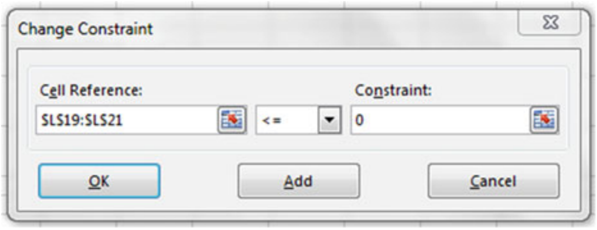


Fig. 7.16 Representation of the limited stock constraint (7.16) in the Excel Solver add-in

Fig. 7.17 Representation of the constraint family (7.17) in the Excel Solver add-in

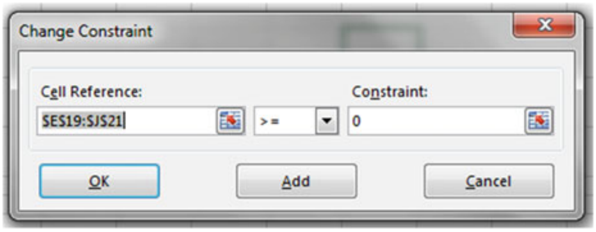


Fig. 7.18 Representation of the constraint family (7.18) in the Excel Solver add-in

In order to test this model, we first use it to solve the WLP scenario. We assumed that each supplier (reseller) is able to handle the overall demand from all markets. Sufficiently high quantities of stock have been specified in the cells C9, C10, and C11. The returned optimal solution is the same as shown in Fig. 7.7. Only reseller #2 is used and the total costs equal 172,000 €.

PowerPong Sports - Distribution Costs, Demand and Availability

Distribution costs per loading unit in EUR

i	re-sellers	max. handling quantities S_i	annual fixed costs	All markets j=1 FRA	j=2 GER	j=3 UK	j=4 SEE	j=5 SWE	j=6 NEU	
1(FRA)	TriColor Sportive (FRA)	25000	95000	0,80	2,82	3,75	8,21	7,62	11,18	
2(GER)	TT Profi (GER)	25000	90000	4,80	0,12	5,94	3,93	6,67	7,65	
3(UK)	Competitive Fitness (UK)	25000	70000	6,00	1,88	0,94	8,57	10,00	10,00	
demanded packages D_j		75000		5000	8500	3200	2800	2100	1700	23300

Decisions about incorporated re-sellers and established delivery links from re-sellers into markets

i	re-sellers	y_i	delivery quantities (z_{ij}) j=1 FRA	j=2 GER	j=3 UK	j=4 SEE	j=5 SWE	j=6 NEU	delivered quantities	excess quantities
1(FRA)	TriColor Sportive (FRA)	0	0	0	0	0	0	0	0	-25000
2(GER)	TT Profi (GER)	1	5000	8500	3200	2800	2100	1700	23300	-1700
3(UK)	Competitive Fitness (UK)	0	0	0	0	0	0	0	0	-25000
fulfilled demand			5000	8500	3200	2800	2100	1700		
uncovered deman			0	0	0	0	0	0		

Cost calculation (all values in EUR)

annual fixed costs from selected re-sellers	90000
re-distribution costs	82000
total costs	172000

Fig. 7.19 Returned optimal solution to the CWLP scenario in the PPS case

In the second experiment, we limit the stock size (max. handling quantity for each reseller) according to the values compiled in Table 7.3. The optimal solution is shown in Fig. 7.20.

In this case, it is necessary to consider a second reseller since TT Profi is unable to handle to total annual demand for the six markets. In the new solution, the model suggests also considering reseller #3. It contributes 100 packages for delivery to market FRA and fulfils the completed UK market demand. The total costs have increased from 172,000 € to 226,120 €. This is an increase of 54,120 €. The consideration of the second reseller incurs 70,000 € in costs per year. Furthermore, the limited handling quantity requires the inclusion of the UK to save the GER market at increased transportation costs of 120 €, but we can profit from cheaper transportation costs into the UK which saves 16,000 €. Therefore, we obtain a total saving of 16,000 €–120 € = 15,880 € in shipment costs, but we have to pay an additional 70,000 € in annual fixed charges to the second reseller.

	A	B	C	D	E	F	G	H	I	J	K	L
2												
3	PowerPong Sports - Distribution Costs, Demand and Availability											
4												
5	Distribution costs per loading unit in EUR											
6			max.	annual fixed costs	All markets							
7	i	re-sellers	handling		j=1	j=2	j=3	j=4	j=5	j=6		
8			quantities S_i		FRA	GER	UK	SEE	SWE	NEU		
9	1(FRA)	TriColor Sportive (FRA)	20000	95000	0,80	2,82	3,75	8,21	7,62	11,18		
10	2 (GER)	TT Profi (GER)	20000	90000	4,80	0,12	5,94	3,93	6,67	7,65		
11	3 (UK)	Competitive Fitness (UK)	15000	70000	6,00	1,88	0,94	8,57	10,00	10,00		
12	demanded packages D_j		55000		5000	8500	3200	2800	2100	1700	23300	
13												
14	Decisions about incorporated re-sellers and established delivery links from re-sellers into markets											
15												
16					delivery quantities (z_{ij})							
17	i	re-sellers		y_i	j=1	j=2	j=3	j=4	j=5	j=6	deliverred	excess
18					FRA	GER	UK	SEE	SWE	NEU	quantities	quantities
19	1(FRA)	TriColor Sportive (FRA)		0	0	0	0	0	0	0	0	-20000
20	2 (GER)	TT Profi (GER)		1	4900	8500	0	2800	2100	1700	20000	0
21	3 (UK)	Competitive Fitness (UK)		1	100	0	3200	0	0	0	3300	-11700
22	fulfilled demand				5000	8500	3200	2800	2100	1700		
23	uncovered deman				0	0	0	0	0	0		
24												
25	Cost calculation (all values in EUR)											
26												
27	annual fixed costs from selected re-sellers						160000					
28	re-distribution costs						66120					
29	total costs						226120					

Fig. 7.20 Returned optimal solution for the CWLP scenario in the PPS case

7.4 Regional Facility Location

The WLP-based approach supports the identification of regions that should be considered for setting up a SC. These regions might be continents, countries, states, or even farms, growing areas, or plantations supplying or consuming products. According to the location planning scheme outlined in Sect. 7.2, the outcome of phase I (the regions to be considered in the prospective SCD) are forwarded into phase II where one or several locations have to be identified for each region as network node.

In the context of the PPS case, the regions are the countries that host the resellers or the markets. A typical phase II decision is now to select a warehouse to which the packages are shipped from China and from where customers in the market receive their deliveries. We can now assume that the regional reseller's existing facilities are too small to handle the additional freight flow associated with the celluloid-free balls and the reseller is looking for a new location in the associated country to build or rent a new warehouse. This section addresses the particular problem of identifying promising candidates for establishing a new facility that can handle incoming and outgoing materials as part of the global SC. In particular, we will

- become familiar with typical phase II decision problems related to location planning;
- introduce a simple model of *center-of-gravity* representing a phase II decision situation;
- develop simple mathematical calculations for the identification and determination of the coordinates of an optimal location;
- consider available demand knowledge while deriving such an optimal location by solving the so-called Steiner-Weber model;
- learn how the *Miehle algorithm* can be used to solve the *Steiner-Weber model*.

We start in Sect. 7.4.1 with the verbal description of the typical phase II decision problem. Next, in Sect. 7.4.2, we propose a modeling approach for a phase II decision problem. In Sect. 7.4.3, we discuss a mathematical calculus for the derivation of the optimal solution of the location model.

7.4.1 Management Problem Description

We consider the phase II decision situation of TT Profi, the German reseller selected by PPS as part of its global SC. TT Profi is looking for a new warehouse in Germany to receive the inbound material flow from the PPS factory in Shanghai. From this facility the five major local retail partners in Germany, shown in Table 7.6, receive their deliveries.

Each delivery is executed by a small forwarding company which is paid according to the distance between the pickup point and the delivery point of a shipment. In order to keep the distribution costs as low as possible, TT Profi wants to open its new warehouse at a location that leads to the smallest annual transportation distance to be bridged. The chairman of TT Profi wants to know at which coordinates the new warehouse should be placed to minimize total transportation costs from the warehouse to all customers.

7.4.2 A Mathematical Model of the Decision Situation

The relevant issues in this decision problem are customer locations, distances from the warehouse to customers, and customer demands. Each customer location is represented by the ordered pair of (x;y)-coordinates. The (x;y)-coordinates of the five locations are given in the third as well as fourth column of Table 7.6. These data cannot be modified; they are input data or problem *parameters*. The coordinates of customer *i* are named $(x_i;y_i)$, e.g. $(x_1;y_1) = (10;-80)$ and so on. Demand for each customer is also given and denoted as $D(x_i;y_i)$.

In contrast, the (x;y)-coordinates $(p_x;p_y)$ of the new warehouse are variable and have to be determined. Consequently, p_x as well as p_y are the *decision variables* in the investigated decision scenario.

We *assume* that the total transportation cost sum is proportional to the distance and the transportation volume (i.e., the demand). This leads us to the formulation of the *objective function,* as shown in Eq. (7.19):

Table 7.6 German customers of TT Profi

i	Name	Coordinates		Annual demand
		x_i	y_i	$D(x_i;y_i)$
1	Sport 1-2-3 KG	10	−80	3 t
2	TT direct	−45	−30	1 t
3	Sports and fun	60	50	1.5 t
4	Leisure outlet	45	−75	3.5 t
5	Raquets & more	−75	80	2 t

$$Z(p_x;p_y) = \sum_{i-1}^{N} d((p_x,p_y);(x_i,y_i)) \cdot D(x_i,y_i) \rightarrow \min \qquad (7.19)$$

We can observe that the total transportation costs depend on the coordinates p_x and p_y of the prospective warehouses and distances. We assume that total transportation cost sum from the prospective warehouse location (p_x;p_y) to a customer location (x_i;y_i) is more or less equivalent to the distance and demand. Therefore, the distance d((p_x;p_y); (x_i;y_i)) between the *i*th customer location and the warehouse should be determined to calculate transportation costs.

To minimize the payments to the forwarding company, it is necessary to vary p_x as well as p_y as long as Z(p_x;p_y) becomes minimal. The minimization of (7.19) represents the decision situation of identifying the lowest cost facility for TT Profi, so that it can be understood as a model for the decision situation outlined in Sect. 7.4.1.

7.4.3 Solving the Mathematical Model: Centre-of-Gravity Approach

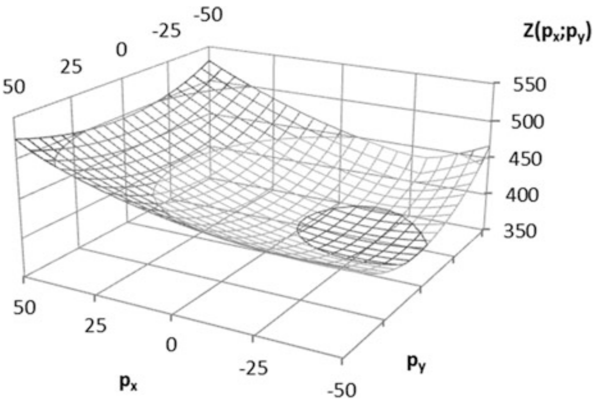
We call each pair (p_x;p_y) that minimizes (7.19) an optimal solution of the model (7.19). Since there are no further limitations to be considered that restrict the selection of values of p_x or p_y, the decision problem represented by (7.19) falls into the category of *global optimization* problems. All possible values of p_x and p_y represent a feasible solution of (7.19) and are therefore candidates to become the optimal solution.

There are two options for calculating the distances. The first option is to use *direct line distance* (Euclidean distance) and the second one is the *orthographic (square)* distance calculation. According to the first option, distance equals the Euclidean distance between these two points in the plane. This value can be determined according to Pythagoras' Theorem leading to Eq. (7.20).

$$d((p_x;p_y);(x_i;y_i)) = \sqrt{(x_i - p_x)^2 + (y_i - p_y)^2} \qquad (7.20)$$

Figure 7.21 depicts the total distance from the warehouse to all customers in dependence of the warehouse coordinates (p_x;p_y) (*without demand considerations*). We observe that the function Z shows exactly one minimum; this means there is

Fig. 7.21 Total distance to all customers (objective function value) in dependence of the values of p_x as well as p_y (all values given in kilometres)



exactly one pair (p_x;p_y) that minimizes Z. Reading the exact values of this optimal pair is hardly possible. Furthermore, if the number of customers N is quite high then drawing a similar picture requires huge computational efforts. For these reasons, a quicker and more reliable method for the determination of the pair of optimal warehouse coordinates is required.

The function Z is continuous and differentiable and the decision variables are unrestricted. Hence, we can determine the optimal point of Z by differential calculus. The following consecutive steps have to be executed in the given order.

1. The first derivative Z′ of Z is determined and
2. The zero of Z′ is determined.

$$\frac{dZ}{dp_x} = \frac{Np_x}{\sqrt{(x_i - p_x)^2 + (y_i - p_y)^2}} - \sum_{i=1}^{N} \frac{x_i}{\sqrt{(x_i - p_x)^2 + (y_i - p_y)^2}} \tag{7.21}$$

$$\frac{dZ}{dp_y} = \frac{Np_y}{\sqrt{(x_i - p_x)^2 + (y_i - p_y)^2}} - \sum_{i=1}^{N} \frac{y_i}{\sqrt{(x_i - p_x)^2 + (y_i - p_y)^2}} \tag{7.22}$$

We start with the situation in which we do not consider individual demand, i.e. $D(x_i;y_i) = 1$ for all i. Since Z is a function of the two decision variables p_x as well as p_y, the derivative Z′ consists of the two partial derivatives (7.21) and (7.22). They can be determined by considering p_y and p_x respectively as invariant.

$$p_x = \frac{\sum_{i=1}^{N} x_i}{N} \tag{7.23}$$

$$p_y = \frac{\sum_{i=1}^{N} y_i}{N} \tag{7.24}$$

Setting the right-hand part of Eq. (7.21) equal to 0 leads to the formula (7.23) and setting the right-hand side of Eq. (7.22) equal to 0 results in the formula (7.24). These two formulas (7.23) and (7.24) can be used to determine the optimal values of the coordinates of the warehouse.

Application of the developed formulas determines the optimal location of the warehouse for TT Profi. We get the optimal coordinates $p_x = \frac{10-45+60+45-75}{5} = -1$ and $p_y = \frac{-80-80+50-75+80}{5} = -11$. Using these two formulas enables us to derive an optimal solution of the model (7.19) (without demand considerations) from the problem parameters provided.

We now incorporate the *demand* associated with each customer subject in the model (7.19). This is necessary since a forwarding company is typically paid according to the bridged distance and quantity moved. The product of distance (measured in km) and weight (measured in tons) is called the transport performance. It is expressed in ton kilometers (tkm).

The model (7.19) is called the *center-of-gravity model* of location analysis (Chopra and Meindl 2012) or the *Steiner-Weber model* (Domschke and Drexl 1985). Using demand data, formulas (7.25) and (7.26) are used to calculate optimal coordinates.

$$p_x = \frac{\sum_{j=1}^{N} \frac{D(x_j;y_j)\cdot x_j}{\sqrt{(p_x-x_j)^2+(p_y-y_j)^2}}}{\sum_{j=1}^{N} \frac{D(x_j;y_j)}{\sqrt{(p_x-x_j)^2+(p_y-y_j)^2}}} \tag{7.25}$$

$$p_y = \frac{\sum_{j=1}^{N} \frac{D(x_j;y_j)\cdot y_j}{\sqrt{(p_x-x_j)^2+(p_y-y_j)^2}}}{\sum_{j=1}^{N} \frac{D(x_j;y_j)}{\sqrt{(p_x-x_j)^2+(p_y-y_j)^2}}} \tag{7.26}$$

The determination of an optimal pair of coordinates for the warehouse again requires the determination of the directional derivatives. These two functions are then set equal to 0 and we get the expressions (7.25) and (7.26), respectively, to express p_x and p_y. Unfortunately, these characterizations of p_x and p_y are recursive, which means that we need p_x (on the right-hand side of the equation) to calculate p_x. The same problem is observed for the determination of p_y. It is impossible to transform the two equations so that the recursion is avoided. We cannot determine the values of $(p_x;p_y)$ as we did in the case without demand data. Another approach is required.

In order to break the circulation in the formulas (7.25) and (7.26), Miehle (1958) proposes an approximation approach. The basic idea of the *Miehle algorithm* comprises the consecutive calculation of a sequence of solutions $(a_0;b_0)$, $(a_1;b_1)$, $(a_2;b_2)$, . . . of (7.19). The values of $(a_i-_1;b_i-_1)$ are used as p_x- and p_y-values in the right-hand part of the Eqs. (7.25) and (7.26) and they are used to calculate the next solution $(a_i;b_i)$. This approach represents an example of a recursive calculation. If we calculate the coordinate pairs in this way, then the sequence of objective function values $Z(a_0;b_0)$, $Z(a_1;b_1)$, $Z(a_2;b_2)$, . . . decreases and converges towards the minimal possible performance value. Therefore, the sequence of calculated coordinates approximates the optimal pair of coordinates of the new warehouse with respect to the minimization of the overall required transport performance.

We demonstrate the application of the Miehle algorithm and apply it to the example data given in Table 7.6. Ignoring customer demand, we can determine a first coordinate pair $(a_0;b_0)$ by means of the application of the formulas (7.23)–(7.24), so that we start with $(a_0;b_0) := (-1;-11)$. The required performance is Z $(-1;11) = 89{,}738$ tkm.

If we set $p_x = a_0 = -1$ and $p_y = b_0 = -11$ in the right-hand sides of (7.25) and (7.26), then we get the updated solution $(a_1;b_1) = (8{,}78;-36{,}16)$ with a reduced required performance value $Z(8{,}78;-36{,}16) = 80{,}837$ tkm. The next iterations are similarly repeated and an existing solution is replaced by an updated one, re-applying the formulas (7.25) and (7.26) (see Table 7.7).

Unfortunately, there is no guarantee that the iterative process terminates after a particular number of repetitions. For this reason, we stop the solution update as soon as we observe that the original solution $(a_i;b_i)$ and its update $(a_{i+1};b_{i+1})$ have become similar. Here, we call two solutions similar if the distance between the two represented points is less than 0.05 km. In the TT Profi example, we stop the Miehle algorithm after ten iterations since the tenth solution proposal (20.50;−66.10) and its update (20.49;−66.14) are less than 0.05 km away from each other (column 6 in Table 7.7). Letting the coordinates for the warehouse be (20.49; −66.14), the total transportation cost is 751.32 €, subject to (7.19).

Table 7.7 Iterations of the Miehle algorithm applied to the TT Profi data

Iteration	Old solution		Updated solution			Costs
i	a_i	b_i	a_{i+1}	b_{i+1}	Distance	$Z(a_i;b_i)$
0	−1.00	−11.00	8.78	−36.16	26.99	897.38
1	8.78	−36.16	14.69	−50.10	15.14	808.37
2	14.69	−50.10	18.05	−58.14	8.71	771.93
3	18.05	−58.14	19.64	−62.48	4.62	757.29
4	19.64	−62.48	20.28	−64.57	2.18	752.67
5	20.28	−64.57	20.49	−65.48	0.94	751.58
6	20.49	−65.48	20.53	−65.87	0.39	751.37
7	20.53	−65.87	20.52	−66.03	0.16	751.33
8	20.52	−66.03	20.50	−66.10	0.07	751.32
9	20.50	−66.10	20.49	−66.14	0.04	751.32

We have seen in the example application of the Miehle algorithm that the Z-objective function value decreases after each executed update and the original point and its update become more and more similar. Now, we summarize the steps of the Miehle approach:

Start: determine an initial pair of coordinates (a_0;b_0) by applying (7.21) to determine a_0 and (7.22) for determining b_0.

Iteration: as long as the distance between the point (a_i;b_i) and its update (a_{i+1};b_{i+1}) exceeds a given threshold, then start another update cycle. Otherwise return (a_{i+1};b_{i+1}) as approximation of the (unknown) optimal solution of the gravity-location model (7.19).

The evolution of the intermediate solutions during the execution of the Miehle algorithm is shown in Fig. 7.22. We can observe that the original proposal (the dark triangle) is far away from the final proposal (the diamond). Since Leisure Outlet requests the largest quantity from TT Profi, it is reasonable to position the warehouse close to this important customer.

If the customer Rackets & More increases its annual demand quantity to 8 tons, then it is beneficial to place the new warehouse in the upper left-hand area of the operations field. This shows that the selection of the right warehouse location is

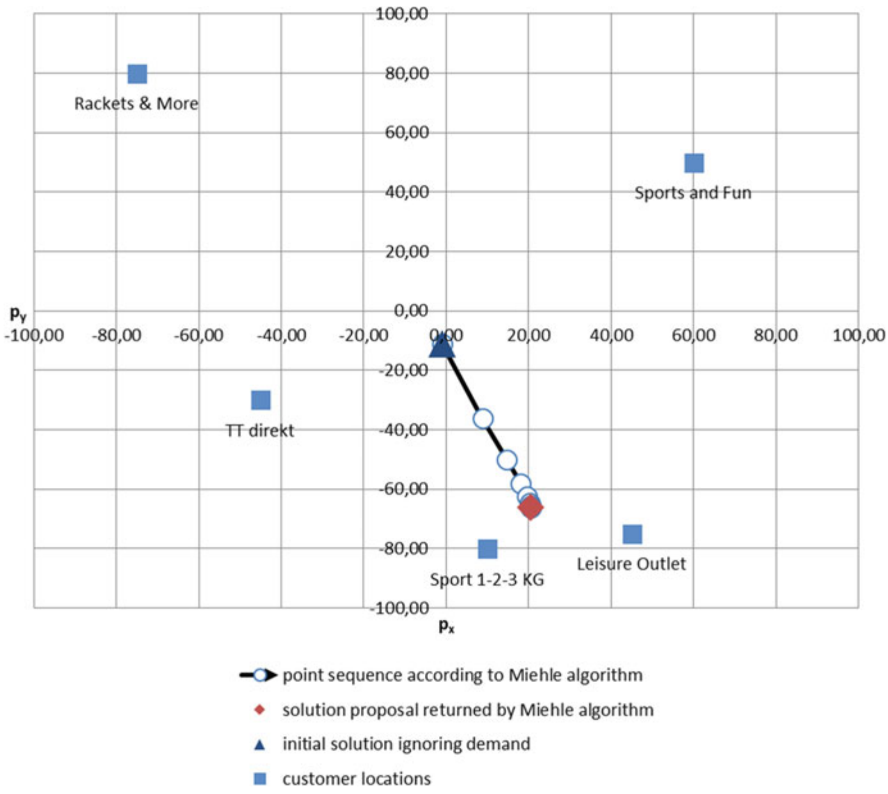


Fig. 7.22 Graphic representation of the progress of the Miehle algorithm

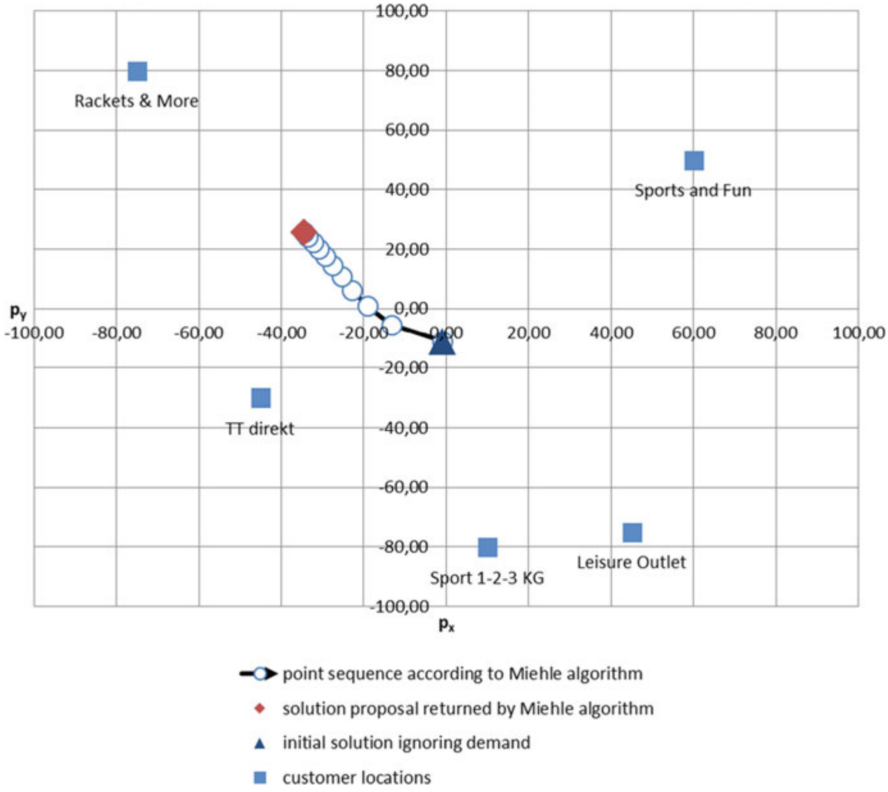


Fig. 7.23 Graphic representation of the progress of the Miehle algorithm if Rackets & More should demand 8 tons

responsive to the demand data. It is therefore very important to take trustworthy and stable demand estimations to select the right warehouse (see Fig. 7.23).

Note: An Excel file containing a spreadsheet model of the Miehle approach to the TT Profi setting can be found in the E-Supplement.

In a second option for distance calculation, we use the rectangular method as shown in formula (7.27), followed by (7.28)–(7.29) to determine $p_x; p_y$:

$$d\left(\left(p_x; p_y\right); \left(x_i; y_i\right)\right) = |x_i - p_x| + \left|y_i - p_y\right| \tag{7.27}$$

$$p_x = \frac{\sum_{i=1}^{N} D_i \cdot x_i}{\sum_{i=1}^{N} D_i} \tag{7.28}$$

Table 7.8 German customers of TT Profi

i	Name	Coordinates		Distances from (7,5; −27)	Demand
		x_i	y_i	$d(x_i;y_i)$	D_i
1	Sport 1-2-3 KG	10	−80	55.5	3 t
2	TT direct	−45	−30	55.5	1 t
3	Sports and Fun	60	50	129.5	1.5 t
4	Leisure Outlet	45	−75	85.5	3.5 t
5	Racquets & More	−75	80	189.5	2 t

$$p_y = \frac{\sum_{i=1}^{N} D_i \cdot y_i}{\sum_{i=1}^{N} D_i} \quad (7.29)$$

Using data from Table 7.6, we get $p_x = \frac{30-45+90+157.5-150}{11} = 7.5$ and $p_y = \frac{-240-30+75-262.5+160}{11} = -27$

The calculation of distances is shown in Table 7.8.

Subject to Eq. (7.19), total cost is calculated as follows assuming that costs per kilometer are $1.00:

$$Z = 55.5 \cdot 3 + 55.5 \cdot 1 + 129.5 \cdot 1.5 + 85.5 \cdot 3.5 + 189.5 \cdot 2 = 1094.5$$

We can observe that total costs in the second case are higher than the result of the Miehle algorithm. This can first be explained by the larger distances in the square method compared to the Euclidian distances. Second, we used a simplified procedure for coordinate calculations without improving them with the Miehle algorithm. Using the Excel file in the E-Supplement of this book, you can prove that letting initial coordinates from Table 7.7 be (7.5;−27), then the Miehle algorithm would provide the same coordinate solution as for the initial case with coordinates (−1;−11). Setting these optimal coordinates (20.49;−66.14) in (7.19) and using square distance metrics, calculate total transportation costs and compare this to the solution with Euclidian distances!

Note: In case of different costs per kilometer in different directions, Eqs. (7.25), (7.26), (7.28), and (7.29) need to be extended. More specifically, the numerators and denominators of the given equations need to be multiplied by the costs for each individual customer, i.e., in each individual component of the sum functions.

7.5 Factor-Ranking Analysis

7.5.1 Case-Study OTLG Germany

Volkswagen Original Teile Logistik GmbH & Co. KG (OTLG) is a service partner for spare parts of Volkswagen, Volkswagen Nutzfahrzeuge, Audi, Seat and Škoda. OTLG is part of the wholesale level in the SC and responsible for sales and marketing in Germany. At present, OTLG operates in seven locations in Germany.

The company's annual revenue is almost 2.5 billion euros. It serves almost 5000 partners in Germany and occupies a total warehouse space of more than 300,000m^2 (equivalent to 47 football pitches). Annually 45,000,000 materials call-off, pick-up, and delivery actions take place, corresponding to approximately 200,000 daily operations.

During the logistics optimization project DNO D (distribution network optimization), OTLG's distribution network was redesigned. Eleven distribution centers (DC) were consolidated into eight as shown in Fig. 7.24.

Among them, a new DC VZ Brandenburg in Ludwigsfelde was established (see Fig. 7.25). The first step was to select a location for the new DC. Initially, many potential locations and selection criteria were identified, as shown in Fig. 7.26. Next, a short list of preferable locations was established (Fig. 7.27).

After evaluation, the location Preußenpark was selected because it had the best scores for the listed criteria. In Fig. 7.28, the new DC is shown.

First, excellent rail and road connections made the selected location preferable. These criteria are crucial for OTLG because of highly dynamic logistics. Daily, 250 trucks are used for regular supplies and 200 small vans are used for day-to-day supplies. This ensures that 98% of orders are fulfilled within 24 h. The total SKU number reaches almost 100,000 positions with an inventory value of 43.2 million euros. Daily, in excess of 30,000 positions are delivered, making it possible to supply 402 VW/Audi and 476 SEAT/Škoda customers with original spare parts.

Discussion

1. Analyze the redesign of the OTLG distribution network. Which type of logistics network has been implemented? Why look for a new location in Brandenburg?
2. On the basis of this case study, describe the basic steps in facility selection decisions! Why were the logistics criteria so important for OTLG? Which criteria would be important, e.g., for the case of a new hotel?

7.5.2 Factor-Rating Method

Having seen how OTLG GmbH & Co. KG conducted their analysis to identify the right location for their distribution center, we need to take a deeper look at the related decision criteria and decision-making procedure. The OTLG case study demonstrated that the region around Berlin, in combination with excellent

Fig. 7.24 OTLG footprint in Germany (© OTLG GmbH & Co. KG)

infrastructure (road/rail connection), highly influenced their decision. In other words, the availability of infrastructure was the factor with the highest priority for OTLG GmbH & Co. KG.

As you can imagine, not all companies will rate the criterion "infrastructure" as the most important in selecting a new facility location. This means that different

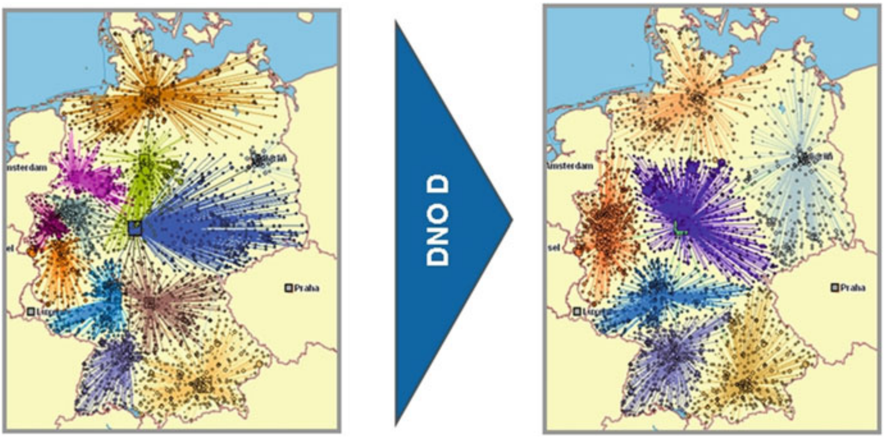


Fig. 7.25 Distribution network re-design at OTLG (© OTLG GmbH & Co. KG)

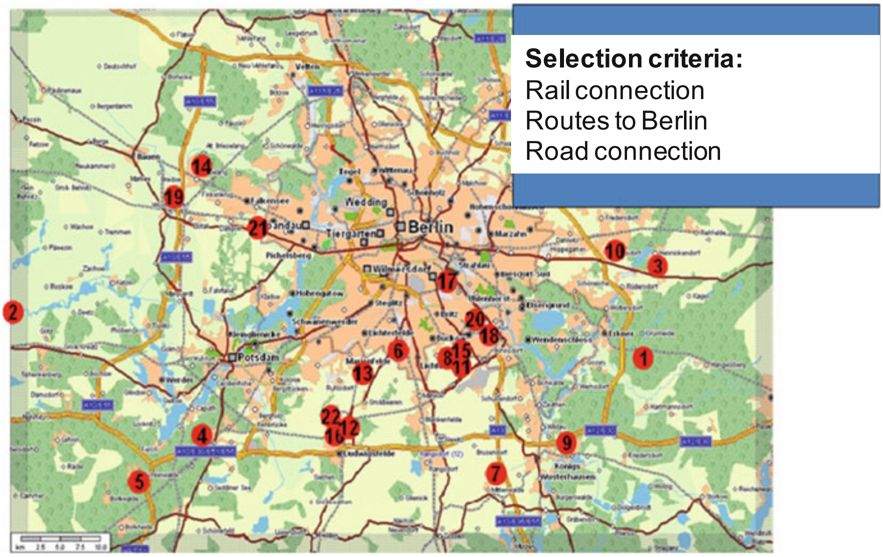


Fig. 7.26 Facility location planning at OTLG (© OTLG GmbH & Co. KG)

companies will select different location criteria or location factors which have different priorities. Therefore, we need to take a closer look at the generic list of possible *plant location criteria*.

Location criteria can be divided into *quantitative* and *qualitative* areas, as summarized in Table 7.9.

Fig. 7.27 Detailed stage of the facility location planning at OTLG (© OTLG GmbH & Co. KG)

Fig. 7.28 New distribution center in Ludwigsfelde (© OTLG GmbH & Co. KG)

Table 7.9 Facility location selection criteria

Quantitative criteria	Qualitative criteria
Transportation costs	Infrastructure
Building and construction costs	Quality of labor
Rental costs	Transportation development
Labor costs	Purchasing power
Material costs	Options for financing (free trade zones, etc.)
Taxes	Suppliers
Financial support from local governments	Political risks
	Natural disaster risks
	Proximity to customers and suppliers
	Business climate
	Environmental regulations
	Competitive advantage
	Government and trading barriers

> **Practical Insights** In practice, the list of location selection criteria is the first step in facility location planning. On the one hand, this list can become long very quickly. This is why it is common practice to build main and sub-groups of criteria to facilitate a clear understanding of the list structure. On the other hand, many experts from different departments are involved with setting up this list. It may take quite a long time to find a compromise on which criteria should be included.

The next step is to evaluate different potential locations according to the defined factors. The *factor-rating method* is a very easy. The team in charge of identifying the new location selects the relevant criteria. As we will see later, this depends on the industry specifics, i.e., each company in a certain industry will compose an individual company-centerd list of site location factors.

To make the process very tangible, let's assume that we are consultants and we need to support another company like OTLG GmbH & Co. KG in their decision-making process. Imagine that in our consulting team, we have compiled the following list with six criteria, as shown in Table 7.10. According to importance, the team decides the maximum amount of points that can be obtained per location factor. For the criterion "Infrastructure" this might hypothetically be 300 points, maximal. Then the team assigns the points for each of the options and per factor.

> **Practical Insights** It might be a reasonable to let the team members make their rating individually and then calculate the averages per factor and option. The individual score sheets are archived so that the pathway of decision making is fully transparent and reproducible for later reviews.

Table 7.10 Factor-rating model

Location factor	Range min-max	Location A	Location B	Location C
Infrastructure	0–300 pts	213	232	204
Proximity to suppliers	0–200 pts	170	182	186
Proximity to customers	0–200 pts	180	171	192
Other facilities	0–150 pts	113	156	78
Quality of labor	0–100 pts	72	65	85
Cost of energy	0–50 pts	42	48	32
Sum	0–1000 pts	790	854	777

For example, if the operations management team consists of five members and each individual scores the first factor of the first option, the resulting scores might look like this:

Member 1: scores 210
Member 2: scores 230
Member 3: scores 220
Member 4: scores 200
Member 5: scores 205.

On average, this will result in 1065/5 = 213 points for the first factor "Infrastructure" for option A. For all other criteria, a similar exercise should be done in practice so that a completely transparent rating can be presented to senior management.

The option that receives the highest score is the one that is suggested as the most suitable new location. In our example, this is location B. If the scores of different options are very close to each other, a *sensitivity analysis* is mandatory.

Shortcomings of the factor-rating method include the fact that the weighting percentages assigned per factor are not clearly visible. A useful method for overcoming this is the so-called *utility value analysis*.

7.5.3 Utility Value Analysis

We will elaborate the principle approach followed by the *utility value analysis* (see Günther and Tempelmeier 2009) in connection with a theoretical case, in which a global player developed a strategy to produce and distribute its goods in Asia.

Just imagine that the top management of a globally functioning firm has asked the SCOM team to look for a suitable location to create a new factory in Asia. The sales department of that hypothetical global firm might have assessed that the market for the firm's products is growing significantly in, for example, India. As a consequence, the SCOM team will run an assessment on potential locations there.

The following list provides an overview for finding a location for a new production facility depending on the different levels of the location decision problem.

Step 1 Selection of the Economic Region First of all, the respective continent for the economic region or trade-zone where the search for an appropriate location should be conducted must be specified,.

In the first step, the following criteria are extremely important:

- attractiveness of the economic region;
- expected sales potential and/or market development;
- political stability of the region;
- legal requirements regarding the establishment of a production facility, etc.

Step 2 Selection of a Country Within the Economic Region Our theoretical case also shows that the options need to be further streamlined, i.e., the search for a site has to be narrowed down (here it is focused on India). This means in the continent of Asia (Step 1); the sub-continent India has been identified in Step 2 for the execution of the location planning and location analysis. Besides the expected market development, there are also such location factors as:

- labor availability;
- quality of human resources, for example, education levels;
- salary and/or wage levels;
- local/regional support for the location of a new facility;
- local/regional support regarding business development;
- availability of appropriate suppliers;
- availability of transport-technology and/or infrastructure which play an important role.

Step 3 Selection of a Region Within the Country in the Economic Region In the third step, the sub-continent or maybe country identified has to be further assessed by the SCOM team. This means a certain kind of county or district will be identified for the placement of the new production facility. In reality, there will most probably be multiple options available and it will be the task of the experts to identify the best location for the company. To do this, further criteria have to be taken into consideration; these are be presented next.

When we refer back to our example, the decision-making operations team for the identification of the new facility in India will need to evaluate different alternatives. This means a long list of alternative sites is drawn up and different options then need to be critically assessed. This critical assessment has to be reproducible and needs to be compiled in such a way that the top management can trace back the different steps that led to the identification of the preferred location(s). In practice, a table will be compiled that shows the different alternatives, which are then mapped and rated against a defined list of location factors (criteria). This is the fundamental principle of the utility value analysis. These criteria can be:

- connection to available infrastructure (e.g. roads, rail, ports, airports);
- availability of utilities (such as electricity or water for cooling);

- availability of raw-material (e.g. iron for steel production);
- availability of green-field properties or existing objects/facilities;
- subsidies or taxation benefits, etc.

Step 4 Selection of the Facility Location In Step 4, the final decision for the selected location has to be substantiated in case there are multiple possible properties available on the same pieces of land. Imagine, for example, that there might be a newly created industrial park where the home community offers different properties for sale. Therefore, the above mentioned location factor table will provide evidence for identification of the most suitable plot of land for the new facility. Final decision factors could therefore be:

- geographic dimensioning of the land (either more longitudinal or rectangular or maybe triangular shape of the property);
- topographic suitability or existing constraints (e.g. hilly grounds or existing electrical pylons);
- cost of the property and later options for enlargement/expansion;
- opportunities for suppliers to locate nearby;
- environmental constraints (e.g. regarding emissions);
- connection to existing infrastructure (accessibility for inbound flows and also shipment of finished goods outbound).

The principle *sequence of the activities* that need to be performed by the SCOM team to conduct such a utility value analysis is as follows:

1. Identify location options.
2. Determine decision criteria (location factors) and their measurement.
3. Determine weighting totalling 100% for the different criteria.
4. Evaluate every location option on a normalized scale to achieve "partial utility values" with a scale from 1 to 10 points (in which 10 = best).
5. Calculate the "total utility value" of a location option by multiplying "partial utility values" with weights and adding these values.
6. Choose the option with the highest "total utility value".

Table 7.11 depicts a simplified example of the potential application of the utility value analysis.

The possible location factors presented above are respective indications of inspirations for the SCOM team. In practice, the location criteria will be different depending on the respective industry and will have different priorities. For example, for a chemical company, ecological restrictions are extremely important and for heavy industry the availability of required resources will most probably have a significant influence on the decision-making process. Also factors such as the company's other existing facilities in the given region might influence the decision about a new site.

Table 7.11 Utility value analysis

Location factor	Weight (%)	Option X		Option Y		Option Z	
		Points	Partial value	Points	Partial value	Points	Partial value
Infrastructure	*35*	7	2.45	8	2.80	6	2.10
Proximity to suppliers	*20*	6	1.20	7	1.40	8	1.60
Proximity to existing sites	*20*	8	1.60	4	0.80	9	1.80
Expansion potential	*10*	6	0.60	7	0.70	7	0.70
Quality of labor	*10*	8	0.80	3	0.30	8	0.80
Topography	*5*	10	0.50	8	0.40	9	0.45
Sum	100						
Total utility value			7.15		6.40		7.45

▶ **Practical Insights** Facility location planning decisions imply the usage of both quantitative and qualitative methods. Despite rigor and technical power, simulation and optimization methods are not the dominant techniques in decision-making on facility location planning and SCD. In practice, these decisions are typically driven by corporate policies and are analyzed with the help of business cases and empirical data.

Case Study "Niedersachsen Park" (Based on www.niedersachsenpark.de)
The objective of this case study is to find out why the Adidas Group selected the Niedersachsenpark as a location for its new distribution center. The Adidas Group is the world's second-biggest sports goods manufacturer and is headquartered in Herzogenaurach, Germany. In Germany, the Adidas Group has three distribution centers. Two of them are in the area of the group's headquarter in Bavaria and the third one, which opened in 2013, is located in Niedersachsenpark, the largest industrial and commercial area in Lower Saxony. This newly established distribution center is the group's largest in terms of throughput. In 2015, the Adidas Group expects a throughput of 100 million pieces per year at this distribution center. In comparison, the two distribution centers in Bavaria (in Uffenheim and Scheinfeld) together achieve a total throughput of 80 million pieces.

Besides the expected throughput, the new distribution center in the Niedersachsenpark has further advantages such as its location. In contrast to the locations in Bavaria, this one is directly located on highway A1 and the main harbors are easily accessible from this location. This is extremely important for the Adidas Group as the main components of its products arrive in Germany by sea (Hamburg, Bremen, Bremerhaven). Therefore, the group can decrease transportation costs from the harbors to the distribution centers. Furthermore, since Niedersachsenpark is a newly established industrial and commercial park, it was highly flexible in terms of construction and development plans for fulfilling the Adidas Group's requirements.

Table 7.12 Factor-rating and utility value analysis

Key success factor	Weight	Scores (out of 100)		Weighted scores	
		N-Park	Bavaria	N-Park	Bavaria
Total scores					

Additionally, the construction rights for the whole area are regulated. There was no possibility of public disputes that might cause long waiting times or potential reputation damages before they started operating at this location. Since there are no residential areas in the immediate vicinity of Niedersachsenpark, the distribution center is allowed to operate 24/7, as opposed to 17 h per day in Uffenheim and Scheinfeld. This allows for highly efficient processes at Niedersachsenpark. Another significant advantage of Niedersachsenpark was the chance to reserve areas for potential future expansion. Companies can reserve these areas in case they do not want to exclude possible future expansion, but as yet do not have any concrete plans. This advantage creates a valuable degree of flexibility for the organizations located in Niedersachsenpark.

To sum up, the advantages outlined indicate that Niedersachsenpark was a favorable location for the Adidas Group's new distribution center. In many aspects, it surpasses the distribution centers in Bavaria. According to Lars Mangels (Corporate Communication Manager at Adidas Group), Niedersachsenpark meets all the requirements that they expect from a location for a distribution center.

The case study reveals that Niedersachsenpark is the optimal location for the Adidas Group's new distribution center. Do you agree? Apply the factor-rating and utility value analysis methods to this case (N-Park = Niedersachsenpark; Bavaria = Uffenheim&Scheinfeld) (use Table 7.12).

7.6 Combining Optimization and Simulation in Supply Chain Design

Consider a combination of simulation and optimization that seeks to find optimal locations for facilities and allocate customers to those locations subject to supply chain profit maximization (i.e., we consider location-allocation problems). Figure 7.29 depicts major interdependencies between the parameters in supply chain design.

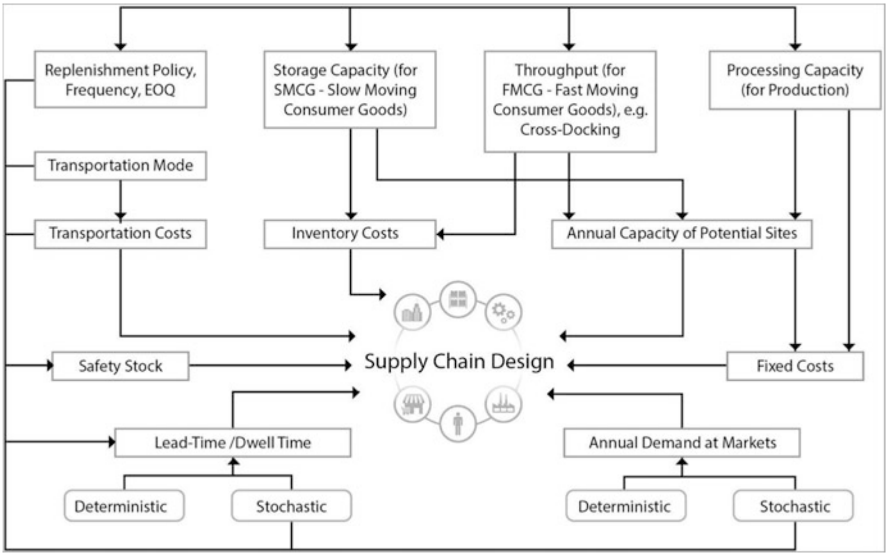


Fig. 7.29 Supply chain design analysis framework

Network optimization can be used for a number of supply chain design problems such as:

- *Incapacitated and capacitated plant location problem;*
- *Distribution network design;*
- *Distribution network design with inventory, lead time, and transportation mode selection;*
- *Production-distribution network design;*
- *Hub location problem;*
- *Supply network design with operational risks;*
- *Supply network design with disruption risks.*

In a generalized form, supply chain design using network optimization considers such parameters as

- Alternative facility locations,
- Customers (markets),
- Production, inventory processing, and transportation costs,
- Fixed facility costs and inventory holding costs,
- Minimum and maximum throughputs and capacities in production, transportation, and storage,
- Demand in the markets,
- Number of periods and products,
- Bill of materials.

The variables to be optimized are facilities to be included in the supply chain design and quantities (flows) to be delivered from sources to destinations in the supply chain. The solutions are usually constrained by maximum/minimum demand in the markets and minimum and maximum throughputs and capacities in production, transportation, and storage. The objective function minimizes total costs.

Even though network optimization can lead to useful insights, some dynamic issues, such as inventory, sourcing, and shipment control policies are not considered within this framework of analysis. As such, simulation can be a useful extension of a network optimization, because it enables consideration of time-dependent uncertainties, such as demand and lead-time fluctuations (i.e., operational risks) and facility breakdowns (i.e., disruption risks). Moreover, simulation can be used to validate optimization results in dynamic and uncertain environments (cf. Chap. 3).

7.7 Key Points

This chapter introduced the problems, models, and techniques for managing location decisions in the context of a supply network setup. We received insights into location analysis processes and understand the importance of selecting the right location for facilities during the formation of a supply network. There are several different important decision tasks to be solved before the network can be set up. We have introduced an SCD framework for aligning these decisions. Finally, we have become familiar with the tools for supporting SCD decisions. The selection of an approach mainly depends on the problem data we want to consider for obtaining optimal decisions.

Section 7.3 provided an introduction into an important decision problem of location planning. The WLP addresses the challenge of researching markets and suppliers and forging transportation links between markets and suppliers from a longer term perspective. The goal of warehouse location planning is the minimization of the total costs for SCD. With the help of the PPS example, we analyzed a typical WLP setting as well as the relevant planning data.

We investigated a model-based approach to identify the best SCD. First, we proposed a mathematical optimization model for the WLP. Second, we configured and applied a spreadsheet decision support tool using the Excel Solver add-in. Third, we learned the technique of branch-&-bound as a general approach for deriving optimal design options for the WLP model. Finally, we analyzed the impacts of limited product availability at certain suppliers for the SCD and introduced the CWLP model for which we configured a spreadsheet-based tool to derive optimal solutions.

It can be concluded that mathematical programing techniques are useful and powerful tools for improving decisions for SCD. They allow for consideration of demand, capacity, and costs while determining global SCD. At the same time, the application of these tools in real life should be considered subject to numerous limitations, such as assumptions on linear functions, deterministic parameter values, and computational complexity. A solution to the mathematical model is not automatically a managerial decision! Up-to-date research trends are involved in consideration of non-deterministic parameters (Lim et al. 2013), reliable SCD (Snyder and Daskin 2005; Klibi et al. 2010; Li et al. 2013), and the ripple-effect in SCs (Ivanov et al. 2014).

Section 7.4 considered the next stage in SCD, where all regions are processed individually. In each region, specific locations (expressed by coordinates) are identified at which a facility can be installed or from which supply quantities can infiltrate the SC. The output of this phase is suggestions for locations for opening facilities with regard to cost efficiency. We learned how to apply the center-of-gravity method to facility location decisions and how to determine optimal location, coordinated with the help of a simple average method and the Miehle algorithm. The center-of-gravity method can help determine the location of one warehouse subject to minimal transportation costs. It is a simple method which is easy to implement. The shortcomings are linear assumptions, impossibility of considering multiple locations, deterministic data, and poor consideration of geographic and real road infrastructure.

In Sect. 7.5, multiple criteria analysis was considered reaching beyond cost minimization. We learned factor-rating and utility value analysis methods, and their advantages and limitations in practice. Factor rating and utility value analysis methods allow for consideration of different qualitative and quantitative factors for location decisions which are easily understood by managers. Some shortcomings are the subjectivity of these methods regarding the selection of factors and their scoring and weighting. Sensitivity analysis is important for practical application of factor rating and utility value analysis methods.

Recall Chap. 4, Supply Chain Strategy, and analyze the PPS case with regard to the following:

- Discuss the SC strategy of PPS with respect to Europe and the celluloid-free table tennis balls. What is the market to be served? Is there a reactive strategy preferred or is there a push strategy intended?
- What are the limitations given to Mr. Chen for the setup of the SCD in Europe?
- Assume that PPS wants to offer a 72 h delivery time to all customers in Europe when they order a packaging unit via a retail website. Discuss whether the SCD as intended by Mr. Chen can be used again or whether significant redesign efforts are required.

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